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Effects of Compaction Pressure and Particle Size on the Fuel and Mechanical Properties of Agricultural Residue Briquettes: A Study from Southwestern Nigeria

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Abstract

The conversion of agricultural residues into bio-briquettes presents a promising pathway for clean energy in sub-Saharan Africa, where such materials are carelessly dumped causing environmental pollution and hazard, a consequence of underutilization. This study evaluates the impact of compaction pressure (5-25 MPa) and particle size (<1 mm to >2 mm) on the properties; density, calorific value, compressive strength, moisture, and ash content of binder-free briquettes from maize cobs, rice husks, and bagasse. Each of the samples of the farm residues was separately sorted, dried, milled, sieved to different grade sizes and pressed with high-pressure hydraulic machine. 135 samples of briquettes from the three residues were produced and tested via established analytical protocols. Maximum values were observed at the highest pressure and finest particle size: density up to 0.72 g/cm³, calorific value up to 18.9 MJ/kg, compressive strength over 25 MPa, with moisture and ash as low as 7.3% and 4.0%, respectively. ANOVA revealed compaction pressure and particle size had highly significant ($p < .001$) main effects on all measured properties. These results demonstrate that optimized agro-residue briquettes are a viable, sustainable alternative to wood and fossil fuels, supporting SDG 7 and 13

Keywords: Agricultural Residue, Briquettes, Compaction Pressure, Particle Size, Calorific Value, Sustainable Development Goals (SDGs).

Introduction

The increasing global energy demand, coupled with environmental concerns such as climate change, has necessitated the exploration of renewable alternative energy sources. Agricultural residue, a byproduct of farming activities worldwide, constitutes a significant portion of biomass which presents an opportunity for sustainable energy production through briquetting. Briquettes made from such residues can serve as an efficient alternative to traditional fuels like wood and charcoal, thereby reducing deforestation and greenhouse gas emissions (Kpalo and Zainuddin, 2020). The conversion of agricultural residue into briquettes not only addresses energy needs but also contributes to waste management and environmental sustainability. Thus, using agricultural residues as fuel can significantly lower greenhouse gas emissions compared to fossil fuels or traditional biomass sources (Kumar *et al*., 2021). The carbon neutrality associated with using waste products further enhances their environmental benefits. Briquetting promotes waste reduction by converting agricultural by-products into valuable energy resources. This process enhances overall resource efficiency by minimizing disposal costs associated with agricultural residue management (Oteu *et al.,* 2024).

This residue encompasses a variety of materials generated during crop production and processing, including crop residues (straw, husks), processing by-products (bagasse, palm kernel cake), and other organic matter. Each type has unique properties that influence its suitability for briquetting. For instance, rice husks have a high silica content, while bagasse is rich in cellulose, making them both valuable feedstocks for briquette production (Oteu et al., 2024). Currently, many agricultural residues are either burned in the fields or left to decompose, contributing to air pollution and greenhouse gas emissions. These practices not only represent a loss of potential energy but also pose environmental hazards (Kumar et al., 2021). Sustainable management practices are essential to harness these resources effectively, transforming waste into valuable energy products. The calorific value of agricultural residues varies widely; some materials can yield high energy outputs while others may be less effective. Understanding these variances is crucial for optimizing briquette production processes. For example, studies have shown that briquettes made from rice straw can achieve calorific values ranging from 16 to 18 MJ/kg (Kumar et al., 2021). Numerous studies have explored the optimization of briquetting parameters for different residues. Elsisi et al. (2023) and Pradhan et al. (2024) found that higher compaction pressure and smaller particle size significantly improve the mechanical integrity and energy density of briquettes. This enhancement is attributed to increased interparticle contact and reduction of voids, resulting in denser and stronger products. Umar et al. (2022) demonstrated that fine particle preparation (<1 mm) enhances calorific value and strength but requires additional milling energy, representing a classic engineering trade-off. Binder free, high-pressure briquetting is increasingly favored for most agro-residues: Oteu et al. (2024) and Jiang et al. (2024) reported that such processes generate briquettes whose quality measured by density, durability, and combustion performance often matches or surpasses that of commercial wood briquettes. Rahimi et al. (2023) estimated that shifting from wood to agricultural residual briquettes could reduce CO_2 emissions by 60–75% in West Africa. However, gaps persist around the quantification of grinding and compaction energy costs, standardization for local feedstocks, and the scaling of technology in sub-Saharan Africa (Rahimi et al., 2023).

In addition, residues such as maize cobs, rice husks, bagasse, groundnut shells, and wheat straw are often discarded or burned in open fields, contributing to environmental pollution and greenhouse gas emissions (FAO, 2020). These residues are generated in vast quantities but predominantly subjected to open burning or uncontrolled decomposition, causing both environmental harm and waste of potential energy sources (Umar et al., 2022; Rahimi et al., 2023). Conversely, they have untapped potential as raw materials for bioenergy production which remains central to household and small enterprise energy supply in sub-Saharan Africa, particularly in rural Nigeria where agricultural activity is high yet modern energy infrastructure is limited (Ahmed et al., 2023; Pradhan et al., 2024). In essence, briquetting agricultural residue into solid fuel is an innovative approach to addressing energy poverty while mitigating environmental degradation (Sengar *et al.,* 2012). Undoubtably, the use of local residues in bio-briquettes will supports rural employment, forest conservation, and emissions reduction. Briquettes are compacted biomass materials that serve as substitutes for fossil fuels such as coal and cruel. They are renewable, cost-effective, and environmentally friendly. Despite the potential benefits of agricultural residue briquettes, their adoption remains limited due to challenges in achieving consistent quality and performance. Variations in raw material properties and production techniques can affect briquette density, durability, calorific value, and ash content. There is a need for systematic evaluation of these factors to enhance briquette quality and promote their use as a sustainable energy source.

