Journal of Renewable Energy and Sustainable Development (RESD) Volume 12, Issue 1, June 2026 - ISSN 2356-8569
http://dx.doi.org/10.21622/RESD.2026.12.1.2018

Received: 19 March 2026 Accepted: 13 May 2026 Published: 14 June 2026

Characterization of Charcoal Briquettes from Sugar Palm (*Arenga pinnata* Merr.) Waste: Physical, Proximate, and Combustion Performance in the Aik Bual Community Forest

Febriana Tri Wulandari [1*], Aluh Nikmatullah [2], Sitti Latifah [3], and Hayati Hayati [4]

[1*,2,3,4] University of Mataram, Postgraduate Program, Sustainable Agriculture, Indonesia

febriana.wulandari@unram.ac.id, aluh_nikmatullah@unram.ac.id, faperta@unram.ac.id, hayati@unram.ac.id

Abstract

The utilization of lignocellulosic biomass as a renewable energy source plays a crucial role in supporting sustainable energy transitions and reducing dependence on fossil fuels. Vegetative waste from sugar palm (Arenga pinnata Merr.) in the Aik Bual Community Forest represents a promising raw material for charcoal briquette production; however, its energy characteristics have not yet been comprehensively evaluated against national standards. This study aimed to analyze the physical properties, proximate composition, and combustion performance of briquettes produced from fruit stalks, leaves, leaf sheaths, and mixed biomass, as well as to assess their compliance with SNI 01-6235-2000 standards. A non-factorial Completely Randomized Design (CRD) with four treatments and three replications was employed. Briquettes were produced through a series of processes, including carbonization at approximately 450°C, particle size reduction using a 60-mesh sieve, addition of 10% tapioca binder, compaction at 400 psi, and drying for 12 days. The evaluated parameters included density, moisture content, volatile matter, ash content, fixed carbon, calorific value, and combustion rate. The results showed that all treatments exhibited low moisture content (1.47–2.31%), meeting the required standards. The calorific value ranged from 4,443 to 5,985 cal/g^{-1}, with leaf-based briquettes demonstrating the highest fixed carbon content (64%) and superior energy performance. Nevertheless, optimization of the carbonization and densification processes is still required to improve overall compliance with the SNI standard.

Index-words: *Sugar Palm (Arenga pinnata), Proximate Characteristics, Calorific Value, SNI 01-6235-2000, Biomass Energy, Community Forest.*

I. Introduction

Global dependence on fossil fuels remains a major challenge in the transition toward sustainable energy *systems*, primarily due to its contribution to greenhouse gas emissions and energy security instability. In this context, solid biomass has emerged as one of the most promising renewable energy sources for developing countries, given its abundant availability, relatively carbon-neutral nature, and capacity to valorize organic waste that previously held limited economic value [1],[2]. The conversion of biomass into charcoal briquettes has attracted increasing attention because it enhances energy density, combustion stability, and efficiency in storage and distribution compared with raw biomass [3],[4].

Indonesia possesses substantial biomass potential derived from agricultural and forestry sectors; however, its utilization as an alternative energy source remains suboptimal. Numerous studies have demonstrated that lignocellulosic residues can be converted into charcoal briquettes with competitive calorific values and adequate combustion characteristics suitable for household and small-scale applications [5],[6]. The energy quality of charcoal briquettes is strongly influenced by their physical and proximate characteristics, including density, moisture content, volatile matter, ash content, and fixed carbon. These parameters directly determine energy efficiency, flame stability, and compliance with established quality standards [7],[3].

Sugar palm (*Arenga pinnata* Merr.) is a non-timber forest product widely managed by local communities within community forest areas, generating substantial amounts of vegetative residues such as fruit stalk, leaves, and leaf sheath.

* Corresponding author

In the Aik Bual Community Forest (HKm Aik Bual), sugar palm (*A. pinnata*) vegetative waste is continuously available as a by-product of community-based management practices. However, most of this biomass remains underutilized and accumulates around production sites without productive valorization. Structurally, sugar palm (*A. pinnata*) biomass contains significant lignocellulosic components and lignin, which are associated with the potential to produce charcoal with high fixed carbon content and favorable calorific values [8],[2].

Several previous studies have evaluated charcoal briquettes derived from various types of lignocellulosic biomass and demonstrated that feedstock type significantly influences proximate characteristics and calorific value [9],[10]. However, most of these studies remain partial in scope, either focusing on a single biomass type, emphasizing selected proximate parameters, or failing to quantitatively relate physical and chemical properties to combustion performance. Other studies have reported that briquette density and porosity affect combustion rate and oxidation reactivity; nevertheless, their findings have not been systematically evaluated against national quality standards as a basis for practical feasibility assessment [3].

In addition, studies focusing on non-timber forest product residues, particularly vegetative waste from sugar palm (*A. pinnata*), remain relatively limited in the literature. Moreover, very few investigations explicitly situate biomass resources within the context of community-based forest management systems, such as community forests. Consequently, issues related to feedstock homogeneity, linkages to local management practices, and socio-economic relevance are often overlooked. This condition highlights a clear research gap, namely the lack of studies that simultaneously compare different fractions of sugar palm (*A. pinnata*) waste originating from the same resource area, integrate physical and proximate characteristics with quantitative combustion performance, and evaluate their compliance with established quality standards as a basis for assessing energy feasibility [5].

Based on this research gap, the present study adopts a location-based, comparative-integrated approach by evaluating the physical properties, proximate composition, and combustion performance of charcoal briquettes produced from different fractions of sugar palm (*A. pinnata*) waste (fruit stalk, leaves, leaf sheath, and mixed biomass) specifically sourced from the Aik Bual Community Forest (HKm Aik Bual). All results were analyzed and directly compared with the Indonesian National Standard SNI 01-6235-2000 to assess the practical feasibility of sugar palm (*A. pinnata*) briquettes as an alternative fuel. This approach provides a novel contribution by linking technical evaluation of biomass energy quality with the context of community forest management, making the findings relevant not only scientifically but also practically for the development of community-based energy solutions.

II. Research methods

A. Material and equipment

The materials used in this study included sugar palm (*A. pinnata*) vegetative wastes, consisting of fruit stalk, leaves, and leaf sheath, as well as a proportional mixture of these fractions as the main studied material.

(a) (b) (c)

Figure 1: Sugar palm (*A. pinnata*) vegetative waste: (a) Fruit Stalk; (b) Leaves; (c) Leaf Sheath.

Palm fronds, which are the raw material for charcoal and consist of fruit stalks, leaves, and leaf sheaths, as well as mixtures thereof, are dried for 7 days under dry conditions. Tapioca starch was used as a commercial binder, and clean water served as the binder solvent. The equipment employed comprised a drum kiln for carbonization, a mortar and pestle or manual charcoal crusher, a 60-mesh sieve for particle size standardization, and a manual hydraulic press with a cylindrical mold (5 cm diameter × 11 cm height). Analytical equipment included a precision digital balance (±0.01 g), Memmert UN30 drying oven, furnace/muffle furnace for proximate analysis, bomb calorimeter for calorific value measurement, thermocouple for temperature monitoring, and a stopwatch for combustion time measurement.

The flow diagram of this study is presented in Figure 2.

