https://doi.org/10.47456/bjpe.v12i4.52845

ARTIGO ORIGINAL | OPEN ACCESS

Brazilian Journal of Production Engineering
BJPE - Revista Brasileira de Engenharia de Produção
Disponível em: https://periodicos.ufes.br/bjpe
ISSN: 2447-5580

SUSTAINABLE BIOCHAR BRIQUETTES FROM BIOMASS RESIDUES: PROCESS CONDITIONS AND ENERGY POTENTIAL

Briquetes sustentáveis de biocarvão a partir de resíduos de biomassa: condições de processo e potencial energético

Briquetas sostenibles de biocarbón a partir de residuos de biomasa: condiciones de proceso y potencial energético

Isabel Francisco Mucusse [1*], Tiago Henrique de Abreu Mateus [2], Gervásio Castro Morais Magaia [3], Baptista Joao Boanha [4], Navin Evaristo Momade Pereira [5], & Lorvelie Decius [6]

[1 2 5] Federal University of Mato Grosso do Sul, Faculty of Engineering, Architecture, Urbanism and Geography
[3] Federal University of Bahia, Polytechnic School [4] Zambeze University, Department of Environmental Engineering
[4] Federal University of Mato Grosso do Sul, Bioscience Institute [6] Federal University of Mato Grosso do Sul, Aquidauna Campus

[1*] isabelfrancisco2080@gmail.com [2] tiago.mateus@ufms.br [3] gervasiomagaia19@gmail.com [4] baptistabuan@gmail.com [5] navin.pereira@ufms.br [6] decius.l@ufms.br

ARTICLE INFO.

Received: 06.05.2026
Approved: 11.04.2026
Released: 11.17.2026

KEYWORDS: Biochar briquets; Lignocellulosic residues; Energy performance; Proximate analysis; Sustainable fuels.
PALAVRAS-CHAVE: *Briquetes carbonizados, Resíduos lignocelulósicos, Desempenho energético, Análise imediata, Combustíveis sustentáveis.*
PALABRAS CLAVE: *Briquetas carbonizadas; Residuos lignocelulósicos; Rendimiento energético; Análisis inmediato; Combustibles sostenibles.*

***Corresponding Author**: **Mucusse, I. F.**

ABSTRACT

This study evaluated the physical, mechanical, and energetic characteristics of carbonized briquettes produced from banana peels, sawdust, and recycled paper, using cassava starch as a binder. Five formulations (F1–F5) were investigated to assess the influence of biomass composition on apparent density, compressive strength, mechanical durability, proximate composition, higher heating value (HHV), and combustion performance. Apparent density ranged from 950 to 1060 kg m^{-3}, with F3 and F4 exhibiting compressive strength above 2 MPa and mechanical durability exceeding 95%. HHV ranged from 20.08 to 24.09 MJ kg^{-1}. F4 showed the highest mechanical resistance and durability, whereas F5 exhibited the highest HHV, associated with lower ash content and higher fixed carbon, together with lower apparent fuel consumption and burning rate. These contrasting responses demonstrate that mechanical robustness and gravimetric energy content are not necessarily maximized by the same formulation. The findings provide a basis for optimizing multi-residue carbonized briquettes according to their intended applications and highlight the potential of locally available biomass residues for alternative solid-fuel production.

RESUMO

Este estudo avaliou as características físicas, mecânicas e energéticas de briquetes carbonizados produzidos a partir de cascas de banana, serragem e papel reciclado, utilizando amido de mandioca como aglutinante. Foram investigadas cinco formulações (F1–F5) para avaliar a influência da composição da biomassa na densidade aparente, resistência à compressão, durabilidade mecânica, composição imediata, poder calorífico superior (PCS) e desempenho da combustão. A densidade aparente variou de 950 a 1060 kg m^{-3}, com as formulações F3 e F4 apresentando resistência à compressão superior a 2 MPa e durabilidade mecânica acima de 95%. O PCS variou de 20,08 a 24,09 MJ kg^{-1}. A formulação F4 apresentou a maior resistência mecânica e durabilidade, enquanto a F5 apresentou o maior PCS, associado ao menor teor de cinzas e ao maior teor de carbono fixo, juntamente com menor consumo aparente de combustível e menor taxa de queima. Esses comportamentos contrastantes demonstram que a robustez mecânica e o conteúdo energético gravimétrico não são necessariamente maximizados pela mesma formulação. Os resultados fornecem uma base para a otimização de briquetes carbonizados produzidos a partir de diferentes resíduos, de acordo com as aplicações pretendidas, e destacam o potencial dos resíduos de biomassa disponíveis localmente para a produção de combustíveis sólidos alternativos.

RESUMEN

Este estudio evaluó las características físicas, mecánicas y energéticas de briquetas carbonizadas producidas a partir de cáscaras de plátano, aserrín y papel reciclado, utilizando almidón de yuca como aglutinante. Se investigaron cinco formulaciones (F1–F5) para evaluar la influencia de la composición de la biomasa sobre la densidad aparente, la resistencia a la compresión, la durabilidad mecánica, el análisis inmediato, el poder calorífico superior (PCS) y el comportamiento durante la combustión. La densidad aparente osciló entre 950 y 1060 kg m^{-3}, y las formulaciones F3 y F4 presentaron una resistencia a la compresión superior a 2 MPa y una durabilidad mecánica superior al 95%. El PCS varió entre 20,08 y 24,09 MJ kg^{-1}. La formulación F4 presentó la mayor resistencia mecánica y durabilidad, mientras que F5 registró el mayor PCS, asociado con un menor contenido de cenizas y un mayor contenido de carbono fijo, junto con un menor consumo aparente de combustible y una menor tasa de combustión. Estos comportamientos contrastantes demuestran que la robustez mecánica y el contenido energético gravimétrico no necesariamente se maximizan con una misma formulación. Los resultados proporcionan una base para optimizar briquetas carbonizadas elaboradas a partir de diferentes residuos, según sus aplicaciones previstas, y destacan el potencial de los residuos de biomasa disponibles localmente para la producción de combustibles sólidos alternativos.

CC BY 4.0 DEED Attribution 4.0 International

INTRODUCTION

The global energy system is facing one of the most pressing challenges of our time: reducing dependence on fossil fuels while transitioning toward cleaner and more sustainable energy sources. This transition is no longer merely an environmental aspiration but has become an urgent necessity to mitigate the impacts of climate change and promote sustainable development (IEA, 2025). In this context, the valorization of organic waste for bioenergy production has gained increasing attention, as it represents a strategy capable of combining resource-use efficiency, environmental impact reduction, and the advancement of a circular economy (Akowuah et al., 2012; FAO, 2018).

Among biomass residues with potential for energy recovery, sawdust from the timber industry, banana peels, and wastepaper represent promising feedstocks for solid biofuel production. In developing regions, particularly Sub-Saharan Africa, limited waste recovery and recycling infrastructure may contribute to the accumulation of sawdust in sawmills and the uncontrolled disposal of organic and paper waste. Under anaerobic conditions, the decomposition of biodegradable residues can generate methane, a potent greenhouse gas, contributing to environmental impacts associated with inadequate waste management (Adeleke et al., 2026; Njimou et al., 2026).

