THERMAL PERFORMANCE COMPARISON OF CARBONIZED AND UNCARBONIZED BRIQUETTES DERIVED FROM MAIZE AGRICULTURAL WASTE
POREĐENJE TOPLITNIH PERFORMANSI KARBONIZOVANIH I NEKARBONIZOVANIH BRIKETA DOBIJENIH OD POLJOPRIVREDNOG OTPADA KUKURUZA

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ABSTRACT

This study presents a comparative evaluation of the thermal performance and combustion characteristics of four biomass briquette samples derived from maize residues: uncarbonized maize cob (Sample A), uncarbonized cob-stalk blend (Sample B), carbonized maize cob (Sample C), and carbonized cob-stalk blend (Sample D). Briquettes were produced using cassava starch as binder and shaped into standardized moulds cylindrical for uncarbonized and cuboidal for carbonized samples. Key performance metrics including density, moisture content, ash content, calorific value, fuel consumption rate, cooking efficiency, and fuel efficiency were analysed using ASTM protocols and empirical equations. Results showed that uncarbonized briquettes exhibited higher calorific values and mass, with Sample A recording the highest energy yield. However, Sample B demonstrated superior cooking efficiency (17.285%) and fuel efficiency (19.765%), coupled with the lowest fuel consumption rate (0.985 kg/hr), indicating optimal combustion dynamics. Carbonized briquettes, particularly Sample D, offered cleaner combustion and competitive fuel efficiency (18.235%) despite slightly lower energy values. These findings suggest that blending maize cob and stalk enhances briquette performance, and that uncarbonized briquettes especially cob-stalk mixtures offer a viable, low-cost solution for household energy needs in rural settings.
Keywords: *Biomass briquettes, Carbonization, Maize cob and stalk, cooking efficiency, Fuel efficiency*

REZIME

Ova studija predstavlja komparativnu procenu toplotnih performansi i karakteristika sagorevanja četiri uzorka briketa od biomase dobijenih od ostataka kukuruza: nekarbonizovana kukuruzna klip (Uzorak A), nekarbonizovana mešavina klipa i stabljike (Uzorak B), karbonizovana kukuruzna klip (Uzorak C) i karbonizovana mešavina klipa i stabljike (Uzorak D). Briketi su proizvedeni korišćenjem skroba od kasave kao veziva i oblikovani u standardizovane kalupe cilindrične za nekarbonizovane i kuboidne za karbonizovane uzorke. Ključni parametri performansi, uključujući gustinu, sadržaj vlage, sadržaj pepela, kalorijsku vrednost, stopu potrošnje goriva, efikasnost kuvanja i efikasnost goriva, analizirani su korišćenjem ASTM protokola i empirijskih jednačina. Rezultati su pokazali da nekarbonizovani briketi imaju višu kalorijsku vrednost i masu, pri čemu je Uzorak A zabeležio najveći energetski prinos. Međutim, Uzorak B je pokazao superiornu efikasnost kuvanja (17,285%) i efikasnost goriva (19,765%), uz najnižu stopu potrošnje goriva (0,985 kg/h), što ukazuje na optimalnu dinamiku sagorevanja. Karbonizovani briketi, posebno Uzorak D, obezbedili su čistije sagorevanje i konkurentnu efikasnost goriva (18,235%) uprkos nešto nižim energetskim vrednostima. Ovi nalazi sugerišu da mešanje kukuruznog klipa i stabljike poboljšava performanse briketa, te da nekarbonizovani briketi naročito mešavine klipa i stabljike predstavljaju održivo i niskobudžetno rešenje za energetske potrebe domaćinstava u ruralnim sredinama.
Ključne reči: *Briketi od biomase, Karbonizacija, Kukuruzni klip i stabljika, Efikasnost kuvanja, Efikasnost goriva*

INTRODUCTION

The global demand for sustainable and affordable energy sources has intensified interest in biomass as a renewable alternative, particularly in regions where agricultural residues are abundant. Among these residues, maize stalks and cobs are widely available byproducts of maize cultivation, often underutilized or disposed of through open field burning, contributing to environmental degradation and air pollution (Abbasi et al., 2014; Meena et al., 2024). Transforming these residues into biomass briquettes offers a dual benefit: mitigating waste and providing a cleaner energy source for domestic and industrial applications.