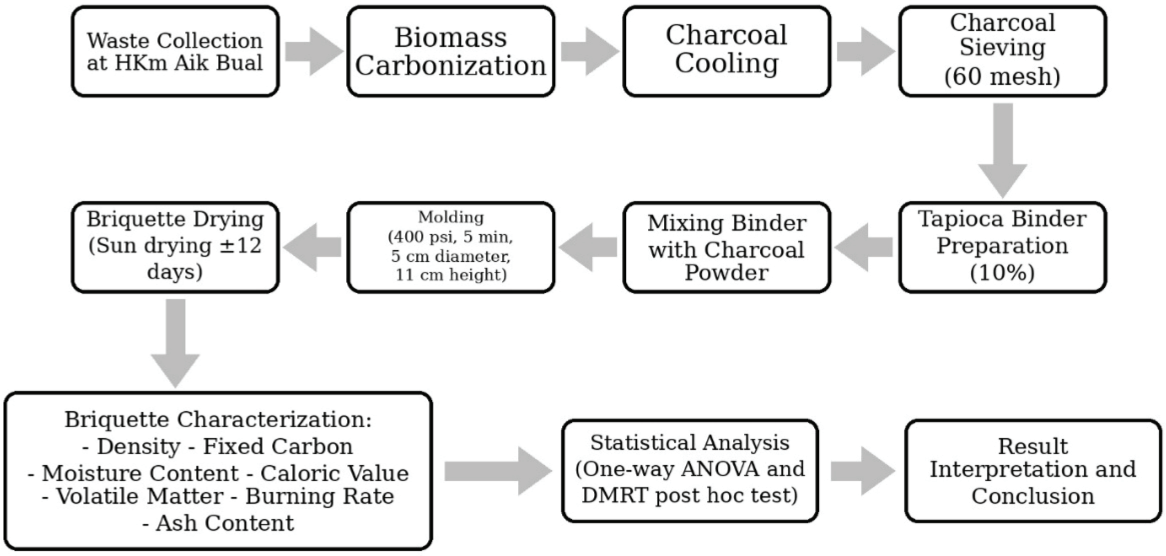


Figure 2: Research flow diagram.

B. *Charcoal briquette production procedure*

1. Charcoal preparation

Charcoal was produced using a closed-air carbonization method in a drum kiln (Figure 3). The biomass waste was ignited from the center and manually rotated to ensure uniform carbonization while preventing complete oxidation. The carbonization time was set at 2 hours for fruit stalks, 1.5 hours for leaf sheaths, and 3 hours for leaves, with the process temperature maintained at approximately 450°C using a temperature gun. After the carbonization process using a drum kiln, the drum kiln is reburied in a pit, which is then covered with soil so that the charcoal can cool naturally.

2. Size reduction and sieving

The charcoal was manually ground using a mortar and pestle to produce uniform particles, facilitating homogeneous mixing with the binder. The ground charcoal was then sieved to obtain a standardized particle size of 60 mesh. Several studies have shown that a 60-mesh particle size in briquette production is often considered the "optimal point" or superior to coarser sizes [11], [12].

3. Binder preparation

Tapioca starch was used as the binder at a fixed concentration of 10% for all biomass treatments. The starch suspension was added to boiling water and stirred continuously until a homogeneous gel was formed, ensuring a consistent binder concentration across all treatments.

4. Binder mixing with charcoal

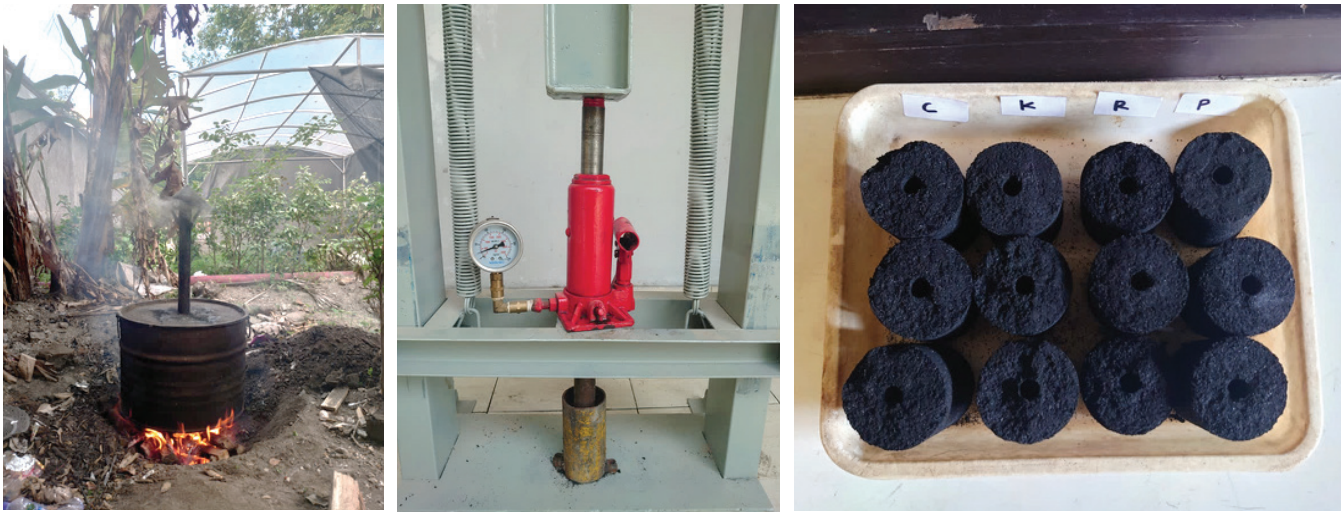
The 10% binder solution was gradually added to 1 kg of charcoal powder, followed by manual mixing and kneading until a homogeneous briquette paste was obtained. Each batch was prepared separately using

Volume 12, Issue 1, June 2026 - ISSN 2356-8569
http://dx.doi.org/10.21622/RESD.2026.12.1.2018

the same mixing procedure to ensure consistency across all treatments.

5. Molding and compaction

The briquette mixture was placed into a cylindrical mold and compacted by applying vertical pressure using a manual hydraulic press. A compaction pressure of 400 psi was applied and maintained for 5 minutes, as illustrated in Figure 3. The applied pressure was calculated based on the mold's cross-sectional area (5 cm diameter × 11 cm height). After compaction, the bottom plate of the mold was removed, and the formed briquettes were carefully ejected from the mold.



(a) (b) (c)

Figure 3: Charcoal briquette production stages: (a) carbonization with the kiln method, (b) Briquette compaction, (c) briquettes after molding.

6. Charcoal briquette drying

The briquettes were air-dried for 12 days until a stable mass was achieved, ensuring they were ready for subsequent physical, proximate, and combustion performance analyses.

C. *Charcoal briquette characterization*

The characterization of charcoal briquettes included physical properties, proximate composition, and combustion performance. The formulas and methods used to calculate these parameters are summarized in Table 1.