Beyond their potential for waste valorization, combining these materials is scientifically relevant due to their distinct chemical compositions and thermal conversion characteristics. Sawdust contains lignocellulosic components that influence char formation, banana peels contain organic and mineral constituents that may affect ash content, and wastepaper provides a predominantly cellulose-based feedstock with distinct thermal degradation properties (Afraz et al., 2024; Chen et al., 2024; Batuer et al., 2026). These differences provide a basis for investigating how blending proportions influence the physicochemical properties and energy performance of carbonized briquettes (Duangkham & Thuadaij, 2023). Briquetting has emerged as an effective approach for converting such residues into value-added solid fuels. The process involves biomass densification, which increases energy density and facilitates transportation, storage, and utilization as an energy source (Olugbade et al., 2019). However, the benefits can be significantly enhanced when the biomass undergoes carbonization prior to briquetting.

Carbonized briquettes exhibit higher fixed carbon content, lower smoke emissions during combustion, and greater calorific values than briquettes produced from non-carbonized biomass, making them a more efficient alternative for both household and industrial energy applications (Alves et al., 2022; Mekonen et al., 2024).

The importance of this technology becomes even more evident when considering the energy reality of many communities in developing countries. Across numerous regions, millions of households rely on traditional charcoal as their primary source of energy for cooking and heating (Mwampamba et al., 2013). This dependence places increasing pressure on forest resources, driving excessive tree harvesting for charcoal production and contributing to environmental degradation and biodiversity loss. In this regard, the development of alternative fuels derived from locally available residues may represent an important strategy for reducing the exploitation of native forests while simultaneously expanding access to sustainable and economically viable energy sources (Kebede et al., 2022).

CC BY 4.0 DEED Attribution 4.0 International

In this context, the present study evaluates the energy potential of carbonized briquettes produced from different proportions of sawdust, banana peels, and recycled paper. To this end, physicochemical analyses and combustion tests were conducted to compare the performance of the different formulations and identify the most efficient composition in terms of fuel quality. The findings are expected to contribute to the development of sustainable alternatives to conventional charcoal by promoting waste valorization and renewable energy generation in regions where biomass continues to play a fundamental role in the energy matrix.

MATERIALS AND METHODS

Raw Materials and Pre-treatment

This study evaluated the energy performance of biomass briquettes produced from locally available organic and lignocellulosic residues. The raw materials (Figure 1) consisted of banana peels (Musa spp.), wood sawdust, recycled paper, cassava starch and water. These materials were selected based on their high local availability, low economic cost, and potential for valorization within circular bioeconomy frameworks. All residues were collected in the municipality of Chimoio, central Mozambique (19°07'54.5"S 33°29'13.4"E), a regional commercial hub characterized by significant daily generation of organic waste from food markets and small-scale agro-processing activities. Banana peels were obtained from fruit vendors, sawdust from local carpentry workshops, and recycled paper from municipal waste streams. Thus, all materials were subjected to controlled pre-treatment procedures to ensure homogeneity and improve briquette quality.

Figure 1. Main materials used for briquette production (A) wood sawdust (B) banana peel



Banana peels were air-dried under controlled laboratory conditions (25 ± 2°C; relative humidity 60 ± 5%) for 48h to reduce moisture content and enhance material pliability. Subsequently, the material was manually fragmented into smaller particles. Recycled paper was shredded into smaller particles to facilitate handling and thermal processing. Each biomass residue (banana peels, sawdust, and recycled paper) was carbonized separately in a muffle furnace using porcelain crucibles fitted with lids to restrict oxygen availability during thermal treatment. The furnace operated under a non-programmed progressive heating regime from ambient temperature to a final carbonization temperature of 500°C, without a predefined heating rate. Once the target temperature was reached, the samples were maintained at 500°C for an isothermal holding period of 2h, excluding the initial heating stage. This temperature was selected to promote the thermal decomposition of lignocellulosic constituents and char formation, while considering the trade-off between carbonization severity and solid char yield (Antal & Grønli, 2003; Demirbas, 2004). Following carbonization, the resulting chars were ground and sieved to obtain particles smaller than 2mm.

CC BY 4.0 DEED Attribution 4.0 International

Cassava starch was used as the sole binding agent at a concentration of 7% (w/w) relative to the dry mass of the carbonized biomass mixture, corresponding to 7g of dry starch per 100g of char. The starch was gelatinized in water before incorporation into the carbonized materials to promote interparticle adhesion and improve briquette cohesion (Adeleke et al., 2026; Nonsawang et al., 2026).

Experimental Design and Briquette Production

The experiment followed a completely randomized design comprising five treatments corresponding to different biomass formulations (F1-F5). Five independent batches were prepared for each formulation (n=5), resulting in a total of 25 experimental batches. Each batch was prepared separately using the predefined proportions of carbonized biomass components, followed by binder incorporation, moisture adjustment, and briquette production. The independently prepared batches constituted the experimental units for statistical comparisons among formulations (Table 1).

Table 1. Dry-mass proportions of carbonized biomass components used in the five briquette formulations

Formulations	Banana peel char (%)	Sawdustchar (%)	Recycled Paper char (%)
F1	50%	50%	0%
F2	40%	40%	20%
F3	30%	40%	30%
F4	20%	40%	40%
F5	20%	60%	20%

* Note: The proportions of carbonized biomass components sum to 100% within each formulation. Cassava starch was added separately at 7g per 100g of dry char and is not included in the percentages shown.

The formulation design was intended to investigate the influence of different proportions of carbonized banana peels, sawdust, and recycled paper on briquette properties. These feedstocks were combined because their distinct chemical compositions and thermal conversion characteristics may influence the physicochemical, mechanical, and combustion performance of the resulting briquettes. Cassava starch was used as the sole binding agent to promote interparticle adhesion and improve briquette cohesion (Demirbas, 2004; Kaliyan & Morey, 2009; Nonsawang et al., 2026). For each independent batch, the previously carbonized biomass components were weighed according to the predefined formulation ratios (Table 1) and thoroughly mixed.

Cassava starch, previously gelatinized in water, was then incorporated at a dosage of 7 g per 100 g of dry char. The mixture was manually homogenized to promote uniform binder distribution throughout the carbonized biomass particles. Prior to compaction, the moisture content of each mixture was adjusted to 15-20% (wet basis), the working moisture range adopted for briquette production. Moisture content was determined using the oven-drying method according to ISO 18134-1:2022. Water was gradually added while manually homogenizing the mixtures until a uniform and moldable consistency was achieved. This moisture range enhances inter-particle bonding through liquid bridge formation and reduces post-compaction expansion (spring back), thereby improving structural stability and density retention (Grover & Mishra, 1996; Kaliyan & Morey, 2009; Mitchual et al., 2014; Dinesha et al., 2019).

Briquettes were produced using a hydraulic press (model YLJ-15T, Shenyang Kejing Auto-Instrument Co., Ltd., Shenyang, China) equipped with a cylindrical metallic mold with an

CC BY 4.0 DEED Attribution 4.0 International

internal diameter of 40mm and a cavity height of 50mm. Approximately 70g of the conditioned char–binder mixture was introduced into the mold for each briquette. Mechanical densification was performed by applying a uniaxial compressive load of 2kN, corresponding to a nominal compaction pressure of 19.89MPa, calculated from the mold cross-sectional area. The applied load was maintained for 30 s before briquette ejection. These compaction conditions were adopted to obtain cohesive briquettes under laboratory-scale production conditions (Kaliyan & Morey, 2009; Mitchual et al., 2014; Dinesha et al., 2019). Five independent experimental batches were prepared for each formulation.