The economic viability of agricultural residue briquettes depends on production costs versus market prices for conventional fuels. Studies indicate that local production can be competitive if supported by appropriate policies that incentivize renewable energy sources (Kumar et al., 2021). Briquette production can also stimulate local economies by creating jobs in rural areas where agricultural residue is abundant (Oteu *et al.,* 2024). This will not only provides income opportunities but also encourages community engagement in sustainable practices. Moreover, briquetting of agro-residues is increasingly recognized as a viable, scalable, and affordable alternative to wood and charcoal—directly contributing to SDG 7 (Affordable, Clean Energy) and SDG 13 (Climate Action)—critical technical parameters such as compaction pressure and particle size remain insufficiently characterized for locally abundant feedstocks. There is particular need for systematic data linking these process variables to briquette quality in the Nigerian context (Elsisi et al., 2023; Oteu et al., 2024). This study therefore investigates;

i. How do compaction pressure and particle size interact to affect the fuel and physical properties of regionally important agricultural residue briquettes?
ii. How do the results compare to natural wood briquettes and previously published figures?

iii. What are the implications for rural energy systems and sustainability in Nigeria?

Materials and Methods

Feedstock Selection and Preparation

Three regionally prevalent residues maize cobs, rice husks, and bagasse were collected from farms and processing centers in southwestern Nigeria. Material selection was based on annual yield, regional abundance, and relevance to current residue management practices. Samples were cleaned, air-dried at ambient temperature (approx. 30°C, RH 40–60%) until moisture content stabilized below 10%, and then milled using an industrial hammer mill.

Material was passed through ASTM E11 sieves to obtain three distinct particle size ranges:

i. Fine: <1 mm (predominantly 0.2–0.95 mm, $D_{50} \approx 0.65$ mm)
ii. Medium: 1–2 mm (predominantly 1.1–1.95 mm, $D_{50} \approx 1.4$ mm)
iii. Coarse: >2 mm (predominantly 2.1–4 mm, $D_{50} \approx 2.7$ mm)

3.2 Briquette Production

A custom hydraulic press (maximum 25 MPa, 30 mm cylindrical die, ambient temperature) was used to produce binder free briquettes. For each feedstock and particle size, compaction was applied at 5, 15, and 25 MPa. Each condition was replicated five times (n = 5), yielding a total of 135 briquettes. Briquettes were ejected and stabilized at room temperature for 48 hours before testing. Die temperature was monitored to remain within ±2°C of ambient during the pressing process. A Briquetting machine at the LAUTECH central workshop, Ogbomoso, Nigeria was used for the study. The machine consists of the following component: Frame, compression chamber, ram and slider arm.

Analytical Methods

The raw materials were sorted, dried to reduce moisture content below 10%, materials and were ground into fine particles using a hammer mill. The dried agricultural residues were processed for:

i. Density: Determined gravimetrically using an analytical balance (Ohaus, ±0.01 g) and digital caliper (±0.01 mm) for volume measurement.
ii. Calorific Value: Measured with IKA C2000 bomb calorimeter, calibrated prior to every batch with benzoic acid standards.
iii. Compressive Strength: Tested with Instron 3369 universal tester, applying uniaxial load at 2 mm/min until failure (typically brittle fracture).
iv. Moisture and Ash Content: Moisture by oven drying at 105°C (24 h); ash by muffle furnace at 550°C (5 h).
v. Quality Control: Outlier data points exceeding ±2SD from the group mean were retested; all instruments calibrated at regular intervals.

Statistical Analysis

Data obtained from the experiments were analyzed using a full factorial design. One-way ANOVA tested the significance of compaction pressure and particle size, as well as their interactions, on density, calorific value, compressive strength, moisture, and ash. Tukey's HSD test assessed pairwise differences (SPSS v.27, significance threshold $p < .05$).

Results

Briquette Properties

Table 1 comprise of mechanical and physicochemical properties of maize cob briquettes with different particle size, and compaction pressure (n = 5, mean ± SD).