Table 1: Formulas for calculating the physical properties, proximate composition, and combustion performance of charcoal briquettes

Parameter	Symbol	Equation	Description
Physical Properties			
Density	ρ (g/cm^3)	$\rho = m / V$	m = briquette mass (g); V = briquette volume (cm^3)
Cylinder Volume	V (cm^3)	$V = \pi r^2 h$	r = radius (cm); h = height (cm)
Proximate Analysis			
Moisture Content	MC (%)	$MC = (m_1 - m_2) / m_1 \times 100$	m_1 = initial mass; m_2 = mass after drying in oven
Volatile Matter	VM (%)	$VM = (m_2 - m_3) / m_1 \times 100$	m_2 = dry mass; m_3 = mass after heating at 950°C
Ash Content	Ash (%)	$Ash = m_4 / m_1 \times 100$	m_4 = mass of ash residue
Fixed Carbon	FC (%)	$FC = 100 - (MC + VM + Ash)$	Calculated by the difference method
Combustion Performance			
Calorific Value	HHV (cal/g)	Measured using a bomb calorimeter	According to ASTM D5865
Burning Rate	BR (g/min)	$BR = (m_a - m\_b) / t$	m_a = initial mass; m_b = final mass; t = combustion time (min)

Note: MC = Moisture Content; VM = Volatile Matter; FC = Fixed Carbon; HHV = Higher Heating Value; BR = Burning Rate

Volume 12, Issue 1, June 2026 - ISSN 2356-8569
http://dx.doi.org/10.21622/RESD.2026.12.1.2018

D. *Experimental design*

This study employed a non-factorial Completely Randomized Design (CRD) with a single factor: the type of sugar palm (*A. pinnata*) waste fraction, consisting of fruit stalk (P), leaves (R), leaf sheath (K), and mixed biomass (C). Each treatment was replicated three times, resulting in a total of 12 experimental units. The production process was kept constant across treatments, including drum kiln carbonization at approximately 450°C, sieving to 60 mesh, addition of 10% tapioca starch binder, compaction at 400 psi for 5 minutes in a cylindrical mold (5 cm diameter × 11 cm height), and air-drying for 12 days until a stable mass was achieved. The parameters measured included density, moisture content, volatile matter, ash content, fixed carbon, calorific value, and burning rate. Data were analyzed using analysis of variance (ANOVA) at $\alpha = 0.05$, followed by Duncan's Multiple Range Test (DMRT) when significant differences were detected among treatments.

E. *Statistical analysis*

Experimental data were analyzed using one-way analysis of variance (ANOVA) at a 95% confidence level ($\alpha = 0.05$) to evaluate the effect of sugar palm (*A. pinnata*) waste fraction on each response variable. The analysis was conducted under the assumptions of normality and homogeneity of variance [13]. When ANOVA results indicated significant differences ($p < 0.05$), Duncan's Multiple Range Test (DMRT) was performed to identify differences among treatment means.

III. *Results & Discussion*

Overall, the physical properties, proximate composition, and combustion performance of sugar palm (*A. pinnata*) waste charcoal briquettes indicated good energy quality, approaching the Indonesian National Standard SNI 01-6235-2000. All briquettes exhibited very low moisture content and high calorific values, supporting efficient, stable, and easily ignitable combustion. Variations in proximate parameters, such as volatile matter, ash content, and fixed carbon, were influenced by the type of feedstock. However, overall values remained within ranges suitable for high-quality solid biomass fuel. Although briquette density did not fully meet the standard, the energy performance and combustion stability demonstrated that sugar palm waste briquettes have strong potential as an efficient and sustainable alternative energy source.

Table 2. Physical properties, proximate composition, and combustion performance of charcoal briquettes produced from sugar palm (A. pinnata) waste.

Parameter	P (Fruit stalk)	R (Leaves)	K (Leaf sheath)	C (Mixed)	CV (%)	F-value	p-value	SNI 01-6235-2000
Density (g/cm^{-3})	0.36 ± 0.01^{a}	0.35 ± 0.01^{a}	0.40 ± 0.02^{b}	0.36 ± 0.01^{a}	3.9	7.73	0.009	≥ 0.5
Moisture content (%)	2.03 ± 0.08^{c}	1.69 ± 0.05^{b}	2.31 ± 0.09^{d}	1.47 ± 0.04^{a}	4.9	37.86	<0.001	≤ 8
Volatile matter (%)	24.3 ± 0.7^{a}	36.8 ± 1.2^{d}	34.6 ± 1.0^{c}	30.5 ± 0.9^{b}	3.1	67.21	<0.001	≤ 15
Ash content (%)	11.5 ± 0.3^{b}	7.8 ± 0.2^{a}	18.2 ± 0.4^{c}	11.4 ± 0.3^{b}	3.2	1034.64	<0.001	≤ 8
Fixed carbon (%)	64 ± 1.0^{d}	55 ± 0.8^{b}	47 ± 0.7^{a}	58 ± 0.9^{c}	2.0	122.95	<0.001	≥ 60
Calorific value (cal/g^{-1})	5985 ± 85^{d}	5420 ± 70^{c}	4443 ± 95^{a}	5077 ± 80^{b}	1.5	117.92	<0.001	≥ 5000
Burning rate (g min^{-1})	0.04 ± 0.002^{a}	0.05 ± 0.002^{b}	0.04 ± 0.001^{a}	0.04 ± 0.001^{a}	9.8	7.17	0.012	–

Notes: Values are presented as mean ± standard deviation (SD) with three replications (n = 3). Different superscript letters within the same row indicate significant differences among treatments according to Duncan's Multiple Range Test (DMRT) at a 95% confidence level ($\alpha = 0.05$). CV represents the coefficient of variation, indicating the degree of variability among replicates. The F-value and p-value were obtained from one-way analysis of variance (ANOVA) to evaluate the effect of biomass fraction on each parameter. P = fruit stalk, R = leaves, K = leaf sheath, and C = mixed biomass. The quality standards refer to the Indonesian National Standard for charcoal briquettes (SNI 01-6235-2000)

Table 2 summarizes the physical properties, proximate composition, and combustion performance of charcoal briquettes produced from different fractions of sugar palm (*A. pinnata*) biomass. One-way ANOVA revealed that biomass type significantly affected all measured parameters ($p < 0.05$), highlighting the strong influence of feedstock characteristics on briquette quality.

Briquette density ranged from 0.35 to 0.40 g/cm^{-3}, with leaf sheath briquettes showing the highest value and forming a distinct statistical group compared with the other treatments. Moisture content remained very low (1.47–2.31%), well below the SNI limit (≤8%), indicating effective drying during the briquetting process.

Volatile matter ranged from 24.3 to 36.8% and exceeded the SNI threshold, suggesting that carbonization conditions require further optimization to improve thermal stability. Ash content showed substantial variation (7.8–18.2%), with twig briquettes producing the lowest ash fraction among the evaluated biomass types.

Among all treatments, frond briquettes exhibited the highest fixed carbon (64%) and calorific value (5,985 cal/g^{-1}), indicating superior combustion performance and energy quality.

A. Density

Density is a key physical parameter in evaluating charcoal briquette quality because it influences mechanical strength, structural stability, burning behavior, and efficiency during storage and transportation. In general, higher density reflects better particle compaction and lower porosity, which improves briquette durability and promotes more stable combustion [14],[15].