Additional briquettes of the same formulations were manufactured using the corresponding biomass proportions and processing conditions to meet the fuel requirements of the Water Boiling Test (WBT). Multiple briquette units were combined to obtain a standardized fuel charge of 200 g per combustion trial. Thus, the total number of briquettes manufactured exceeded the number of experimental batches used for laboratory characterization. After compaction, the briquettes were removed from the molds and oven-dried at 105 ± 2 °C for 24hr to reduce residual moisture and promote dimensional stability before characterization.

Physicochemical Characterization and Fuel Performance Assessment

The apparent density of each briquette was determined from its dry mass and geometric volume. Assuming a cylindrical shape, the briquette volume was calculated as:

$$V = \pi r^2 h \quad (1)$$

Density was calculated as:

$$\rho = \frac{m}{V} \quad (2)$$

Where: r is the briquette radius and h is the briquette height, ρ is the apparent density (kg m^{-3}), m is the dry mass of the briquette (kg), and V is briquette volume (m^3).

The mechanical performance of the briquettes was evaluated through compressive strength and durability tests, and the compressive strength was evaluated using a hydraulic press (model YLJ-15T, Shenyang Kejing Auto-Instrument Co., Ltd., Shenyang, China). Individual briquette specimens were subjected to uniaxial compression until mechanical failure, and the maximum applied force (Fmax, N) was recorded. Compressive strength (σ, MPa) was calculated as:

$$\sigma = \frac{F_{max}}{A} \quad (3)$$

where σ is the compressive strength (Pa), Fmax is the maximum applied force (N), and A is the loaded cross-sectional area (m^2). Values were converted to MPa for reporting. Measurements were performed using five specimens per formulation, corresponding to the five independently prepared batches (n=5). Resistance to impact-induced fragmentation was assessed using a drop test. Each briquette specimen was initially weighed and subsequently subjected to 10 consecutive drops from a height of 1m onto a rigid surface. The mass of material retained after the drop sequence was used to calculate the percentage of mass retained. Durability was calculated as:

$$D = \frac{m_f}{m_i}.100 \quad (4)$$

where D is the mass retention after the drop test (%), mi is the initial briquette mass (g), and mf is the mass retained after the drop sequence (g).

CC BY 4.0 DEED Attribution 4.0 International

Proximate analysis was performed to determine volatile matter (VM), ash content (AC), and fixed carbon (FC) in the carbonized briquette samples. All results were expressed on a dry-mass basis. Volatile matter (Equation 5) was determined by heating oven-dried samples in covered crucibles at 900 ± 10 °C for 7min (ASTM D3175). Ash content was determined by complete combustion at 550 ± 10°C for 4hr in an open crucible (ISO 18122:2022). The residue was weighed after cooling in a desiccator, and AC was calculated relative to the dry mass according to Equation 6. The fixed carbon content, which represents the solid combustible residue that remains after the volatiles are expelled, was estimated by difference on a dry basis according to Equation 7.

$$VM(\%) = \frac{(M_i - M_f)}{M_s} * 100 \quad (5)$$

$$AC(\%) = \left(\frac{M_{ash}}{M_s}\right) * 100 \quad (6)$$

$$FC(\%) = 100 - (VM + AC) \quad (7)$$

where Mi is the initial mass of the crucible and dry sample before volatile matter determination (g), Mf is the mass of the crucible and remaining residue after heating (g), Ms is the initial dry sample mass (g), and Mash is the mass of ash remaining after combustion, excluding the crucible mass (g). VM, AC, and FC represent volatile matter, ash content, and fixed carbon, respectively, expressed as percentages on a dry-mass basis. The higher heating value (HHV) of briquettes was determined using an adiabatic bomb calorimeter (model 5E-C5500®, manufactured by Changsha Kaiyuan Instruments Co., Ltd., Changsha, Hunan, China), following ASTM D5865.

The calorimeter was calibrated using benzoic acid as a reference standard prior to measurements. Each sample was tested in five replicates, and results were expressed as mean values in MJ kg^{-1} (dry basis) (Kaliyan & Morey, 2009).

Combustion performance was evaluated using a laboratory-scale water boiling test (WBT) adapted from the methodology described by Bailis et al. (2007). The test was used to assess the combustion performance of the different briquette formulations under comparable experimental conditions. Thus, they were conducted under laboratory conditions at an ambient temperature of 25 ± 2°C. In each trial, 1L of water was heated in an aluminum pot using a standardized fuel charge of 200g in a laboratory-scale combustion chamber. For each formulation, the fuel charge consisted of multiple briquettes produced using the same biomass proportions and processing conditions as those used for laboratory characterization.

The following parameters were recorded during each trial: time required for the water to reach boiling (min), initial and final fuel mass (g), and residual mass, including ash and unburned material (g). Five independent combustion trials were conducted for each briquette formulation (n=5), each using an initial fuel charge of 200g and 1L of water. At the end of each trial, the total residual mass, including ash and unburned material, was weighed. Accordingly, fuel consumption (FCu) was operationally defined as the apparent loss of fuel mass, calculated by subtracting the total residual mass from the initial fuel mass. Specific fuel consumption and burning rate were derived from this apparent mass loss under the adopted experimental conditions.

CC BY 4.0 DEED Attribution 4.0 International

Fuel consumption (FCu, g) was calculated using Equation 8, and specific fuel consumption (SFC, g kg^{-1}) was calculated as the mass of fuel consumed per unit mass of water initially used in the test:

$$FCu = m_i - m_f \quad (8)$$

Specific fuel consumption (SFC, g kg^{-1}) was calculated as the mass of fuel consumed per unit mass of water initially used in the test:

$$SFC = \frac{FCu}{M_w} \quad (9)$$

The average burning rate (BR, g min^{-1}) was calculated as the mass of fuel consumed divided by the elapsed combustion time:

$$BR = \frac{FCu}{t} \quad (10)$$

Where: m_i and m_f are initial and final fuel mass (g), respectively, SFC is the specific fuel consumption (g kg^{-1}) and Mw is the mass of water boiled (Kg). Also, the water boiling tests were conducted using the same experimental setup and operating conditions for all briquette formulations. Commercial charcoal was included as a reference fuel and evaluated under comparable experimental conditions.

STATISTICAL ANALYSIS

Data were summarized as mean ± standard deviation (SD). For comparisons among biomass formulations, the five independently prepared batches per formulation (n=5) were considered the experimental units. The assumptions of normality and homogeneity of variances were assessed using the Shapiro–Wilk and Levene tests, respectively. Differences among the five biomass formulations were assessed using one-way analysis of variance (ANOVA), with formulation as the explanatory factor. When a significant overall effect was detected, Tukey's honestly significant difference (HSD) test was applied for pairwise comparisons among formulations. Comparisons between briquette formulations and commercial charcoal were performed using independent-samples t-tests for the corresponding fuel performance variables. Pearson correlation analysis was performed to examine linear relationships among briquette apparent density, ash content, higher heating value (HHV), and fuel consumption. All statistical analyses were performed using Python version 3.11. Statistical significance was evaluated at α=0.05.