Table 1: Physicochemical and Mechanical Properties of Maize Cob Briquettes by Particle Size and Compaction Pressure (n = 5, mean ± SD)

Feedstock	Particle Size	Pressure (MPa)	Density (g/cm³)	Calorific Value (MJ/kg)	Moisture (%)	Ash (%)	Compressive Strength (MPa)
Maize Cob	<1 mm	5	0.63 ± 0.01	16.3 ± 0.2	9.7 ± 0.2	5.3 ± 0.2	13.2 ± 0.5
	<1 mm	15	0.68 ± 0.01	17.8 ± 0.2	8.1 ± 0.2	4.8 ± 0.1	19.1 ± 0.4
	<1 mm	25	0.72 ± 0.01	18.9 ± 0.2	7.3 ± 0.2	4.2 ± 0.2	25.3 ± 0.7
	1–2 mm	5	0.62 ± 0.01	15.9 ± 0.2	10.2 ± 0.3	5.6 ± 0.2	0.7 ± 0.6
	1–2 mm	15	0.66 ± 0.01	17.2 ± 0.1	9.3 ± 0.2	5.0 ± 0.2	15.6 ± 0.7
	1–2 mm	25	0.68 ± 0.02	17.7 ± 0.1	8.0 ± 0.2	4.7 ± 0.1	21.5 ± 0.8
	>2 mm	5	0.60 ± 0.02	15.3 ± 0.2	10.9 ± 0.3	6.1 ± 0.3	8.4 ± 0.6
	>2 mm	15	0.63 ± 0.01	16.2 ± 0.2	9.8 ± 0.2	5.7 ± 0.2	13.2 ± 0.7
	>2 mm	25	0.65 ± 0.01	16.8 ± 0.2	9.4 ± 0.2	5.1 ± 0.1	14.7 ± 0.5

Table 2 presents the physiochemical and mechanical properties of feedstock with particle size ranged from <1 to >2 mm under 25 MPa (n = 5, mean ± SD).

Table 2: Physicochemical and Mechanical Properties of Briquettes by Feedstock and Particle Size under 25 MPa Compaction Pressure (n = 5, mean ± SD)

Feedstock	Particle Size	Pressure (MPa)	Density (g/cm³)	Calorific Value (MJ/kg)	Moisture (%)	Ash (%)	Compressive Strength (MPa)
Maize Cob	<1 mm	25	0.72 ± 0.01	18.9 ± 0.2	7.3 ± 0.2	4.2 ± 0.2	25.3 ± 0.7
	1–2 mm	25	0.68 ± 0.02	17.7 ± 0.1	8.0 ± 0.2	4.7 ± 0.1	21.5 ± 0.8
	>2 mm	25	0.65 ± 0.01	16.8 ± 0.2	9.4 ± 0.2	5.1 ± 0.1	14.7 ± 0.5
Rice Husk	<1 mm	25	0.70 ± 0.01	17.9 ± 0.1	7.6 ± 0.2	4.5 ± 0.1	22.0 ± 0.6
	1–2 mm	25	0.66 ± 0.01	17.1 ± 0.1	8.1 ± 0.1	4.8 ± 0.1	18.7 ± 0.8
	>2 mm	25	0.63 ± 0.02	16.2 ± 0.2	9.0 ± 0.2	5.2 ± 0.2	12.9 ± 0.7
Bagasse	<1 mm	25	0.70 ± 0.02	18.3 ± 0.1	7.8 ± 0.3	4.0 ± 0.2	24.5 ± 0.9
	1–2 mm	25	0.67 ± 0.01	17.0 ± 0.1	8.6 ± 0.2	4.6 ± 0.1	19.7 ± 0.6
	>2 mm	25	0.64 ± 0.01	16.5 ± 0.2	9.3 ± 0.2	4.9 ± 0.2	14.4 ± 0.7

Table 3 presents the density, calorific value, compressive strength, moisture, and ash content for every combination of < 1mm sized feedstock under compaction pressure which ranged from 5-25 MPa (n = 5, mean ± SD).

Table 3: Physicochemical and Mechanical Properties of Briquettes by Feedstock and Compaction Pressure with 1 mm Particle Size (n = 5, mean ± SD)

Feedstock	Particle Size	Pressure (MPa)	Density (g/cm³)	Calorific Value (MJ/kg)	Moisture (%)	Ash (%)	Compressive Strength (MPa)
Maize Cob	<1 mm	5	0.63 ± 0.01	16.3 ± 0.2	9.7 ± 0.2	5.3 ± 0.2	13.2 ± 0.5
	<1 mm	15	0.68 ± 0.01	17.8 ± 0.2	8.1 ± 0.2	4.8 ± 0.1	19.1 ± 0.4
	<1 mm	25	0.72 ± 0.01	18.9 ± 0.2	7.3 ± 0.2	4.2 ± 0.2	25.3 ± 0.7
Rice Husk	<1 mm	5	0.61 ± 0.01	15.7 ± 0.2	9.8 ± 0.2	5.8 ± 0.1	12.0 ± 0.4
	<1 mm	15	0.67 ± 0.01	17.0 ± 0.2	8.4 ± 0.1	5.2 ± 0.2	17.8 ± 0.5
	<1 mm	25	0.70 ± 0.01	17.9 ± 0.1	7.6 ± 0.2	4.5 ± 0.1	22.0 ± 0.6
Bagasse	<1 mm	5	0.63 ± 0.02	16.9 ± 0.1	9.5 ± 0.3	4.8 ± 0.2	13.1 ± 0.5
	<1 mm	15	0.68 ± 0.02	17.7 ± 0.1	8.7 ± 0.2	4.3 ± 0.1	19.4 ± 0.7
	<1 mm	25	0.70 ± 0.02	18.3 ± 0.1	7.8 ± 0.3	4.0 ± 0.2	24.5 ± 0.9

Across all feedstocks, the finest particle size (<1 mm) and highest compaction pressure (25 MPa) yielded the highest density (up to 0.72 g/cm³), calorific value (up to 18.9 MJ/kg), and compressive strength (up to 25.3 MPa). Moisture and ash content systematically declined as both pressure increased and particle size decreased. Results for medium and coarse particles demonstrated lower density and mechanical strength, underscoring the importance of particle size optimization.