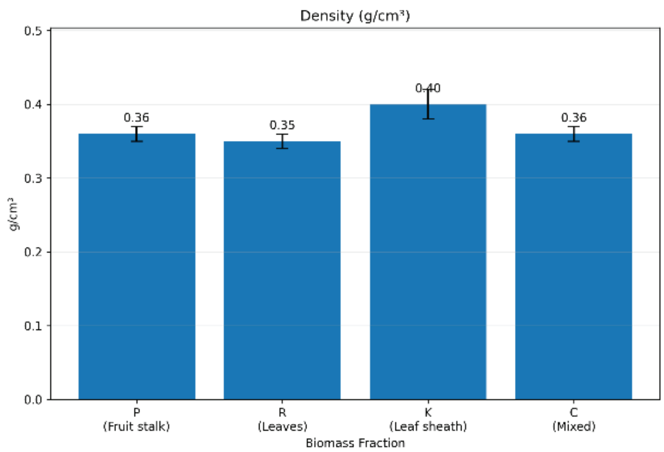


Figure 4: Density of *A. pinnata* waste materials.

In this study, the density of charcoal briquettes produced from sugar palm (*A. pinnata*) waste ranged from 0.34 to 0.41 g/cm^{-3}. Leaf sheath produced the highest density (0.40 g/cm^{-3}), followed by the mixed fraction (0.36 g/cm^{-3}) and fruit stalk (0.36 g/cm^{-3}), whereas leaves exhibited the lowest density (0.35 g/cm^{-3}). These values fall within the range reported in previous studies on lignocellulosic briquettes, such as [16] (0.36–0.44 g/cm^{-3}), [17] (0.38–0.46 g/cm^{-3}), [18] (0.42–0.50 g/cm^{-3}), [19] (0.34–0.43 g/cm^{-3}), and [20] (0.40–0.55 g/cm^{-3}), confirming that feedstock characteristics strongly influence briquette density.

The observed differences can be explained by the anatomical and chemical characteristics of the biomass. Briquette density is influenced by lignocellulosic composition, charcoal porosity after carbonization, particle size distribution, and the effectiveness of the compaction process. Biomass with a more compact structure and higher lignin content tends to produce denser charcoal because lignin acts as a natural binder that strengthens interparticle cohesion during densification [8]. Palm fronds contain about 45% cellulose, which provides good structural strength during the briquette compaction process [21]. In this study, sugar palm leaf sheath, being anatomically harder and denser than the fruit stalk and leaves, formed a more compact charcoal matrix under the applied compaction pressure of 400 psi. In contrast, the lighter and more porous tissues of fruit stalk and leaves likely generated higher microporosity during carbonization, resulting in lower final density [5]. Because a uniform particle size (60 mesh) was used for all treatments, the density variation mainly reflects intrinsic feedstock properties rather than grinding or particle distribution effects [22].

Statistical analysis confirmed these observations. ANOVA results showed that feedstock type significantly affected briquette density ($F = 7.733$; Sig. = $0.009 < 0.05$). Duncan's Multiple Range Test (DMRT) further indicated that leaf sheath formed a distinct group with significantly higher density than fruit stalk, leaves, and the mixed fraction, which exhibited relatively similar values. This result suggests that leaf sheath structure responds more effectively to compaction than the other biomass fractions.

The consistency of the measurements was also reflected in the relatively low variability. The mixed fraction showed the lowest coefficient of variation (CV = 2.29%), followed by leaf sheath (2.99%) and fruit stalk (3.53%), while leaves displayed the highest variation (6.91%), although still within the acceptable stability range (<10%). These low CV values indicate that the briquetting and measurement processes were performed consistently, and that density differences primarily originated from feedstock characteristics rather than experimental variability.

Although all density values were lower than the minimum requirement of SNI 01-6235-2000 (≥0.5 g/cm^{-3}), the briquettes still demonstrate functional potential as biomass fuel. Lower density generally corresponds to higher porosity, which may facilitate air diffusion and promote faster ignition during combustion [3]. Nevertheless, optimization of densification parameters, such as increasing compaction pressure, adjusting binder ratio, or modifying particle size distribution, is recommended to improve briquette compactness and meet national quality standards.

B. *Moisture content*

Moisture content is a fundamental parameter in evaluating charcoal briquette quality because it directly influences combustion efficiency, effective calorific value, ignition behavior, and storage stability. Residual water in briquettes absorbs part of the released heat during the early stage of combustion for evaporation, thereby reducing flame temperature and delaying char oxidation [15][23]. Consequently, low moisture content is considered a key indicator of high-quality solid biomass fuel.

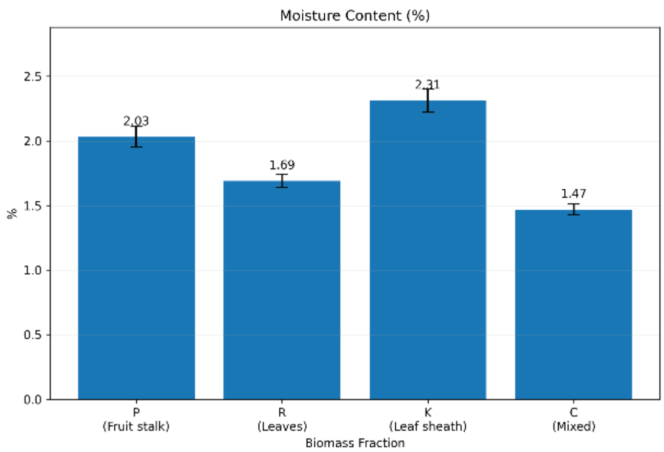


Figure 5: Moisture content of *A. pinnata* waste materials.

In this study, the moisture content of charcoal briquettes produced from sugar palm (*A. pinnata*) waste ranged from 1.47% to 2.31%, with an average value of 1.87%. The highest moisture content was observed in the leaf sheath fraction, while the mixed fraction showed the lowest value, with fruit stalk and leaves presenting intermediate levels. These values are considerably lower than those reported in previous studies on lignocellulosic briquettes, such as [5] (3.2–4.6%), [22] (2.8–3.9%), [3] (3–6%), [2] (2.5–5.0%), and [24] (4.1–6.3%). The very low moisture content indicates that carbonization at 450°C followed by natural drying for 12 days effectively reduced residual moisture prior to briquetting.

The differences among biomass fractions can be explained by variations in anatomical structure, hygroscopic properties, and charcoal porosity after carbonization. Biomass with higher lignin content tends to retain slightly more moisture due to the interaction between lignin polymers and water molecules [8]. This may explain the relatively higher moisture observed in the leaf sheath fraction. Conversely, leaves possess a lighter and more porous structure that facilitates water vapor diffusion during drying [5]. The mixed fraction likely formed a more balanced pore system that enhanced moisture release during the drying process.

All moisture values were well below the maximum limit of SNI 01-6235-2000 (≤8%), indicating full compliance with national briquette quality standards. The consistency of the measurements was also reflected in the relatively low variability, with coefficients of variation ranging from 0.00% to 7.39%. These values are within the acceptable range for experimental stability (<10%) and indicate that the drying and testing procedures were conducted consistently [12].

Statistical analysis further confirmed these observations. ANOVA results indicated that feedstock type had a highly significant effect on moisture content (F = 37.863; Sig. = 0.000 < 0.05). Duncan's Multiple Range Test (DMRT) revealed a clear statistical separation among treatments, with leaf sheath showing the highest moisture content, followed by fruit stalk, leaves, and the mixed fraction. This pattern confirms that the intrinsic anatomical and hygroscopic characteristics of each biomass fraction influence the final moisture retention in the briquettes.