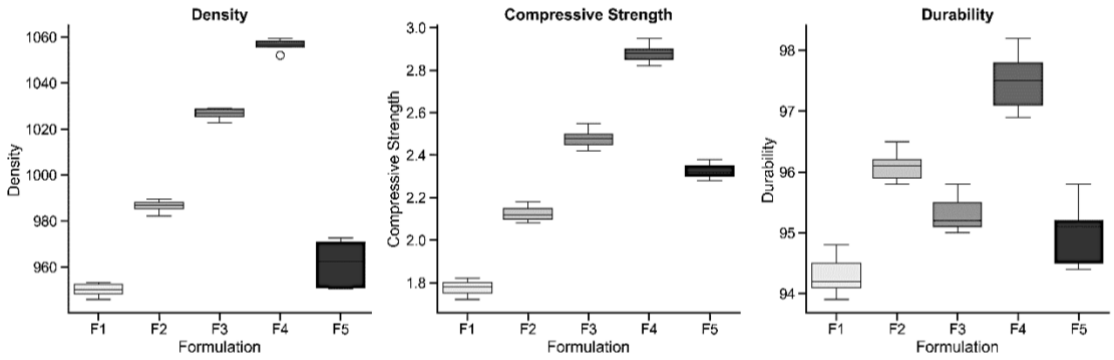
RESULTS

Physical Properties of Carbonized Briquettes

Physical properties varied among formulations (F1-F5), reflecting differences in biomass composition, while binder concentration remained constant (Figure 2). Apparent density increased from 950kg m^{-3} in F1 to 1056.46kg m^{-3} in F4, before decreasing to 961.42kg m^{-3} in F5. This deviation indicates that increasing the sawdust char proportion in F5 did not favor further densification under the adopted processing conditions. Compressive strength generally followed the density trend, increasing from 1.77MPa in F1 to 2.88MPa in F4, while mechanical durability reached its maximum in F4 (97.5%). Both properties decreased in F5, with compressive strength of 2.32MPa and durability of 95.0%. Thus, F4 exhibited the most favorable overall mechanical performance among the evaluated formulations.

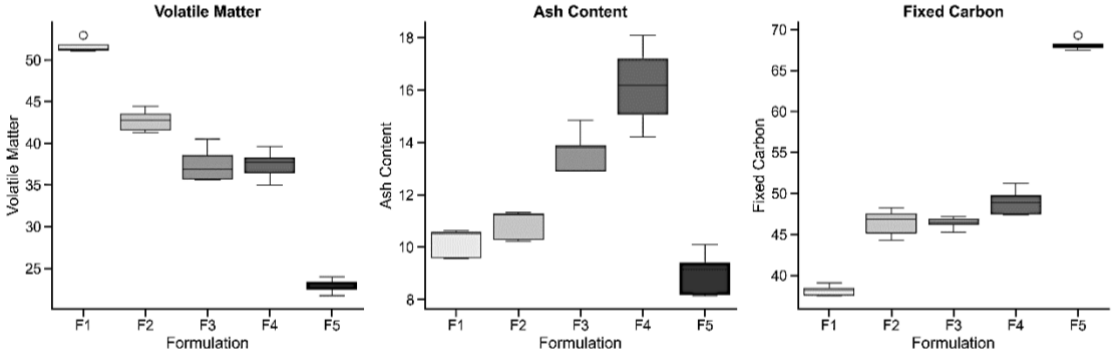
CC BY 4.0 DEED Attribution 4.0 International

Figure. 2. Physical properties of briquette formulations (F1-F5): (a) bulk density; (b) compressive strength;and (c) durability



Ash content increased from 10.17% in F1 to 16.16% in F4, followed by a marked decrease to 8.99% in F5. Volatile matter declined from 51.67% in F1 to 22.83% in F5, whereas fixed carbon increased from 38.16% to 68.18%. Unlike F4, F5 combined lower ash content with substantially higher fixed carbon, indicating a distinct fuel composition associated with its greater proportion of sawdust char. Figure 3 illustrates the chemical composition of the briquette samples obtained through proximate analysis. The boxplots depict the percentage distribution of volatile matter, ash content, and fixed carbon for each formulation (F1–F5).

Figure 3. Proximate analysis of briquette formulations (F1-F5): (a) volatile matter; (b) ash content; and (c) fixed carbon



The thermochemical characterization and physic-mechanical properties of the produced carbonized briquettes are summarized in Table 2. The data represent mean values and standard deviations for five distinct formulations (F1-F5), processed under controlled carbonization and compaction conditions.

Table 2. Physical, mechanical, and proximate properties of carbonized briquettes produced from different biomass residue formulations. (Mean ± Standard Deviation, n=5)

Formulation	Density (Kg m^{-3})		Comp.Strength		Durability		VM		AC		FC	
	mean	std	mean	std	mean	std	mean	std	mean	std	mean	std
F1	950	3.11	1.77	0.04	94.3	0.35	51.67	0.772	10.17	0.55	38.16	0.65
F2	986.38	2.84	2.13	0.04	96.1	0.27	42.71	1.32	10.87	0.56	46.42	1.62
F3	1026.52	2.66	2.48	0.049	95.32	0.33	37.44	2.073	13.67	0.81	46.4	0.73
F4	1056.46	2.82	2.88	0.049	97.5	0.52	37.38	1.75	16.16	1.56	48.94	1.59
F5	961.42	10.54	2.32	0.04	95	0.57	22.83	0.89	8.99	0.84	68.18	0.68

*Density (kg/m^3), Compressive Strength (MPa), Durability (%), VM - Volatile Matter (%), AC - Ash Content (%), FC - Fixed Carbon (%).