Biomass briquettes are compacted blocks of organic material that serve as solid fuel substitutes for wood, charcoal, and fossil fuels. Their production can follow two primary pathways: carbonization and uncarbonized densification. Carbonized briquettes are produced by pyrolyzing biomass in limited oxygen conditions to enhance energy density, reduce smoke emissions, and improve combustion efficiency (Oyewusi et al., 2020; Akinyemi & Ojo, 2021). In contrast, uncarbonized briquettes retain more of the original biomass structure and are typically easier and less energy-intensive to produce, though they may exhibit higher moisture content and lower calorific values (Adebayo & Olayemi, 2021).

The choice between carbonized and uncarbonized briquettes involves trade-offs in thermal performance, environmental impact, and production cost. While carbonized briquettes often offer superior combustion characteristics, uncarbonized briquettes

may be more accessible to rural communities due to simpler processing requirements (Ferronato et al., 2022). Understanding the comparative performance of these two briquette types is essential for guiding energy policy, rural development strategies, and sustainable waste management practices.

This study investigates the thermal performance of carbonized and uncarbonized briquettes derived from maize stalks and cobs. By evaluating key parameters such as calorific value, fuel consumption rate, cooking efficiency, and combustion behavior, the research aims to determine which briquette type offers the most efficient and practical solution for household and small-scale energy needs. The findings will contribute to optimizing biomass utilization and promoting cleaner energy alternatives in maize-producing regions.

MATERIALS AND METHOD

Biomass collection and preparation

Maize stalks and cobs were sourced from post-harvest fields in Oyo State, Nigeria. These residues were selected due to their abundance and suitability for briquette production, as supported by Muazu and Stegemann (2015) and Krizan et al. (2018). The biomass was divided into two treatment groups: carbonized and uncarbonized.

1.   For the uncarbonized group, maize residues were air-dried for five days to reduce moisture content below 15%, which is optimal for briquette formation and combustion efficiency (ASTM D4442-20). The drying process minimizes the energy required to evaporate water during combustion, thereby improving thermal performance.

2.   For the carbonized group, maize stalks and cobs were subjected to pyrolysis in a muffle furnace at 450°C for two hours under limited oxygen conditions. This process converts the biomass into a more energy-dense material by removing volatile compounds and increasing fixed carbon content (Oyewusi et al., 2020; Akinyemi & Ojo, 2021).

After drying or carbonization, the biomass was shredded using a mechanical grinder and sieved to achieve a uniform particle size of less than 10 mm. This particle size enhances compaction and binder interaction during briquette formation, as demonstrated by Chaloupková et al. (2018).

Fig. 1. Collected maize stalk and cob; prepared biomass

Binder preparation

Cassava starch was selected as the binder due to its natural adhesive properties, affordability, and local availability. Its role in briquette production is critical for enhancing structural integrity and combustion stability, especially in uncarbonized briquettes which lack the inherent cohesion of carbonized material (Zhang et al., 2018; Olugbade et al., 2019).

The binder was prepared from cassava processing effluent collected during the garri production stage. The liquid starch was allowed to sediment in a plastic container for 24 hours. After sedimentation, the supernatant was decanted, leaving behind a dense starch sludge. This sludge was sun-dried for another 24 hours to reduce moisture and concentrate the starch content.

To activate its binding properties, the dried starch was mixed with water in a stainless-steel pot and heated over a burner for approximately 8 minutes with continuous stirring. This process transformed the mixture into a gelatinous paste with viscous consistency, suitable for blending with biomass particles. The gelatinization process enhances the binder's ability to form cohesive briquettes by increasing its adhesive strength and thermal stability (Temmerman et al., 2006).

Although no direct formula is used in binder preparation, its proportion in the briquette mix was standardized at a 2:1 ratio of biomass to binder by weight. This ratio was selected based on prior studies indicating optimal performance in terms of durability and combustion efficiency (Aransiola et al., 2019).

Fig. 2. Prepared binder

Briquette formation

To facilitate comparative analysis, four distinct briquette samples were prepared based on feedstock composition and thermal treatment:

- Sample A: Uncarbonized maize cob

- Sample B: Uncarbonized mixture of maize cob and stalk (1:2 ratio)
- Sample C: Carbonized maize cob
- Sample D: Carbonized mixture of maize cob and stalk (1:2 ratio)

The briquetting process was conducted separately for carbonized and uncarbonized biomass samples to ensure consistency in comparative analysis. Each biomass type was mixed with cassava starch binder in a 2:1 weight ratio (biomass to binder), a proportion shown to enhance durability and combustion performance (Aransiola et al., 2019).