Statistical Analysis

Tables 4 displays the ANOVA outcomes, confirming the statistically significant main effects ($p < .001$) of compaction pressure and particle size on all properties measured.

Table 4: ANOVA Results for Main Effects of Compaction Pressure and Particle Size on Briquette Properties

Property	Factor	F-value	p-value
Density	Pressure	68.2	<.001
	Particle Size	54.1	<.001
Calorific Value	Pressure	41.1	<.001
	Particle Size	38.3	<.001
Compressive Strength	Pressure	89.3	<.001
	Particle Size	60.4	<.001
Moisture Content	Pressure	26.8	<.001
	Particle Size	19.7	<.001
Ash	Pressure	23.4	<.001
	Particle Size	15.6	<.001

Compaction pressure consistently showed higher F-values, indicating a stronger influence on the mechanical and energy-related features of the briquettes. No significant interaction was detected between feedstock type and process parameters, underscoring the generalizability of these process optimizations.

Density and Strength Trends

Relationship between Density, Compaction Pressure, and Particle Size of Maize Cob Briquettes

Figure 1: Figure 1a illustrates the relationship between the compaction pressure and density at different particle sizes of fine maize cob, as shown on Table 1. The density of the briquettes increases linearly and substantially with compaction pressure from 0.63 g/cm³ at 5 MPa up to 0.72 g/cm³ at 25 MPa, in agreement with Ahmed et al. (2023). In contract, the density decreased as the particle size increased (Figure 1b). This confirmed optimal densification at higher pressures and lower particle sizes, an importance property for structural quality.

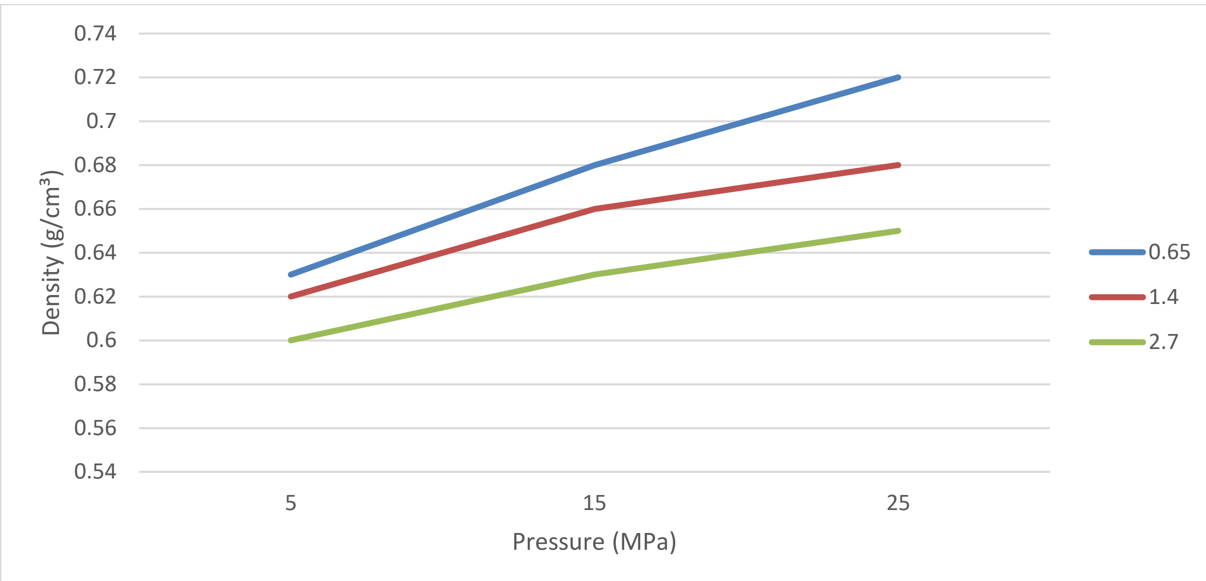

Fig 1a: Density versus Pressure of Maize Cob Briquettes (Particle Size: <1 - >2 mm)