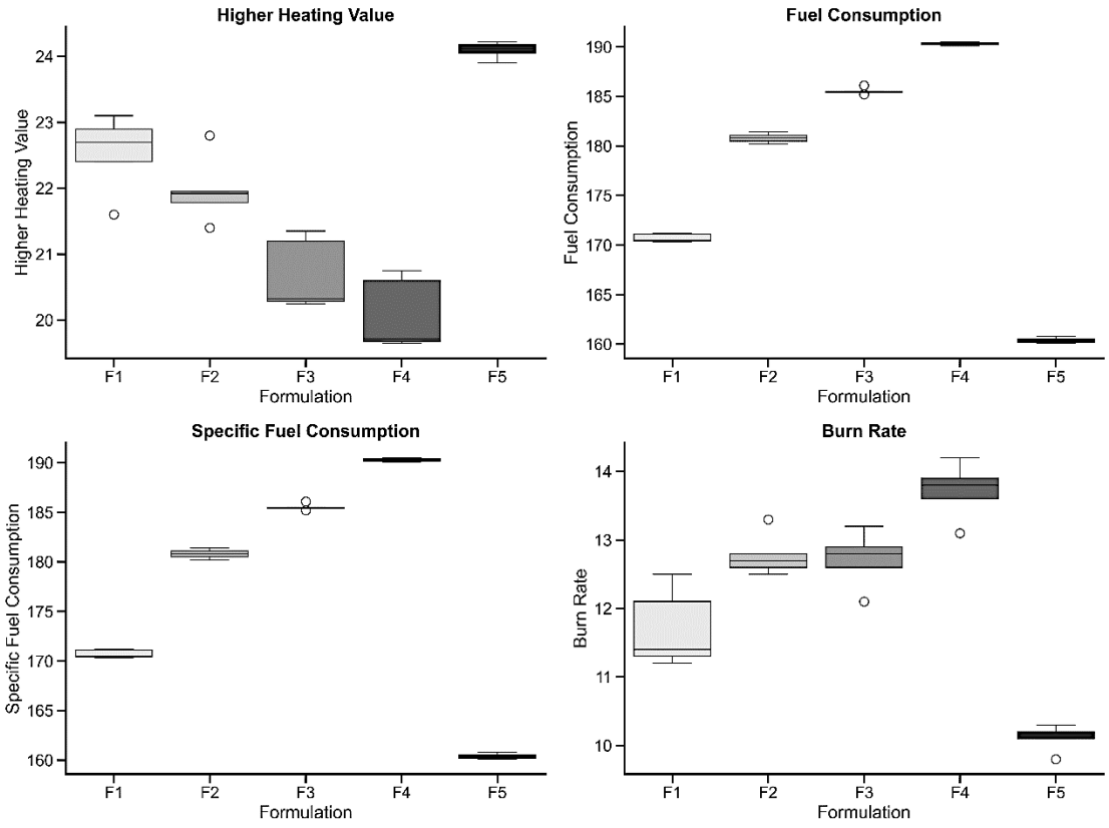
Combustion Performance

The higher heating value (HHV) decreased from 22.54MJ kg^{-1} in F1 to 20.08MJ kg^{-1} in F4, before increasing to 24.09MJ kg^{-1} in F5. This reversal coincided with the lower ash content and higher fixed-carbon fraction observed in F5, contrasting with the superior mechanical performance of F4. Fuel consumption and specific fuel consumption (SFC), calculated from

CC BY 4.0 DEED Attribution 4.0 International

apparent fuel mass loss, increased from F1 to F4, reaching 190.30g and 190.30g kg^{-1}, respectively, before decreasing to 160.40g and 160.40g kg^{-1} in F5. Burning rate followed a similar pattern, reaching 13.72g min^{-1} in F4 and decreasing to 10.10g min^{-1} in F5. These results indicate contrasting combustion responses between the formulations with the highest mechanical performance (F4) and the highest HHV (F5). The higher rate observed in F4 coincided with its greater density and ash content, whereas F5 combined a lower burning rate with higher fixed-carbon content and HHV. These contrasting patterns suggest that the effects of biomass composition on combustion behavior cannot be explained by density alone. The lower average burning rate in F5 may indicate slower apparent fuel mass loss under the adopted test conditions; however, it does not independently establish more stable combustion or prolonged heat release (Figure 4).

Figure 4. Thermal performance and combustion kinetics indicators for briquette formulations (F1-F5): (a) higher heating value (MJ kg^{-1}); (b) fuel consumption (g); (c) specific fuel consumption (g Kg^{-1}); (d) burning rate (g min^{-1})



The energy potential and combustion efficiency of the produced carbonized briquettes are summarized in Table 3. The data characterize the thermal performance of the 5 experimental formulations (F1-F5).

Table 3. Higher heating value and combustion performance indicators of carbonized briquettes produced from different biomass residue formulations

Formulation	HHV		Fuel_Cons		SFC		Burn_Rate	
	mean	std	mean	std	mean	std	mean	std
F1	22.54	0.586	170.7	0.418	170.7	0.418	11.7	0.57
F2	21.97	0.513	180.8	0.474	180.8	0.474	12.78	0.311
F3	20.68	0.546	185.54	0.336	185.54	0.336	12.72	0.409
F4	20.08	0.546	190.3	0.158	190.3	0.158	13.72	0.409
F5	24.094	0.126	160.4	0.274	160.4	0.274	10.1	0.187

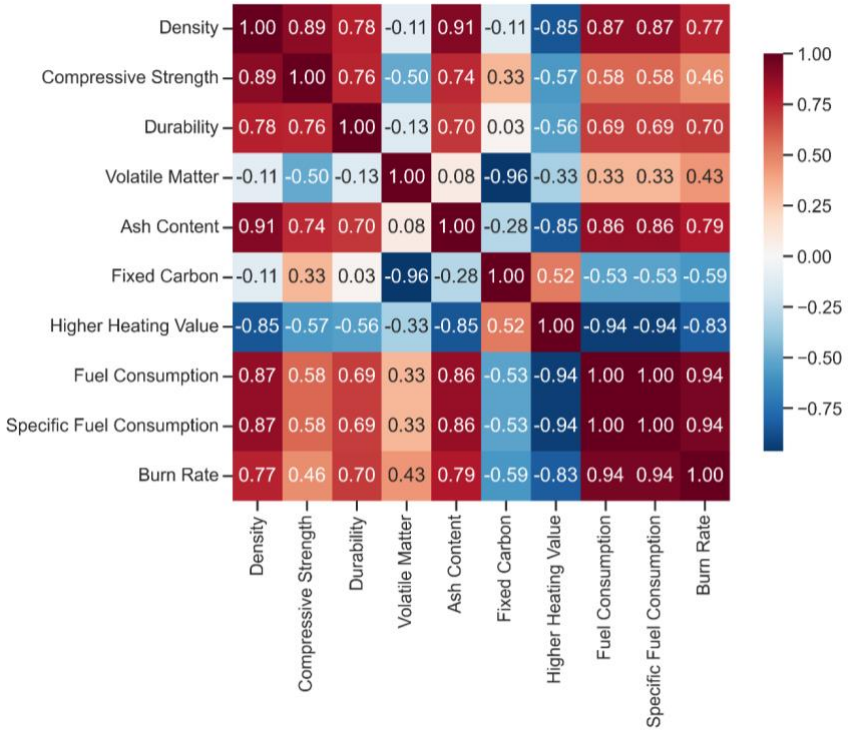
*HHV - Higher Heating Value (MJ/kg), FC - Fuel Consumption (g), SGC - Specific Fuel Consumption (g/Kg), Burn Rate (g/min)

CC BY 4.0 DEED

Statistical Analysis and Correlations

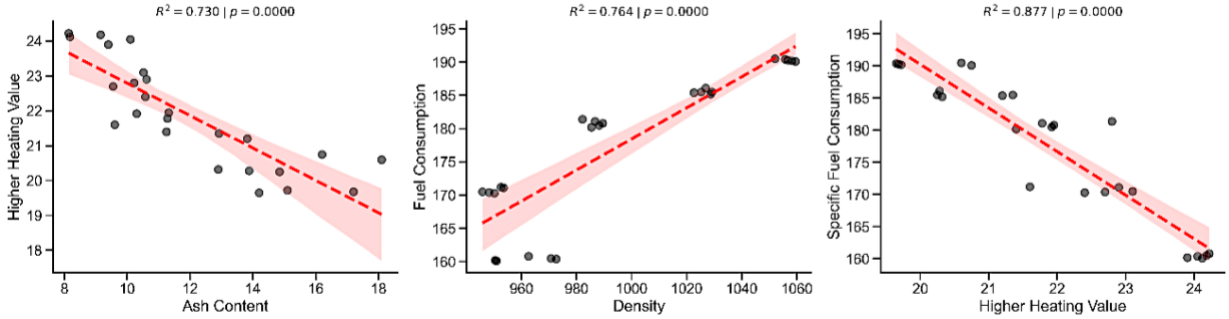
Pearson correlation analysis (Figure 5) revealed strong negative associations between ash content and higher heating value (HHV; r= −0.95), as well as between HHV and both fuel consumption and specific fuel consumption (SFC; r= −0.98 for both). Apparent density was positively correlated with compressive strength (r= 0.89) and mechanical durability (r= 0.83), while ash content was positively associated with burning rate (r= 0.86). Fixed carbon showed a strong negative correlation with volatile matter (r= −0.97) and a moderate negative correlation with SFC (r= −0.53). These relationships highlight the contrasting associations of physical structure and proximate composition with briquette performance.