For the uncarbonized briquettes, the mixture was compacted using a hydraulic press into cylindrical moulds with dimensions of 70 mm diameter and 100 mm height. The volume of each cylindrical briquette was calculated using the formula:

$$V = \pi \times r^2 \times h \qquad 1$$

Where:

- r = radius of the cylinder (35 mm)
- h = height of the cylinder (100 mm)

For the carbonized briquettes, the mixture was pressed into rectangular cuboid moulds. The dimensions of these moulds were standardized at 60 mm × 60 mm × 30 mm. The volume of each cuboid briquette was calculated using:

$$V = l \times w \times h \qquad 2$$

Where:

- l = length (60 mm)
- w = width (60 mm)
- h = height (30 mm)

After moulding, all briquettes were oven-dried at 100°C until their moisture content stabilized between 8% and 15%, as recommended by ASTM D4442-20. This drying step is essential for improving combustion efficiency and mechanical strength.

To assess compaction quality, the density of each briquette was calculated using:

$$D = M/V \qquad 3$$

Where:

- M = mass of the briquette (kg)
- V = volume of the briquette (mm³)

This allowed for direct comparison of structural integrity and material packing between the carbonized cuboid and uncarbonized cylindrical briquettes.

Fig. 3. Processed uncarbonized briquette after drying

Fig. 4. Processed carbonized briquette after drying

Performance evaluation

To assess the thermal and combustion characteristics of both carbonized and uncarbonized briquettes, a series of laboratory tests were conducted. These tests focused on moisture content, ash content, calorific value, fuel consumption rate, cooking efficiency, and fuel efficiency. All evaluations followed standardized procedures and referenced established methodologies.

Moisture content

Moisture content was determined by weighing the briquette samples before and after oven drying at 105°C. The percentage moisture content was calculated using the formula:

$$Moisture\ Content\ (\%) = \frac{W_i - W_f}{W_i} \times 100 \qquad 4$$

Where:

- W_i = Initial weight before drying
- W_f = Final weight after drying

This metric is critical for combustion efficiency, as excess moisture reduces energy output and increases smoke production.

Ash content

Ash content was measured by combusting the briquette samples in a muffle furnace at 550°C for two hours. After cooling in a desiccator, the residue was weighed. The ash content was calculated using:

$$Ash\ Content\ (\%) = \frac{W_a}{W_s} \times 100 \qquad 5$$

Where:

- W_a = Weight of ash residue
- W_s = Initial sample weight

Ash content reflects the inorganic fraction of the briquette and influences combustion residue and stove maintenance.

Calorific value

The energy content of the briquettes was estimated using empirical formulas adapted from Onukak et al. (2017). Both Higher Calorific Value (HCV) and Lower Calorific Value (LCV) were calculated:

$$HCV \left(\frac{MJ}{kg}\right) = 20 \times (1 - A - M) \qquad 6$$

$$LCV \left(\frac{MJ}{kg}\right) = 18.7 \times [(1 - A - M) - (2.5 \times M)] \qquad 7$$

Where:

- A = Ash content (%)
- M = Moisture content (%)

These values provide insight into the energy potential of each briquette type.

Fuel consumption rate

Fuel consumption rate was determined by measuring the mass of briquettes before and after combustion over a fixed cooking time. The formula used was:

$$\text{Fuel Consumption Rate} \left(\frac{\text{kg}}{\text{hr}}\right) = \frac{W_i - W_f}{t} \qquad 8$$

Where:

- W_i = Initial fuel weight
- W_f = Final fuel weight
- t = Total cooking time (hr)

This metric indicates how quickly the briquette burns under cooking conditions.

Cooking efficiency

Cooking efficiency was evaluated using a water boiling test. The amount of water evaporated, and the energy released by the fuel were used to calculate efficiency:

$$\eta_c = \frac{M_w \times H_c}{M_f \times C_f} \qquad 9$$

Where:

- η_c = Cooking efficiency (%)
- M_w = Mass of water evaporated (kg)
- H_c = Heat of evaporation (2,260 kJ/kg)
- M_f = Fuel consumption rate (kg/hr)
- C_f = Calorific value of fuel (MJ/kg)

This test simulates real-world cooking scenarios and helps determine practical usability.