Overall, the very low and stable moisture content observed in this study provides a favorable condition for briquette combustion performance and energy efficiency. These results indicate that sugar palm (*A. pinnata*) waste has strong potential as a high-quality raw material for charcoal briquette production.

C. Volatile matter

The volatile matter content of charcoal briquettes produced from sugar palm (*A. pinnata*) waste ranged from 24.3% to 36.8%, with an average of 31.55%. The fruit stalk fraction exhibited the lowest volatile matter content (24.3%), followed by the mixed fraction (30.5%) and leaf sheath (34.6%), while leaves showed the highest value (36.8%). These differences indicate that feedstock type strongly influences the volatile compounds retained in the charcoal after carbonization. Volatile matter plays an important role in combustion behavior because it affects ignition characteristics, initial flame intensity, and the rate of fuel consumption during burning.

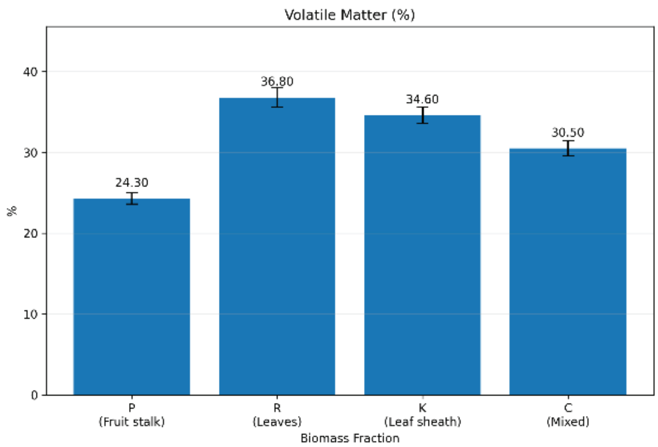


Figure 6: Moisture content of *A. pinnata* waste materials.

From a thermochemical perspective, volatile matter content is closely related to the lignocellulosic composition of the biomass and the degree of devolatilization during pyrolysis. Biomass with higher lignin content generally produces charcoal with lower volatile matter and higher fixed carbon due to the aromatic and thermally stable structure of lignin [2],[25]. This mechanism likely explains the relatively low volatile matter observed in the fruit stalk fraction. In contrast, leaves contain relatively higher proportions of cellulose and hemicellulose, which decompose more readily at moderate carbonization temperatures and generate larger quantities of volatile gases such as CO, CO_2, CH_4, and tar compounds, resulting in higher residual volatile matter.

The mixed fraction exhibited intermediate values, reflecting the combined contribution of different biomass components. Meanwhile, the leaf sheath showed relatively high volatile content, which may be associated with the presence of extractives and other non-structural organic compounds commonly found in leaf sheath tissues.

When compared with the SNI 01-6235-2000 standard (≤15%), all treatments exceeded the allowable volatile matter limit, indicating that carbonization at 450°C did not fully optimize devolatilization. However, the observed values remain within the typical range reported for biomass-derived briquettes (20–40%) [3],[7]. Increasing carbonization temperature, extending residence time, or improving oxygen control during pyrolysis could further reduce the volatile fraction and enhance the stability of the carbon structure.

The reliability of the data was supported by relatively low variability across treatments. Leaf sheath showed the lowest coefficient of variation (CV = 0.43%), followed by leaves (2.20%) and fruit stalk (4.65%), while the mixed fraction exhibited slightly higher variation (6.13%), although still within the acceptable range (<10%). These values indicate that the carbonization and testing procedures were performed consistently and that the observed differences primarily reflect the intrinsic properties of the feedstock.

Statistical analysis further confirmed these observations. ANOVA results indicated that feedstock type had a highly significant effect on volatile matter content ($F = 67.211$; Sig. = $0.000 < 0.05$). Duncan's Multiple Range Test (DMRT) at the 95% confidence level showed that each treatment formed a statistically distinct group, indicating that each biomass fraction possesses a unique devolatilization behavior during carbonization.

Overall, the variation in volatile matter content reflects differences in biomass composition and carbonization behavior among the evaluated sugar palm fractions. Although the values did not meet the SNI standard, the results provide important insights for optimizing carbonization conditions to improve the combustion quality and structural stability of sugar palm briquettes.

D. Ash content

Ash content is an important parameter in proximate analysis because it represents the fraction of inorganic minerals remaining after complete combustion. These minerals are non-combustible and therefore reduce the proportion of carbon available for energy release. High ash content may also influence combustion performance by affecting heat transfer and oxidation processes within the fuel matrix [2],[25].

In this study, the ash content of charcoal briquettes produced from sugar palm (*A. pinnata*) waste ranged from 7.8% to 18.2%, with an average value of 12.2%. The lowest ash content was observed in the leaves fraction (7.8%), followed by the mixed fraction (11.4%) and fruit stalk (11.5%), while leaf sheath exhibited the highest ash content (18.2%). This pattern indicates that the mineral composition of the feedstock strongly influences the residual ash fraction after combustion.

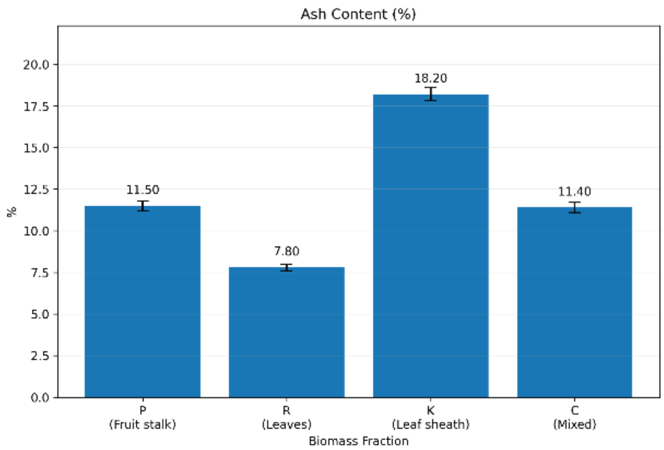


Figure 7: Ash content of *A. pinnata* waste materials.

The relatively high ash content in leaf sheath can be attributed to its physiological role as a protective tissue that accumulates inorganic minerals such as silica, calcium, potassium, and magnesium. These minerals remain as solid residues after carbonization and combustion, thereby increasing the final ash content of the briquettes. Similar observations have been reported in other lignocellulosic biomass studies, where mineral-rich tissues tend to produce higher ash fractions during thermochemical conversion [3].

The ash values obtained in this study are comparable to those reported for other lignocellulosic biomass briquettes, such as [5] (9–16%), [22] (8–14%), and [7] (6–18%). Therefore, the observed range still falls within the typical ash content of solid biomass fuels (5–20%). However, when compared with the Indonesian standard SNI 01-6235-2000, which specifies a maximum ash content of ≤8%, only the leaves fraction meets the national requirement, whereas fruit stalk, the mixed fraction, and especially leaf sheath exceed this limit.

The reliability of the data was confirmed by the low variability observed across treatments. Standard deviation (SD) and coefficient of variation (CV) values were relatively small, with CV values ranging from 0.82% to 3.65%, indicating highly consistent measurements and homogeneous mineral distribution among replicates.