Figure 5. Pearson correlation matrix between the physical and chemical properties and combustion parameters of the briquette formulations. Numerical values represent the Pearson correlation coefficient (ρ)



Linear regression analyses (Figure 6) showed a negative relationship between ash content and HHV (R^2= 0.730), a positive relationship between apparent density and fuel consumption (R^2= 0.764), and a negative relationship between HHV and SFC (R^2= 0.877). These relationships illustrate the associations between briquette composition, physical properties, and combustion performance.

Figure 6. Linear regression models illustrating the relationships between key physicochemical and energetic parameters of bio-char briquettes: (a) ash content vs. higher heating value (HHV), (b) density vs. fuel consumption, and (c) HHV vs. specific fuel consumption (SFC). Solid lines represent fitted linear models, and shaded areas indicate confidence intervals. Coefficients of determination (R^2) and significance levels ($p < 0.0001$) are shown for each relationship



CC BY 4.0 DEED Attribution 4.0 International

DISCUSSION

Physicochemical Properties and Energy Performance of Carbonized Briquettes

The physicochemical and energetic characteristics of carbonized briquettes are influenced by the composition of the constituent biomass residues and their interactions during densification. In the present study, variations in feedstock proportions, under constant binder concentration and compaction conditions, revealed a trade-off between mechanical integrity and gravimetric energy content. This distinction highlights the importance of considering both structural and fuel-quality attributes when evaluating briquette performance (Grover & Mishra, 1996; Kaliyan & Morey, 2009; Nwankwo et al., 2023).

The positive relationship between apparent density and compressive strength suggests that particle consolidation played an important role in the mechanical performance of the briquettes. The superior mechanical properties of F4 may be attributed to more favorable particle packing and interparticle bonding, which can enhance structural cohesion and resistance to mechanical loading. In contrast, the higher proportion of sawdust char and lower proportion of recycled paper char in F5 may have altered these interactions, resulting in reduced density and compressive strength relative to F4. Nevertheless, F5 maintained satisfactory mechanical durability, indicating that its improved gravimetric energy characteristics were not accompanied by a substantial loss of structural integrity.

These observations are consistent with the established influence of feedstock characteristics and densification processes on briquette quality (Temmerman et al., 2006; Tumuluru et al., 2011; Mitchual et al., 2014; Handayani et al., 2023). The inverse relationship between ash content and higher heating value (HHV) reflects the diluting effect of non-combustible mineral matter on the energy content of solid fuels. Higher ash fractions reduce the proportion of combustible material per unit mass, thereby contributing to lower gravimetric heating values (Vassilev et al., 2013; Bot et al., 2023a). This mechanism helps explain the lower HHV observed in F4, whereas F5 exhibited a contrasting pattern characterized by lower ash content and substantially higher fixed carbon.

The greater proportion of sawdust-derived char in F5 may have contributed to this favorable proximate composition, although the individual char components were not characterized separately. Consequently, the superior HHV of F5 appears to be associated with its lower mineral fraction and higher combustible carbon content, rather than with greater mechanical densification (Antal & Grønli, 2003; Demirbas, 2004; Nhuchhen & Salam, 2012; Nwankwo et al., 2023).

The contrasting combustion behavior of F4 and F5 suggests that fuel performance depends on the combined effects of physical structure and proximate composition. Although higher density is generally associated with greater particle consolidation, its influence on combustion also depends on oxygen accessibility and the characteristics of the carbonized material. The higher apparent fuel consumption and burning rate observed in F4, despite its superior mechanical properties, indicate that greater densification does not necessarily reduce fuel mass loss under the tested conditions. Conversely, the lower burning rate of F5, together with its higher fixed-carbon content and HHV, suggests a different combustion response associated with its composition. These findings are consistent with the complex influence of fuel

CC BY 4.0 DEED Attribution 4.0 International

structure, volatile matter, and fixed carbon on solid-fuel combustion (Antal & Grønli, 2003; Yang et al., 2007; Hassan et al., 2017).

The observed relationships highlight a trade-off between mechanical robustness and gravimetric energy performance, indicating that these properties are not necessarily maximized by the same biomass formulation. While greater particle consolidation may improve resistance to handling and mechanical stress, fuel composition remains critical in determining heating value and combustion characteristics. Accordingly, briquette optimization should consider mechanical durability, ash content, energy content, and fuel consumption in relation to the intended application, rather than prioritizing a single performance indicator (Tumuluru et al., 2011; Walozi et al., 2026).

The comparison with selected quality parameters for solid biofuels (Table 4) provides further insight into the practical suitability of the developed briquettes. Although the evaluated formulations exhibited favorable mechanical and energetic characteristics, the available measurements are insufficient to establish full compliance with ISO 17225-6:2021. From an application perspective, F4 offers advantages where mechanical resistance and durability are priorities, particularly during handling and transportation, whereas F5 may be preferable for applications requiring higher gravimetric energy content and lower ash production. These differences demonstrate the potential to tailor briquette properties through adjustments in the proportions of carbonized biomass residues.

Table 4. Comparison of selected physical, mechanical, and energetic properties of the produced briquettes with reference quality indicators for solid biofuels

Parameter	ISO 17225-6 (Reference)	Results (F1-F5)	Evaluation/Compliance Assessment
Density (kg/m³)	No fixed limit; values > 900kg/m³ are considered adequate	950-1060 (except F5: 961)	All formulations meet the criteria; F3/F4 stand out for their higher density
Mechanical Durability (%)	> 90%	F1: 94.3%; F2: 96.1%; F3: 95.3%; F4: 97.5%; F5: 95%	All formulations are complying; F4 shows superior performance
Compressive Strength (MPa)	Not standardized; values > 2MPa indicate high structural robustness	F3: 2.48; F4: 2.88	F3/F4 demonstrate excellent structural integrity
Ash Content (%)	Accepts high values (up to 20%) for mixed biomass	F1-F4: 10-16%; F5: 9%	All within the permitted range; F5 presents the lowest ash content
HHV (MJ/kg)	> 15MJ/kg	F1: 22.5; F2: 22.0; F3: 20.7; F4: 20.1; F5: 24.1	All in compliance; F5 stands out as the highest quality energy fuel

Environmental and Socioeconomic Implications

The heating values obtained in this study indicate that briquettes produced from carbonized biomass residues have potential as alternative solid fuels for household energy applications. Their energetic characteristics suggest opportunities for partially replacing conventional wood charcoal, particularly where locally available residues can be converted into usable fuels. However, heating value alone does not establish practical suitability, as household performance also depends on combustion emissions, ignition characteristics, stove compatibility, and heat-transfer efficiency. Further evaluation of these parameters is therefore necessary to determine the feasibility of their widespread domestic use (Demirbas, 2004; Kpalo et al., 2020).

CC BY 4.0 DEED Attribution 4.0 International

The conversion of agricultural, wood-processing, and urban residues into carbonized briquettes offers an opportunity to valorize locally available waste streams and promote resource recovery within a circular economy framework. By transforming these materials into usable solid fuels, briquette production may reduce the disposal of biomass residues and partially offset demand for conventional wood charcoal. Such substitution could contribute to reducing pressure on forest resources, particularly in regions where household energy consumption relies heavily on woody biomass. However, the magnitude of these environmental benefits depends on feedstock availability, production practices, and the extent to which briquettes effectively replace conventional fuels (FAO, 2018; IEA, 2025).