Fuel efficiency

Fuel efficiency was calculated using the method described by Richards (1990), which considers both sensible heat and latent heat contributions:

$$\eta_f = \frac{M_{w \times i} \times C_{p \times w} \times (t_e - t_i) + M_{w \times evp} \times H_l}{M_f \times H_f} \qquad 10$$

Where:

- η_f = Fuel efficiency (%)
- $M_{w \times i}$ = Initial water mass (kg)
- $C_{p \times w}$ = Specific heat of water (4.2 kJ/kg°C)
- t_e = Final water temperatures (°C)
- t_i = Initial water temperatures (°C)
- $M_{w \times evp}$ = Mass of water evaporated (kg)
- H_l = Latent heat of vaporization (2,260 kJ/kg)
- M_f = Fuel mass consumed (kg)
- H_f = Calorific value of fuel (MJ/kg)

This comprehensive metric captures the total useful energy delivered during cooking.

RESULTS AND DISCUSSION

Physical properties of briquettes

The physical characteristics of the briquettes varied significantly based on both shape and thermal treatment. Uncarbonized briquettes (Samples A and B) were moulded into cylindrical shapes with a volume of 384,845 mm³, while carbonized briquettes (Samples C and D) were cuboidal with a smaller volume of 108,000 mm³. Despite the larger volume,

uncarbonized briquettes exhibited higher mass and density values, indicating tighter compaction and greater binder retention.

Table 1. Physical properties of briquettes

Parameter	Sample A (Uncarbonized Cob)	Sample B (Uncarbonized Cob + Stalk)	Sample C (Carbonized Cob)	Sample D (Carbonized Cob + Stalk)
Shape	Cylinder	Cylinder	Cuboid	Cuboid
Volume (mm³)	384,845	384,845	108,000	108,000
Mass (kg)	0.221	0.207	0.193	0.185
Density (kg/mm³)	5.74×10^{-7}	5.38×10^{-7}	1.79×10^{-6}	1.71×10^{-6}

Carbonized briquettes had lower mass due to the loss of volatile matter during pyrolysis, yet their density was higher because of reduced moisture and increased fixed carbon content. This supports the findings of Oyewusi et al. (2020), who reported that carbonization enhances energy density but reduces bulk weight. The higher density of carbonized briquettes may contribute to faster ignition and more intense combustion, though it can also lead to quicker burnout if not properly managed.

Moisture and ash content

Moisture content is a critical factor in combustion performance. Uncarbonized briquettes retained more moisture (9.7–9.9%), while carbonized samples had significantly lower moisture levels (<5%), consistent with the drying effect of pyrolysis. Lower moisture improves combustion efficiency by reducing the energy needed to evaporate water before ignition.

Table 2. Moisture and ash content

Sample	Moisture Content (%)	Ash Content (%)
A	9.725	6.2
B	9.875	5.9
C	4.85	8.1
D	4.65	8.4

Ash content was higher in carbonized briquettes, ranging from 8.1% to 8.4%, compared to 5.9%–6.2% in uncarbonized samples. This increase is attributed to the concentration of inorganic matter following the removal of volatiles during carbonization.
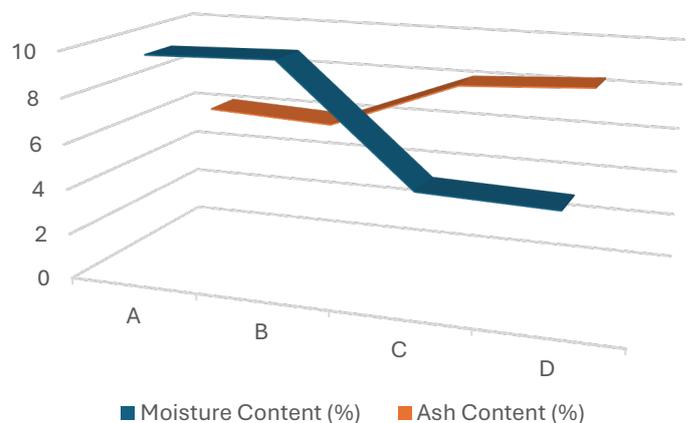

Fig. 5. Graphical representation of moisture and ash content

These results align with Akinyemi & Ojo (2021), who found that carbonized briquettes tend to produce less smoke but more ash, which can affect stove maintenance and residue disposal.

Calorific value

Calorific value determines the energy potential of a fuel. It was calculated using Equations 6 and 7, accounting for moisture and ash content. Uncarbonized briquettes, particularly Sample A, had slightly higher LCV and HCV values, likely due to the retention of organic compounds that contribute to energy release during combustion.