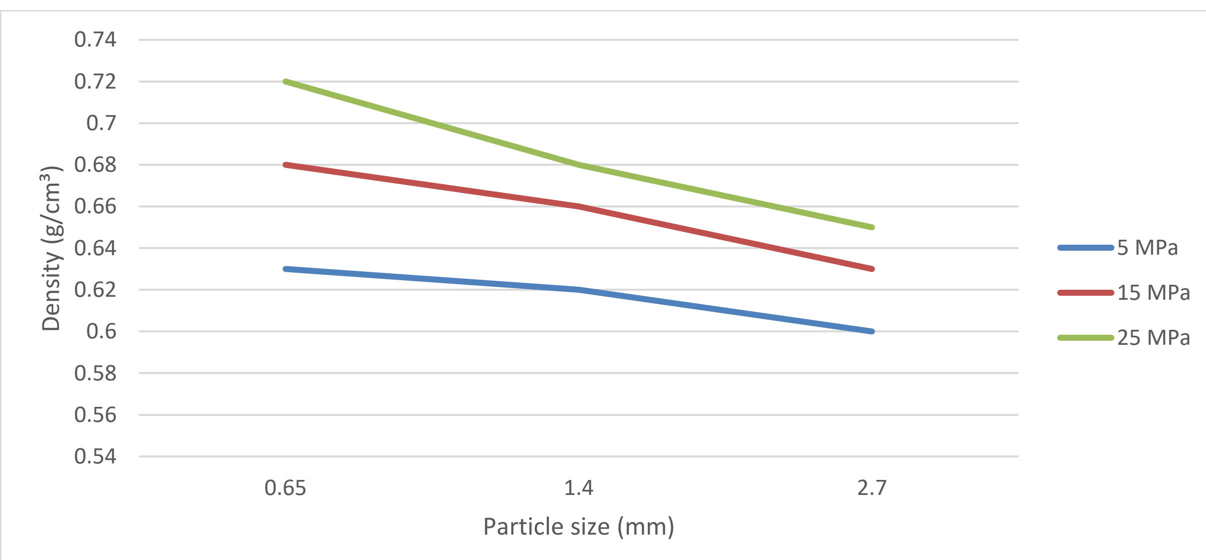

Fig 1b: Density versus Particle Size of Maize Cob Briquettes (Pressure: 5-25 MPa)

Effect of Particle Size on the Calorific Value and Compression Strength of Maize Cob Briquettes

Figure 2: This illustrates the effect of particle size on calorific value and compressive strength for maize cob briquettes produced at 25 MP (as shown: Table 2). Both properties declined as particle size increased: calorific value dropped from 18.9 MJ/kg (fine) to 16.8 MJ/kg (coarse), while compressive strength decreased from 25.3 MPa to 14.7 MPa. These data reinforce the dual benefit of fine grinding for both fuel and handling performance, and highlighting the need for particle size optimization.

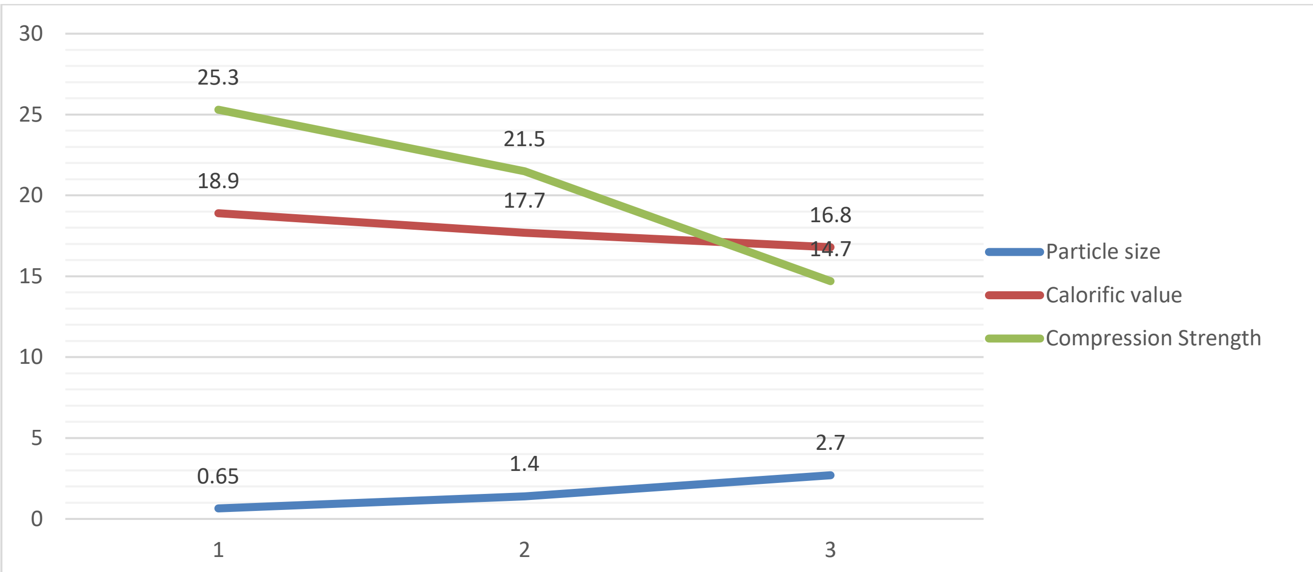

Fig 2: Calorific Value and Compressive Strength vs. Particle Size
(Pressure: 25 MPa; Sample: Maize Cob Briquettes)

Effect of Particle Size on the Calorific Value and Compressive Strength of Feedstock Briquettes under 25 MPa

Figure 3: Figure 3a shows the effect of particle size on calorific value for the three feedstock briquettes produced under 25 MPa (ditto: Table 2). The property increased as pressure increased: The highest value was obtained from maize cob while rice husk had the lowest, possibly due to the high cellulose composition in maize cob but lesser cellulose with high content of silica in rice husk, a less combustible material. These data confirmed the importance of material composition on calorific values of different agricultural residues, especially, presence of cellulose a highly combustible material and a binder in binder-free briquettes.