Statistical analysis further supported these findings. ANOVA results indicated that feedstock type had a highly significant effect on ash content ($F = 1034.641$; Sig. = $0.000 < 0.05$). Duncan's Multiple Range Test (DMRT) also revealed clear statistical separation among treatments, with leaves showing the lowest ash content, leaf sheath the highest, and fruit stalk and the mixed fraction occupying intermediate positions.

From an energy perspective, higher ash content reduces the effective calorific value and may lead to operational issues such as slagging, reduced combustion efficiency, and increased residue formation. Nevertheless, since the measured values remain within the common range for biomass fuels, sugar palm charcoal briquettes still demonstrate practical potential for small-scale energy applications. Further improvements may be achieved through selective feedstock utilization, such as prioritizing twig biomass, or through pretreatment methods like washing the raw material to reduce mineral content prior to carbonization.

Overall, the variation in ash content observed in this study primarily reflects differences in mineral composition among the evaluated sugar palm biomass fractions, highlighting the importance of feedstock selection in improving briquette quality.

E. Fixed carbon

Fixed carbon is an important parameter in proximate analysis because it represents the solid carbon fraction remaining after the removal of moisture, volatile matter, and ash during carbonization. This fraction determines char stability, combustion duration, and energy density, and therefore directly reflects the energy quality of charcoal briquettes.

In this study, the fixed carbon content of charcoal briquettes produced from sugar palm waste ranged from 47% to 64%, with an average value of 56%. The highest fixed carbon was observed in the fruit stalk treatment (64%), followed by the mixed fraction

(58%), leaves (55%), and leaf sheath (47%). These results indicate that feedstock type significantly influences the formation of stable carbon structures during carbonization.

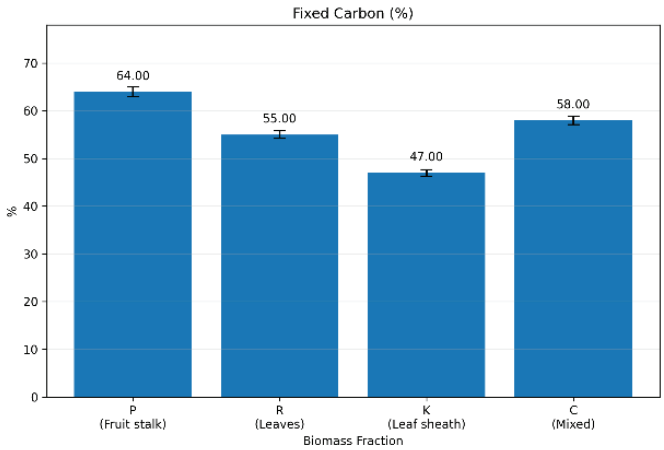


Figure 8: Ash content of *A. pinnata* waste materials.

From a thermochemical perspective, fixed carbon formation is strongly related to the lignocellulosic composition of the biomass. Biomass with higher lignin content generally produces greater carbon residues because lignin contains complex aromatic structures that are more resistant to thermal degradation. During pyrolysis, lignin undergoes depolymerization and condensation reactions that form stable aromatic carbon networks, thereby increasing the fixed carbon fraction [25],[2]. This mechanism likely explains the higher fixed carbon content observed in the fruit stalk fraction. In contrast, biomass dominated by cellulose and hemicellulose tends to undergo more intensive devolatilization, producing larger quantities of gases and tar compounds, which reduces the remaining carbon residue [3].

Mineral content also plays an important role in determining fixed carbon. The ash fraction is inert and does not contribute to the carbon structure; therefore, higher mineral content reduces the proportion of effective carbon within the briquette matrix ([26]). This phenomenon explains the relatively low fixed carbon observed in the leaf sheath treatment, which also exhibited the highest ash content.

Compared with the SNI 01-6235-2000 standard, which requires a minimum fixed carbon content of ≥60%, only the fruit stalk treatment satisfied the national requirement. Nevertheless, the observed range of 47–64% remains within the typical fixed carbon values reported for lignocellulosic biomass (approximately 45–70%) in thermochemical studies [15].

The reliability of the results was supported by low variability across treatments. The coefficient of variation (CV) ranged from 1.05% to 2.98%, indicating highly consistent measurements and homogeneous carbon distribution among replicates [14].

Statistical analysis further confirmed the significant effect of feedstock type on fixed carbon content. One-way ANOVA indicated a highly significant treatment effect ($F = 122.952$; $Sig. = 0.000 < 0.05$). Duncan's Multiple Range Test (DMRT) also showed that each treatment formed a statistically distinct group, indicating that each biomass fraction exhibits different carbonization behavior.

Overall, the variation in fixed carbon content primarily reflects differences in lignocellulosic composition and mineral content among the evaluated sugar palm biomass fractions. The fruit stalk fraction demonstrated the highest carbon quality, while the other fractions may require optimization of carbonization conditions, such as higher temperature or longer residence time, to improve the formation of stable carbon structures and enhance briquette energy quality.

F. *Calorific value*

Calorific value is a primary indicator of the energy quality of charcoal briquettes because it represents the amount of heat released per unit mass during complete combustion. In this study, the calorific values of sugar palm (*A. pinnata*) waste briquettes ranged from 4,443 to 5,985 cal/g^{-1}, with an overall average of 5,231 cal/g^{-1}. The highest value was obtained from the frond treatment (5,985 cal/g^{-1}), followed by leaves (5,420 cal/g^{-1}) and the mixed fraction (5,077 cal/g^{-1}), while leaf sheath exhibited the lowest calorific value (4,443 cal/g^{-1}). According to the SNI 01-6235-2000 standard, which specifies a minimum calorific value of ≥5,000 cal/g^{-1}, the frond, twig, and mixed treatments meet the national quality requirement, whereas the leaf sheath fraction does not.

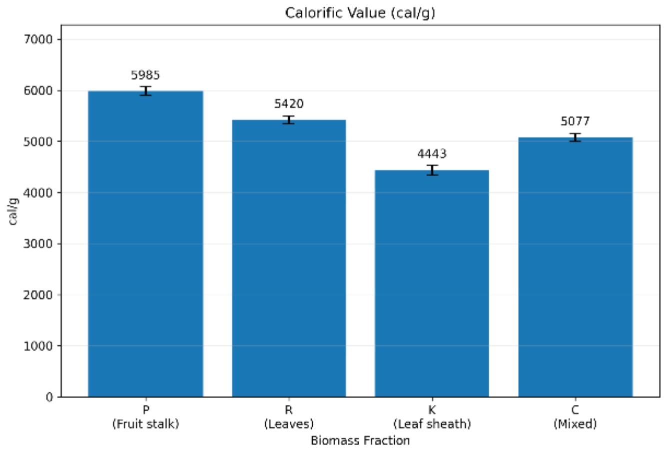


Figure 9: Calorific value of *A. pinnata* waste materials.

The calorific values obtained in this study are consistent with previously reported ranges for lignocellulosic biomass charcoal briquettes. Hendra and Darmawan [27] reported calorific values between 5,200 and 6,300 cal/g^{-1}, while Putra et al. [5] found values ranging from 4,800 to 6,000 cal/g^{-1} for briquettes derived from agricultural and plantation residues. These results indicate that the thermal characteristics of sugar palm briquettes remain within the typical range for carbonized biomass fuels.