Table 3. Energy values of briquettes

Sample	LCV (MJ/kg)	HCV (MJ/kg)
A	16.385	17.785
B	16.075	17.385
C	15.845	17.145
D	15.625	16.985

Although carbonized briquettes had slightly lower calorific values, their combustion was cleaner and more stable. This trade-off between energy density and combustion quality is well-documented in biomass fuel studies (Onukak et al., 2017).

Fuel Consumption, Cooking Efficiency, and Fuel Efficiency

Fuel consumption rate and cooking efficiency were calculated using Equations 8 and 9. Sample B (uncarbonized cob + stalk) demonstrated the lowest fuel consumption (0.985 kg/hr) and highest cooking efficiency (17.285%), indicating optimal combustion dynamics. Sample D (carbonized cob + stalk) also performed well, suggesting that blending cob and stalk improves combustion regardless of carbonization.

Table 4. Cooking performance metrics

Sample	Fuel Consumption (kg/hr)	Cooking Efficiency (%)	Boiling Time (min)	Fuel Efficiency (%)
A	1.315	10.265	14	12.745
B	0.985	17.285	19	19.765
C	1.245	11.845	15	14.865
D	1.015	16.325	18	18.235

Fuel efficiency, calculated using Equation 10, provides a more comprehensive measure of how effectively the fuel converts energy into useful heat. Sample B again led with 19.765%, followed by Sample D at 18.235%. These results suggest that cob-stalk blends offer better thermal performance due to balanced porosity and binder interaction.
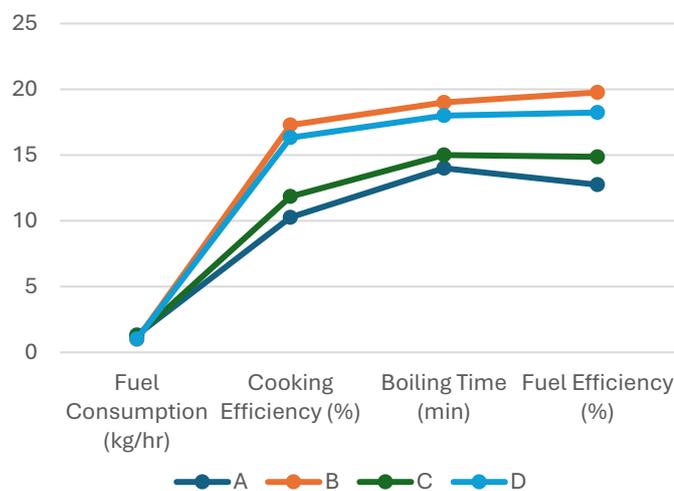

Fig. 6. Graphical representation of fuel consumption, cooking efficiency, and fuel efficiency

The longer boiling times observed in Samples B and D reflect slower, more sustained combustion, which is desirable for cooking applications. These findings are consistent with Ferronato et al. (2022), who emphasized the importance of fuel stability and efficiency in household energy use.

CONCLUSION

This study evaluated the thermal performance and combustion characteristics of four briquette samples derived from maize residues: uncarbonized maize cob (Sample A), uncarbonized cob-stalk blend (Sample B), carbonized maize cob (Sample C), and carbonized cob-stalk blend (Sample D). The results revealed that both feedstock composition and carbonization significantly influence briquette efficiency, energy yield, and practical usability.

Uncarbonized briquettes demonstrated higher calorific values and mass, with Sample A leading in energy content. However, Sample B an uncarbonized blend of cob and stalk outperformed all others in cooking efficiency (17.285%) and fuel efficiency (19.765%), while maintaining the lowest fuel consumption rate (0.985 kg/hr). This suggests that blending maize cob and stalk enhances combustion stability and heat retention, even without carbonization.

Carbonized briquettes, particularly Sample D, showed cleaner combustion and competitive fuel efficiency (18.235%), validating the benefits of pyrolysis in reducing moisture and volatile emissions. However, their slightly lower calorific values and faster burn rates may limit their effectiveness for prolonged cooking tasks unless optimized with binder and compaction strategies.

Overall, the findings support the viability of maize residues as a sustainable biomass resource. Uncarbonized cob-stalk briquettes offer a practical, low-cost solution for rural energy needs, while carbonized blends provide cleaner alternatives with moderate efficiency gains. Future work should explore binder variations, stove compatibility, and emissions profiling to further refine briquette performance and promote widespread adoption.

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