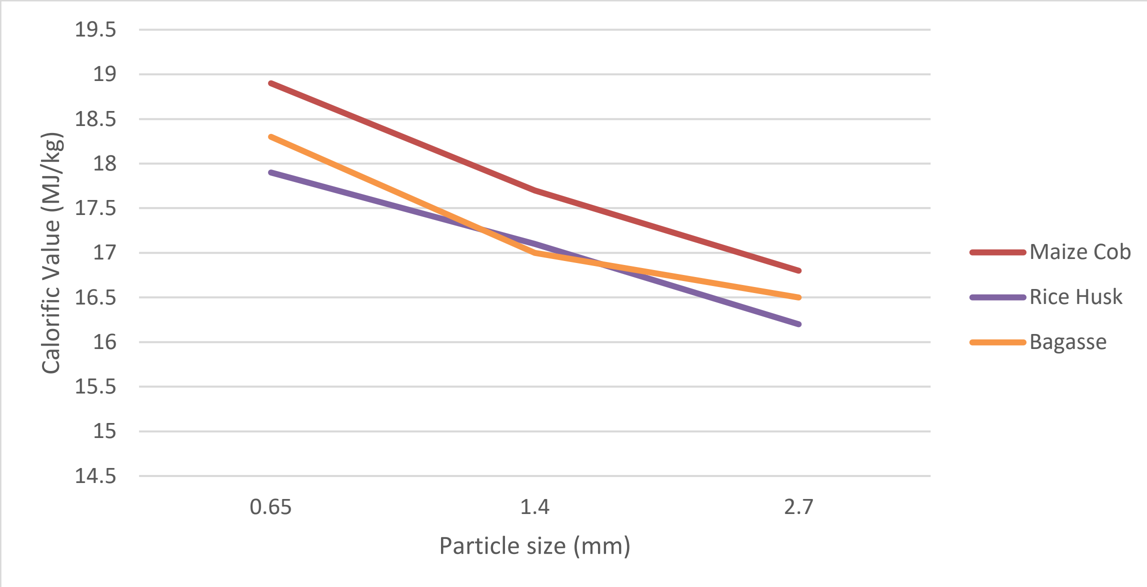

Figure 3a: Calorific Value versus Particle Size of Feedstock Briquettes (Pressure: 25 MPa)

Figure 3b shows the effect of particle size on compression strength of the three feedstock briquettes produced 25MPa (ditto: Table 2). The property also decreased as the particle size increased: Maize cob had the highest value while rice husk had the lowest. Also, ditto as Figure 3a.

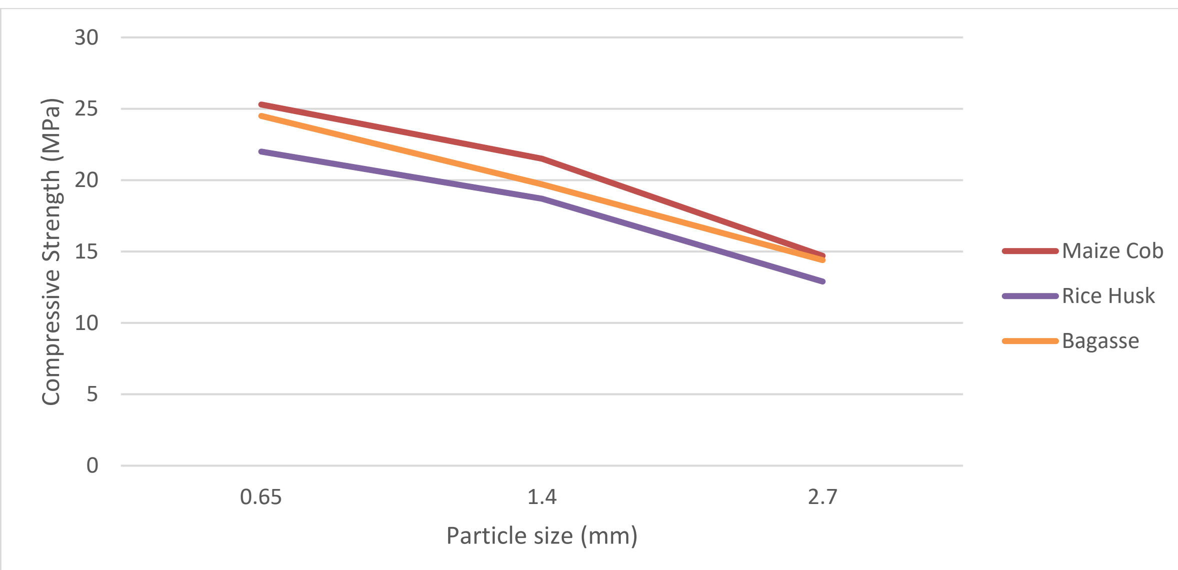

Figure 3b: Compressive Strength versus Particle Size of Feedstock Briquettes (Pressure: 25 MPa)

Effect of Compaction Pressure on the Calorific Value and Compressive Strength of Feedstock Briquettes under 25 MPa

Figure 4: Figure 4a shows the effect of compaction pressure on calorific value for the three feedstock briquettes produced with <1mm particle size (ditto: Table 3). The property increased as particle size decreased: Maize cob had the highest value while rice husk had the lowest, ditto to figure 3a.