Variations in calorific value are primarily influenced by the chemical composition of the biomass, particularly the balance between fixed carbon and ash content. Biomass fractions with higher fixed carbon generally produce higher calorific values because carbon-rich structures formed during carbonization contain greater energy density. This mechanism explains the high calorific value observed in the fruit stalk fraction, which also showed the highest fixed carbon content. In contrast, the leaf sheath exhibited the lowest calorific value due to its relatively high ash content. Ash is inert and does not contribute to heat release, thereby reducing the proportion of effective carbon in the briquette matrix [26]. The leaves and mixed fractions displayed intermediate calorific values, reflecting a balanced composition between combustible carbon and mineral content [26],[22].

The reliability of the measurements was supported by low variability across treatments. The coefficient of variation (CV) ranged from 0.37% to 3.55%, indicating highly consistent experimental procedures and uniform energy distribution among briquette samples.

Statistical analysis further confirmed the influence of feedstock type on calorific value. One-way ANOVA indicated a highly significant treatment effect (F = 117.915; Sig. = 0.000 < 0.05). Duncan's Multiple Range Test (DMRT) also revealed clear statistical separation among treatments, with fruit stalk forming the highest group, followed by leaves, the mixed fraction, and leaf sheath.

Overall, the results demonstrate that most sugar palm biomass fractions possess good energy potential as briquette feedstock. Further improvements for the leaf sheath fraction may be achieved by optimizing carbonization conditions or blending with low-ash biomass to enhance calorific value and meet national quality standards.

G. *Burning rate*

The burning rate is an important performance parameter that describes the rate of mass loss of briquettes during combustion, reflecting fuel reactivity, combustion stability, and the efficiency of heat release [28]. In this study, the burning rate of charcoal briquettes produced from sugar palm (*A. pinnata*) waste ranged from 0.03 to 0.06 g min^{-1}, indicating relatively moderate combustion characteristics.

Among the evaluated treatments, leaf sheath exhibited the highest burning rate (0.06 g min^{-1}), followed by the mixed fraction (0.05 g min^{-1}), leaves (0.04 g min^{-1}), and fruit stalk (0.03 g min^{-1}). These differences can be attributed to variations in the physical and chemical properties of the biomass. Briquettes with higher porosity and volatile matter content tend to burn more rapidly because oxygen diffusion into the carbon matrix occurs more efficiently, accelerating oxidation reactions [15]. Conversely, materials with higher fixed carbon content and more stable aromatic carbon structures require greater activation energy for oxidation, resulting in slower burning rates but longer combustion duration [29]. In addition, the presence of ash may reduce combustion reactivity by forming an inert layer that partially blocks heat transfer and oxygen diffusion within the briquette structure [30].

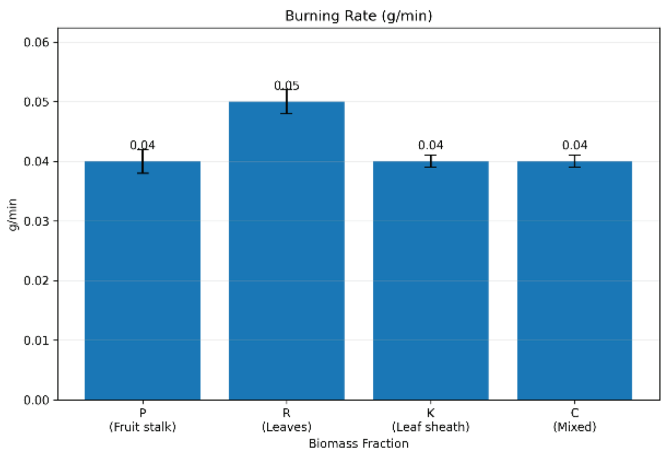


Figure 10: Burning rate of *A. pinnata* waste.

Analysis of internal variation also revealed differences in combustion stability among treatments. Leaves exhibited the highest variability (SD = 0.0109; CV = 25.35%), suggesting less consistent combustion behavior across replicates. This variability may be associated with heterogeneous fiber density and pore distribution within the woody tissue, which affect devolatilization and carbon oxidation kinetics [15],[31]. In contrast, the fruit stalk showed the most stable combustion performance (SD = 0.0024; CV = 7.23%), followed by the mixed fraction (SD = 0.0044; CV = 8.80%). Coefficients of variation below 10% generally indicate stable combustion characteristics and controlled heat release [23]. The leaf sheath treatment showed moderate variation (CV = 13.16%), reflecting high combustion reactivity but less uniform briquette structure.

Statistical analysis further confirmed that feedstock type significantly influenced the burning rate ($F = 7.167$; Sig. = $0.012 < 0.05$). Duncan's Multiple Range Test (DMRT) also demonstrated significant differences among treatments, indicating that each biomass fraction exhibited distinct combustion behavior.

From a practical perspective, briquettes with moderate burning rates and stable combustion are generally preferred for household energy applications because they provide longer burning duration and more efficient fuel utilization [25]. In this study, the fruit stalk and mixed treatments demonstrated the most stable combustion characteristics, while the leaf sheath showed higher reactivity, and leaves exhibited greater combustion variability.

Overall, the burning rate of sugar palm briquettes is influenced by the interaction of structural properties and proximate composition, particularly porosity, fixed carbon, ash, and volatile matter. These findings highlight the importance of optimizing feedstock selection and briquette formulation to achieve more stable and efficient combustion performance.

IV. Conclusions

Based on the results of this study on sugar palm (*A. pinnata*) biomass briquettes from HKm Aik Bual, the briquettes exhibit good potential as an alternative solid biofuel. All treatments demonstrated very low moisture content (1.47–2.31%) and complied with the SNI standard (≤8%), supporting efficient combustion. The calorific values ranged from 4,443 to 5,985 cal/g, with fruit stalk, leaves, and the mixture meeting the minimum SNI requirement (≥5,000 cal/g), while leaf sheath remained below the threshold. In terms of proximate composition, fruit stalk produced the highest fixed carbon content (64%) and the best energy quality, whereas leaves had the lowest ash content (7.8%) and were the only fraction meeting the ≤8% ash limit. All treatments exceeded the volatile matter standard, indicating a need for carbonization optimization. Although density did not meet the SNI minimum, the burning rate (0.04–0.05 g min^{-1}) was relatively stable and suitable for household applications. Overall, fruit stalks represent the most promising fraction, and sugar palm biomass waste has the potential for development as a community-based renewable energy source, provided that further process optimization is implemented to achieve full compliance with SNI 01-6235-2000.

Acknowledgments

The authors sincerely express their gratitude to the Institute for Research and Community Service (LPPM) at the University of Mataram for providing funding support that enabled this research to be carried out successfully. Appreciation is also extended to all members of the research team for their active contributions at every stage of the study, as well as to the managers and community of HKm Aik Bual for their cooperation and support during field activities. It is hoped that the results of this research will contribute to the development of sustainable biomass energy and the empowerment of local communities based on local potentials.