From a socioeconomic perspective, the availability of agricultural, wood-processing, and urban residues may support decentralized briquette production and create opportunities for local entrepreneurship in rural and peri-urban communities. The utilization of these resources could contribute to income diversification and the development of small-scale bioenergy enterprises, particularly where conventional household fuels are costly or difficult to access. However, the economic viability of briquette production depends on feedstock collection and processing costs, equipment requirements, production scale, and market acceptance. Further techno-economic assessments are therefore necessary to determine whether these briquettes can provide a competitive and accessible alternative to conventional charcoal (Onukak et al., 2017; Handayani et al., 2023).

From a scientific perspective, this study provides experimental evidence that varying the proportions of banana peel, sawdust, and recycled paper chars under consistent processing conditions produces distinct mechanical and energetic responses. The contrasting performance of F4 and F5 demonstrates that improvements in structural integrity do not necessarily coincide with higher gravimetric energy content, emphasizing the importance of formulation-specific evaluation. These findings contribute to the understanding of performance trade-offs in multi-residue carbonized briquettes and provide a basis for further optimization of biomass blends for different energy applications.

FINAL CONSIDERATIONS

This study demonstrates the potential of carbonized banana peels, sawdust, and recycled paper, combined with cassava starch as a binder, for producing solid biofuel briquettes with distinct mechanical and energetic characteristics. The contrasting performance of the formulations highlights the importance of biomass composition in balancing structural integrity and gravimetric energy content. F4 exhibited the most favorable mechanical properties, making it particularly suitable for applications requiring greater resistance to handling and transportation, whereas F5 showed superior energy-related characteristics, associated with its higher fixed-carbon content, lower ash fraction, and higher heating value.

Beyond identifying the best-performing formulations, this study provides experimental evidence that adjusting the proportions of different carbonized residues under consistent processing conditions can influence mechanical and energetic properties in different ways. These findings contribute to the understanding of performance trade-offs in multi-feedstock briquette systems and demonstrate that formulation optimization should be guided by the intended application rather than by a single quality indicator.

The valorization of locally available biomass residues through briquette production offers a promising pathway for developing alternative solid fuels while supporting resource recovery

CC BY 4.0 DEED Attribution 4.0 International

and circular bioeconomy strategies. However, further investigations addressing combustion emissions, thermal efficiency, production costs, and environmental impacts are necessary to establish their practical and economic viability. Overall, the study provides a scientific basis for the application-specific design of carbonized briquettes and supports further development of residue-based bioenergy solutions in biomass-dependent regions.

REFERENCES

Adeleke, A. E., Mosuro, T. S., & Musa, A. I. (2026). Production of briquettes from the mixture of sawdust, banana peels and palm fronds using cassava starch as binder. *Agricultural Engineering International: CIGR Journal*, 28(1), 179-88. https://cigrjournal.org/index.php/Ejounral/article/view/9987/4571

Akowuah, J. O., Kemausuor, F., & Mitchual, S. J. (2012). Physico-chemical characteristics and market potential of sawdust charcoal briquette. *International Journal of Energy and Environmental Engineering,* 3, 20. https://doi.org/10.1186/2251-6832-3-20

Alves, M. B. F., Chaves, R. M., Saraiva, T. dos S., da Silva, E. K. S., & Candeia, R. A. (2022). Physico-chemical and energy profile of briquettes composed of coconut shells, banana peels and/or sawdust. *Brazilian Journal of Development*, 8(2), 8893-909. https://doi.org/10.34117/bjdv8n2-032

Antal, M. J. & Grønli, M. (2003). The art, science, and technology of charcoal production. *Industrial & Engineering Chemistry Research*, 42(8), 1619-40. https://doi.org/10.1021/ie0207919

ASTM International. (2019). Standard test method for gross calorific value of coal and coke (ASTM D5865/D5865M-19). *ASTM International* https://store.astm.org/d5865_d5865m-19.html

ASTM International. (2020). Standard test method for volatile matter in the analysis sample of coal and coke (ASTM D3175-20). *ASTM International*. https://store.astm.org/d3175-20.html

Bot, B. V., Axaopoulos, P. J., Sakellariou, E. I., Sosso, O. T., & Tamba, J. G. (2023). Economic viability investigation of mixed-biomass briquettes made from agricultural residues for household cooking use. *Energies*, 16(18), 6469. https://doi.org/10.3390/en16186469

Bot, B. V., Sosso, O. T., Tamba, J. G., Lekane, E., Bikai, J., & Ndame, M. K. (2023a). Preparation and characterization of biomass briquettes made from banana peels, sugarcane bagasse, coconut shells and rattan waste. *Biomass Conversion and Biorefinery*, 13, 7937-46. https://doi.org/10.1007/s13399-021-01762-w

Demirbas, A. (2004). Combustion characteristics of different biomass fuels. *Progress in Energy and Combustion Science*, 30(2), 219-30. https://doi.org/10.1016/j.pecs.2003.10.004

Dinesha, P., Kumar, S., & Rosen, M. A. (2019). Biomass briquettes as an alternative fuel: a comprehensive review. *Energy Technology*, 7(5), 1801011. https://doi.org/10.1002/ente.201801011

Food and Agriculture Organization of the United Nations. (2017). The charcoal transition: greening the charcoal value chain to mitigate climate change and improve local livelihoods. *FAO*. https://openknowledge.fao.org/handle/20.500.14283/i6935en

Food and Agriculture Organization of the United Nations. FAO. (2018). Improved charcoal technologies and briquette production from woody residues in Malawi: Bioenergy and Food Security (BEFS) case study (FAO Forestry Paper No. 154). *FAO*. https://openknowledge.fao.org/handle/20.500.14283/ca2087en

Grover, P. D. & Mishra, S. K. (1996). Biomass briquetting: Technology and practices (Field Document No. 46). *Food and Agriculture Organization of the United Nations*. https://www.fao.org/4/AD579E/AD579E00.htm

Handayani, S. A., Widiati, K. Y., & Putri, F. (2023). Quality of charcoal briquettes from sawdust waste of Ulin (Eusideroxylon zwageri) and coconut shell (Cocos nucifera) based on variations in ratio and particle size. *IOP Conference Series: Earth and Environmental Science*, 1282, 012049. https://doi.org/10.1088/1755-1315/1282/1/012049

Hassan, L. G., Sani, N. A., Sokoto, A. M., & Tukur, U. G. (2017). Comparative studies of burning rates and water boiling time of wood charcoal and briquettes produced from carbonized Martynia annua woody shells. *Nigerian Journal of Basic and Applied Sciences*, 25(2), 21-7. https://doi.org/10.4314/njbas.v25i2.4

International Energy Agency. (2025). World Energy Outlook 2025. *IEA*. https://www.iea.org/reports/world-energy-outlook-2025

International Organization for Standardization. ISO. (2021). Solid biofuelsFuel specifications and classes—Part 6: Graded non-woody pellets (ISO 17225-6:2021). *ISO*. https://www.iso.org/standard/76093.html

International Organization for Standardization. ISO. (2022). Solid biofuels—Determination of ash content (ISO 18122:2022). *ISO*. https://www.iso.org/standard/83190.html