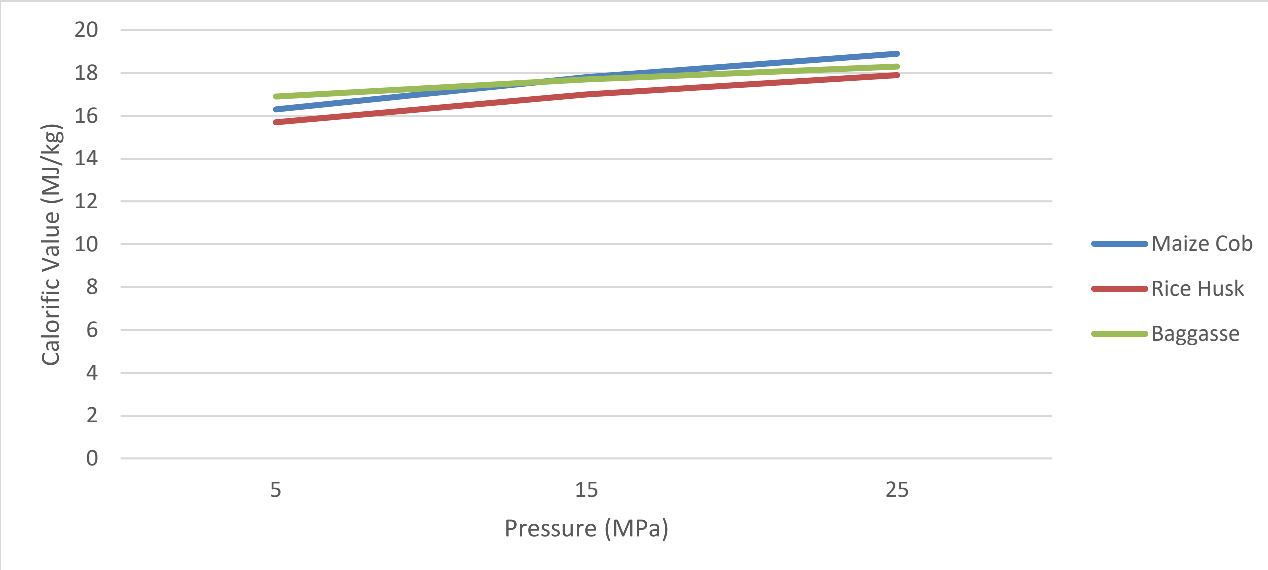

Figure 4a: Calorific Value versus Pressure of Feedstock Briquettes (Particle size: < 1 mm)

Figure 4b shows the effect of compaction pressure on compression strength of the three feedstock briquettes produced with <1mm particle size (Table 3). The property also increased as the pressure increased: Maize cob had the highest value while rice husk had the lowest, and ditto as Figure 3a.