References

[1] J. Limantara, P. E. D. Tedjokoesoemo, and M. T. Rizqy, "Penggunaan Ampas Kopi Sebagai Material Alternatif pada Produk Interior," *Jurnal INTRA*, vol. 7, no. 2, pp. 846–848, 2018, Available: https://garuda.kemdiktisaintek.go.id/documents/detail/1244055

[2] X. Chen, H. Yang, Y. Chen, and S. Zhang, "Influence of drying conditions on moisture content and combustion characteristics of biomass briquettes," *Energy Reports*, vol. 5, no. 1, pp. 997–1004, 2019.

[3] A. Kaur, M. Roy, and K. Kundu, "DENSIFICATION OF BIOMASS BY BRIQUETTING: A REVIEW," *International Journal of Recent Scientific Research*, vol. 8, no. 10, pp. 20561–20568, Oct. 2017, doi: https://doi.org/10.24327/ijrsr.2017.0810.0916.

[4] Y. Zhang, X. Li, and H. Chen, "Lignin-derived carbon structure and its influence on calorific value of biomass char," *338*, p. 127327, 2023, doi: https://doi.org/10.1016/j.fuel.2023.127327.

[5] A. Putra, S. Suryaningsih, and R. Prayoga, "Characterization of lignocellulosic biomass briquettes and their combustion properties," *Heliyon*, vol. 9, no. 3, p. 91233, 2022.

[6] S. Suryaningsih, O. Nurhilal, R. A. Widyarini, N. Suhendi, and Rukiah, "The analysis of ignition and combustion properties of the burning briquettes made from mixed biomass of rice husk and corn cob," *IOP Conference Series: Materials Science and Engineering*, vol. 550, no. 1, p. 012006, Jul. 2019, doi: https://doi.org/10.1088/1757-899x/550/1/012006.

[7] X. Li, Y. Zhang, Q. Wang, and H. Chen, "Proximate characteristics and thermal degradation behavior of lignocellulosic biomass briquettes," *Fuel*, vol. 322, p. 124176, 2022.

[8] H. Zhou, Y. Long, A. Meng, Q. Li, and Y. Zhang, "The role of lignin in biomass pyrolysis and char formation," *Energy & Fuels*, vol. 32, no. 2, pp. 1547–1583, 2018.

[9] M. Rahman, M. Hasan, and M. Islam, "Effect of biomass type on proximate and ultimate analysis of briquettes," *Energy Reports*, vol. 6, no. 1, pp. 215–221, 2020.

[10] B. Santoso, E. Widodo, and A. Fauzi, "Thermal degradation and combustion kinetics of lignocellulosic biomass briquettes," *Renew. Energy*, vol. 170, pp. 123–132, 2021.

[11] A. Syarif, "Pengaruh Ukuran Partikel dan Variasi Komposisi Briket pada Campuran Limbah Arang Kayu Alaban dengan Sekam Padi terhadap Karakteristik Briket," *JMIO: Jurnal Mesin Industri dan Otomotif*, vol. 1, no. 02, May 2020, doi: https://doi.org/10.46365/jmio.v1i02.381.

[12] S. Rahmadani and R. Fitria, "Pengaruh konsentrasi perekat terhadap karakteristik briket arang limbah kulit pinang (Areca catechu L.)," *Jurnal Teknologi Pertanian*, vol. 11, no. 2, pp. 85–94, 2022.

[13] D. C. Montgomery, *Design and analysis of experiments*, 10th ed. 2021.

[14] N. Kaliyan and R. Vance Morey, "Factors affecting strength and durability of densified biomass products," *Biomass and Bioenergy*, vol. 33, no. 3, pp. 337–359, Mar. 2009, doi: https://doi.org/10.1016/j.biombioe.2008.08.005.

[15] P. Basu, *Biomass Gasification, Pyrolysis and Torrefaction*, 1st Edition. Elsevier, 2018. doi: https://doi.org/10.1016/c2016-0-04056-1.

[16] D. Prayogo, "Optimization of briquette density from agricultural residues.," *International Journal of Renewable Energy Development*, vol. 15, no. 2, pp. 110–128, 2023.

[17] A. Khabibi, "nalisis densitas dan karakteristik pembakaran briket limbah lignoselulosa," *Jurnal Teknologi Energi*, vol. 12, no. 1, pp. 45–52, 2025.

[18] M. Rosadi, "Karakteristik fisik dan kimia briket berbahan dasar limbah pertanian," *Jurnal Teknik Pertanian*, vol. 14, no. 3, pp. 201–210, 2025.

[19] R. Muhammad, "Pengaruh tekanan kempa terhadap kualitas fisik briket biomassa," *Institut Teknologi Dirgantara Adisutjipto*, 2022.

[20] B. Setyawan, "Studi variasi bahan baku terhadap densitas dan nilai kalor briket," *Jurnal Riset Industri*, vol. 8, no. 2, pp. 75–83, 2019.

[21] A. R. Pratama, "Analisis Komposisi Kimia Serat Pelepah Aren (Arenga pinnata) sebagai Bahan Baku Papan Partikel dan Briket Terintegrasi," *Jurnal Teknologi Hasil Hutan*, vol. 14, no. 1, pp. 45–52, 2019.

[22] S. Suryaningsih, A. Putra, and R. Prayoga, "Moisture reduction and combustion stability of biomass briquettes," *Heliyon*, vol. 7, no. 6, p. 7291, 2021.

[23] I. Obemberger and G. Thek, "The pellet handbook: The production and thermal utilization of biomass pellets," *Earthscan*, 2010.

[24] I. E. Onukak, I. A. Mohammed Dabo, O. A. Ameh, S. I. R. Okoduwa, and O. O. Fasanya, "Production and characterization of biomass briquettes from tannery solid waste," *Recycling*, vol. 2, no. 4, p. 17, 2017.

[25] Y. Zhang and W. Yu , "Effect of steam heating on the color and chemical properties of Neosinocalamus affinis bamboo," *Journal of Wood Chemistry and Technology*, vol. 33, pp. 235–246, 2013.

[26] F. Sulaiman, N. Abdullah, and H. Gerhauser, "Mineral content effect on calorific value of biomass char," *Fuel Processing Technology*, vol. 227, p. 107113, 2022, doi: https://doi.org/10.1016/j.fuproc.2021.107113.

[27] D. Hendra and S. Darmawan, "Sifat fisik dan kimia briket arang kayu," *Jurnal Penelitian Hasil Hutan*, vol. 18, no. 1, pp. 21–28, 2000.

[28] A. Fauzi, B. Santoso, and Y. Nugroho, "Burning rate characteristics of biomass briquettes and their thermal performance evaluation," *Energy Reports*, vol. 9, no. 1, pp. 1542–1550, 2023.

[29] B. Santoso, "Pandangan Fiqih Siyasah Terhadap Program Kerja Pemerintah Kota Bandar Lampung Dalam Penanganan Kemiskinan," *Universitas Islam Negeri Raden Intan*, 2017.

[30] Maryono, Sudding, and Rahmawati, "Pembuatan dan Analisis Mutu Briket Arang Cangkang Kelapa Ditinjau dari Kadar Kanji," vol. 14, pp. 74–83, 2013.

[31] D. Nhuchhen and M. Afzal, "HHV Predicting Correlations for Torrefied Biomass Using Proximate and Ultimate Analyses," *Bioengineering*, vol. 4, no. 4, p. 7, Jan. 2017, doi: https://doi.org/10.3390/bioengineering4010007.