International Organization for Standardization. ISO. (2022). Solid biofuels—Determination of moisture content—Part 1: Reference method (ISO 18134-1:2022). ISO. https://www.iso.org/standard/83191.html

Kaliyan, N. & Morey, R. V. (2009). Factors affecting strength and durability of densified biomass products. *Biomass and Bioenergy*, 33(3), 337-59. https://doi.org/10.1016/j.biombioe.2008.08.005

Kebede, T., Berhe, D. T., & Zergaw, Y. (2022). Combustion characteristics of briquette fuel produced from biomass residues and binding materials. *Journal of Energy*, 2022, 4222205. https://doi.org/10.1155/2022/4222205

Kirchherr, J., Reike, D., & Hekkert, M. (2017). Conceptualizing the circular economy: An analysis of 114 definitions. *Resources, Conservation and Recycling,* 127, 221-32. https://doi.org/10.1016/j.resconrec.2017.09.005

CC BY 4.0 DEED

Kpalo, S. Y., Zainuddin, M. F., Manaf, L. A., & Roslan, A. M. (2020). A review of technical and economic aspects of biomass briquetting. *Sustainability*, 12(11), 4609. https://doi.org/10.3390/su12114609

Mekonen, A. G., Berhe, G. G., Desta, M. B., Belete, F. A., & Gebremariam, A. F. (2024). Production and characterization of briquettes from sugarcane bagasse of Wonji Sugar Factory, Oromia, Ethiopia. *Materials for Renewable and Sustainable Energy*, 13(1), 27-43. https://doi.org/10.1007/s40243-023-00248-1

Mitchual, S. J., Frimpong-Mensah, K., & Darkwa, N. A. (2014). Evaluation of fuel properties of six tropical hardwood timber species for briquettes. *Journal of Sustainable Bioenergy Systems*, 4(1), 1-9. https://doi.org/10.4236/jsbs.2014.41001

Mwampamba, T. H., Owen, M., & Pigaht, M. (2013). Opportunities, challenges and way forward for the charcoal briquette industry in Sub-Saharan Africa. *Energy for Sustainable Development*, 17(2), 158-70. https://doi.org/10.1016/j.esd.2012.10.006

Nhuchhen, D. R. & Salam, P. A. (2012). Estimation of higher heating value of biomass from proximate analysis: a new approach. Fuel, 99, 55-63. https://doi.org/10.1016/j.fuel.2012.04.015

Njenga, M., Karanja, N., Karlsson, H., Jamnadass, R., Iiyama, M., Kithinji, J., Sundberg, C., & Jirjis, R. (2013). Charcoal production and strategies to enhance its sustainability in Kenya. *Development in Practice*, 23(3), 359-71. https://doi.org/10.1080/09614524.2013.780529

Njimou, J. R., Danga, G. M. N., Balike, M., Haman, Z., Ngouyamnsa-Ghenmi, E. M., Njike, R. M. T., Genola, O. B., Talla, A., & Elambo, N. G. (2026). Optimizing calorific value of energy briquettes from agricultural biomass: a novel approach utilizing maize and cassava residues. *Waste Disposal & Sustainable Energy*, 8, 89-103. https://doi.org/10.1007/s42768-025-00123-4

Nonsawang, S., Sokudlor, N., Sanchumpu, P., Suaili, W., Khaeso, K., Oupathum, C., Sethanan, K., & Laloon, K. (2026). Insights into the co-utilization of cassava industry waste and invasive woody biomass for charcoal briquettes production. *Carbon Resources Conversion. Advance online publication*. https://doi.org/10.1016/j.crcon.2026.100416

Nwankwo, C. I., Onuegbu, T. U., Okafor, I. F., & Igwenagu, P. C. (2023). Utilization of agricultural waste in the production of charcoal briquette blend as alternative source of energy. *IOP Conference Series: Earth and Environmental Science*, 1178, 012015. https://doi.org/10.1088/1755-1315/1178/1/012015

Olugbade, T. O., Ojo, O. T., & Mohammed, T. I. (2019). Influence of binders on combustion properties of biomass briquettes: a recent review. *BioEnergy Research*, 12(2), 241-59. https://doi.org/10.1007/s12155-019-09973-w

Onukak, I. E., Mohammed-Dabo, I. A., Ameh, A. O., Okoduwa, S. I. R., & Fasanya, O. O. (2017). Production and characterization of biomass briquettes from tannery solid waste. *Recycling*, 2(4), 17. https://doi.org/10.3390/recycling2040017

Python Software Foundation. (2023). *Python 3.11 documentation*. https://docs.python.org/3.11/

Ramdas, V., Njokweni, S. G., Letsoalo, P., Motaung, S., & Ramchuran, S. O. (2025). Bio-coal briquetting as a potential sustainable valorization strategy for fine coal: a South African perspective in a global context. *Energies*, 18(14), 3746. https://doi.org/10.3390/en18143746

Rawat, S. & Kumar, S. (2022). Critical review on processing technologies and economic aspect of bio-coal briquette production. *Preparative Biochemistry & Biotechnology*, 52(8), 855-71. https://doi.org/10.1080/10826068.2021.2001754

Saeed, A. A. H., Harun, N. Y., Bilad, M. R., Afzal, M. T., Parvez, A. M., Roslan, F. A. S., Rahim, S. A., Vinayagam, V. D., & Afolabi, H. K. (2021). Moisture content impact on properties of briquette produced from rice husk waste. *Sustainability*, 13(6), 3069. https://doi.org/10.3390/su13063069

Temmerman, M., Rabier, F., Jensen, P. D., Hartmann, H., & Böhm, T. (2006). Comparative study of durability test methods for pellets and briquettes. *Biomass and Bioenergy*, 30(11), 964-72. https://doi.org/10.1016/j.biombioe.2006.06.008

Tumuluru, J. S., Wright, C. T., Hess, J. R., & Kenney, K. L. (2011). A review of biomass densification systems to develop uniform feedstock commodities for bioenergy application. *Biofuels, Bioproducts and Biorefining*, 5(6), 683-707. https://doi.org/10.1002/bbb.324

Vaish, S., Sharma, N. K., & Kaur, G. (2022). A review on various types of densification/briquetting technologies of biomass residues. *IOP Conference Series: Materials Science and Engineering*, 1228, 012019. https://doi.org/10.1088/1757-899X/1228/1/012019

Vassilev, S. V., Baxter, D., Andersen, L. K., & Vassileva, C. G. (2013). An overview of the composition and application of biomass ash. Part 2: Potential utilisation, technological and ecological advantages and challenges. *Fuel*, 105, 19-39. https://doi.org/10.1016/j.fuel.2012.10.001

Walozi, R., Onep, G. S., Sanusi, Y. S., Babiker, O. E., Dennison, M. S., Candia, A., & Okurut, S. (2026). Critical review of biomass heterogeneity effects on briquette combustion. *Discover Applied Sciences*, 8, 309. https://doi.org/10.1007/s42452-025-08212-6

Yang, H., Yan, R., Chen, H., Lee, D. H., & Zheng, C. (2007). Characteristics of hemicellulose, cellulose and lignin pyrolysis. *Fuel*, 86(12-13), 1781-8. https://doi.org/10.1016/j.fuel.2006.12.013

CC BY 4.0 DEED Attribution 4.0 International