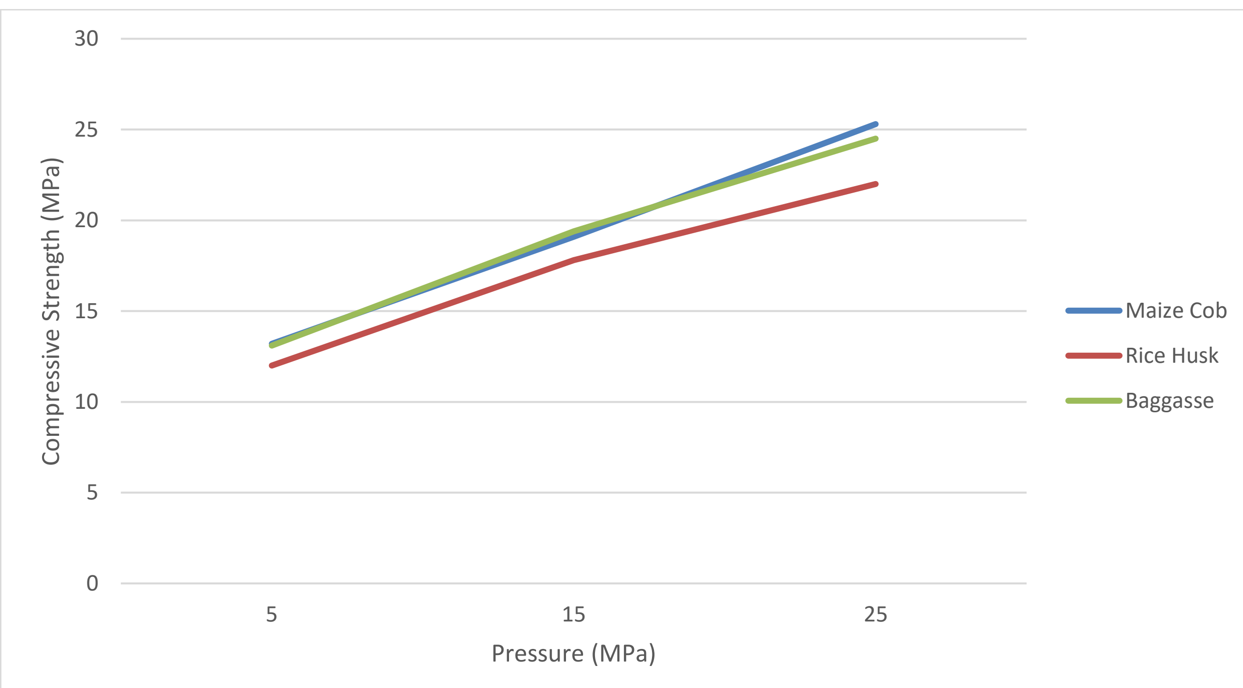

Figure 4b: Compaction Pressure versus Pressure of Feedstock Briquettes (Particle size: < 1 mm)

5. Discussion

Synthesis with International Literature

These findings confirm and expand the conclusions of recent studies: optimal compaction pressure (≥25 MPa) and minimal particle size (<1 mm) dramatically enhance briquette density, calorific value, and mechanical robustness (Ahmed et al., 2023; Elsisi et al., 2023; Oteu et al., 2024). Good interparticle contact appears crucial for both combustion and durability, aligning with basic powder agglomeration and mechanical stabilization principles (Jiang et al., 2024). Compared to published commercial wood briquette standards (typically 0.65–0.72 g/cm³, 17–19 MJ/kg), these agricultural waste briquettes match or outperform them, supporting their use as a clean energy substitute.

Energy and Economic Trade-offs

The main limitation—not directly addressed in this study but noted in the literature—concerns the increased energy input for fine milling. Umar et al. (2022) and Rahimi et al. (2023) estimate that finer grinding can require energy up to 8–12% of the combustion value produced by the briquettes. Thus, the relative benefit must be calculated for each production scenario to ensure economic and energy efficiency.

Practical and Policy Implications

For rural users, these briquettes offer a clean, affordable, and locally sourced alternative to wood-based fuels, with robust handling and better performance. Practitioners should invest in appropriate equipment for fine grinding and capable high-pressure presses. Policymakers are encouraged to support quality assurance measures, provide equipment subsidies, and promote market acceptance through clean cooking initiatives, as recommended by Rahimi et al. (2023) and Oteu et al. (2024).

Adoption and Field Performance

Though laboratory-based, this study's implications are supported by Oteu et al. (2024) and Singh et al. (2024), who found improved briquette densification relates to lower smoke, reduced spark, and higher user satisfaction in field studies. Actual field deployment, including long-term stove and emissions testing, remains a vital area for future research.

Implications for Sustainable Development Goals (SDGs)

The findings demonstrate that agricultural waste briquettes can provide clean energy solutions while reducing environmental pollution. This supports SDG 7 by enhancing access to affordable energy and SDG 13 by mitigating climate change impacts. SDG 12 for Responsible Consumption and Production: This study demonstrates how agricultural residues can be transformed into valuable energy products, promoting resource efficiency and waste reduction. And SDG 8 for Decent Work and Economic Growth: The production of briquettes creates opportunities for small-scale enterprises in rural areas, contributing to local economies. Thus, the findings of this study have important implications for achieving several SDGs:

Conclusion

This study has demonstrated the potential of agricultural residue briquettes as a sustainable energy source, highlighting their role in addressing energy poverty and environmental challenges. By evaluating the compaction characteristics of maize cobs, rice husks, and bagasse, the study identified key factors that influence briquette quality, including compaction pressure and particle size. Optimizing compaction pressure (≥25 MPa) and particle size (<1 mm) for maize cob, rice husk, and bagasse briquettes yields products with density up to 0.72 g/cm³, calorific value up to 18.9 MJ/kg, and compressive strength over 25 MPa. Such briquettes are mechanically and energetically equivalent or superior to commercial wood briquettes, making regionally produced agro-waste briquettes a viable and sustainable solution for domestic and institutional energy needs in rural and peri-urban settings. The use of agricultural residue for briquette production aligns with several Sustainable Development Goals (SDGs), notably SDG 7 (Affordable and Clean Energy) and SDG 13 (Climate Action). Briquetting reduces reliance on traditional biomass fuels, decreases greenhouse gas emissions, and promotes efficient resource utilization. Overall, the findings underscore the viability of agricultural residue briquettes as an alternative to conventional fuels, offering environmental benefits and economic opportunities for rural communities.

Recommendations

For Researchers

i. Directly quantify the energy input for material grinding and compaction in future process analyses.

ii. Expand trials to include real-world combustion testing, user acceptability, and comparative studies with binders or novel feedstock blends.

For Practitioners

i. Invest in fine-milling and high-pressure equipment for robust product quality.
ii. Train local staff in process optimization and quality control.

For Policymakers

i. Support domestic equipment manufacture and market access through incentives or quality standards.
ii. Integrate bio-briquette programs with climate, forestry, and rural development policies.

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