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Quality and Energy Performance of Briquettes Derived from Non-Timber Forest Product Residues: A Case Study of Sugar Palm (*Arenga pinnata*)

***Febriana Tri Wulandari, Aluh Nikmatullah, Sitti Latifah, Hayati**
Doctor of Sustainable Agriculture, Postgraduate Program, University of Mataram, Mataram, Indonesia
*Corresponding Author e-mail: febriana.wulandari@unram.ac.id

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Abstract

The utilization of non-wood biomass residues as alternative solid fuels is important for supporting low-carbon energy transitions and circular bioenergy development. This study evaluated the quality and energy performance of charcoal briquettes produced from vegetative residues of sugar palm (*Arenga pinnata*), specifically fronds, fruit stalks, and a mixture of both materials. A completely randomized design was applied, and the briquettes were assessed based on physical properties, proximate composition, combustion performance, and charcoal yield, with SNI 01-6235-2000 used as the primary quality benchmark. The results showed that all briquette types had very low moisture content (1.69–2.03%) and high calorific values (5,427–5,985 cal g^{-1}), meeting the SNI requirements for these parameters. Significant differences among plant parts were observed in ash content, volatile matter, and fixed carbon content ($p < 0.05$), indicating that raw material characteristics strongly influenced briquette quality. Briquettes produced from sugar palm fronds exhibited the highest fixed carbon content and calorific value, as well as the lowest burning rate, reflecting better thermal stability and longer combustion duration. Meanwhile, briquettes made from the mixture of fronds and fruit stalks showed the lowest ash content and the most balanced quality profile. Although some proximate parameters, particularly volatile matter and fixed carbon, did not fully meet the SNI limits, these limitations are process-dependent and may be improved through optimization of carbonization conditions. Overall, sugar palm vegetative residues represent a promising non-wood biomass resource for sustainable charcoal briquette production within a circular bioenergy framework.

Keywords: Charcoal briquette; Arenga pinnata; Non-wood biomass; Proximate analysis; Calorific value; SNI 01-6235-2000

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INTRODUCTION

Indonesia has substantial biomass potential, particularly from agricultural and forestry residues, including residues derived from non-timber forest products. One important commodity in this context is sugar palm (*Arenga pinnata*), which is widely known as a source of palm sap and palm sugar. However, the vegetative parts of sugar palm, particularly fronds and fruit stalks, remain underutilized and are commonly treated as agricultural waste, despite their promising chemical characteristics. These residues are not only locally abundant but also relevant for biomass-based energy development because they contain lignocellulosic components that can be converted into charcoal through carbonization. Therefore, sugar palm residues represent a potential raw material for developing alternative solid fuels based on locally available non-wood biomass resources.

The lignocellulosic components of sugar palm residues play an important role in the formation of charcoal structure during the carbonization process. Previous studies have reported that sugar palm biomass contains ash content of approximately 2.38% (Sanyang et al., 2016). In addition, Aminah et al. (2020) reported that sugar palm material contains holocellulose ranging from 47.79% to 49.2%, consisting of cellulose (21.97%–27.2%) and hemicellulose (22%–23%). Biomass from the genus *Arenga* has also been reported to have significant potential for conversion into charcoal and further processing into briquettes as a biomass-based alternative energy source (Hakim et al., 2024). Therefore, the quality of charcoal briquettes produced from sugar palm residues is expected to vary among plant parts due to differences in anatomical structure and chemical composition, making systematic quality evaluation necessary.

The utilization of biomass waste as a solid fuel has become increasingly relevant in the context of low-emission energy transitions. The energy sector remains the main contributor to global greenhouse gas emissions, with more than three-quarters of total emissions originating from energy-related activities, while global energy-related CO_2 emissions reached 37.4 Gt in 2023 (IEA, 2024, 2025). This condition highlights the urgent need to accelerate the development of sustainable and low-emission renewable energy sources, including locally based energy systems, as part of broader efforts to mitigate climate change and strengthen long-term energy resilience (IPCC, 2022). In this context, lignocellulosic biomass has considerable potential as a renewable energy source, particularly through the utilization of biomass residues in accordance with circular economy principles, as it can reduce environmental burdens while producing value-added products (Saravanan et al., 2025).

Despite its potential, raw biomass generally has low density, high heterogeneity, and unfavorable physical characteristics for direct use as a solid fuel; therefore, quality improvement through further processing is required (Bajwa et al., 2018). The direct use of biomass as fuel is often considered inefficient due to its relatively low energy density, with an average calorific value of approximately 3,000 cal/g. Conversion of biomass into biochar through pyrolysis, or combustion under limited oxygen conditions, has been shown to increase its calorific value to around 5,000 kcal/g. This improvement in thermal quality makes biochar a more effective renewable energy alternative than its original biomass form (Fachry et al., 2020). Once biomass has undergone carbonization, the development of charcoal briquettes becomes more relevant because this process produces a solid fuel with higher thermal stability and more controlled combustion characteristics.

The quality of charcoal briquettes is strongly influenced by biomass type, plant part, carbonization conditions, and briquetting techniques, all of which collectively determine the mechanical strength and energy performance of the final product (Ngene et al., 2024). Densification through briquette production is therefore an effective approach to improving biomass quality as a solid fuel by increasing density, combustion stability, and ease of storage and transportation (Kpalo et al., 2020). In this regard, briquetting is not merely a shaping process but also a quality improvement strategy that enhances the practical value of biomass residues. Through densification, loose and heterogeneous biomass residues can be converted into more uniform solid fuels with better handling characteristics, more stable combustion, and improved suitability for household or small-scale energy applications.

The quality of charcoal briquettes is determined by the integration of physical and proximate characteristics. Physical parameters, such as moisture content and density, influence ignition ease, combustion stability, and energy storage capacity. Meanwhile, proximate parameters, including ash content, volatile matter, and fixed carbon, determine energy efficiency, flame characteristics, and combustion residue (Obi et al., 2021). Evaluations that focus only on a single parameter, such as calorific value, are insufficient to describe briquette performance comprehensively and may lead to partial or biased conclusions (Ngene et al., 2024; Obi et al., 2021). Therefore, a comprehensive evaluation is required to assess charcoal briquette quality more accurately, especially when the raw materials are derived from non-wood biomass with highly variable physical and chemical properties.

In Indonesia, SNI 01-6235-2000 is widely used as a benchmark for evaluating the quality of biomass-based charcoal briquettes (Widodo et al., 2021). In addition, the quality standards established by P3HH, or the Center for Forest Product Research and Development, provide a more comprehensive set of parameters than SNI 01-6235-2000 because they include requirements for density and compressive strength. The P3HH guidelines also specify stricter minimum thresholds for fixed carbon and calorific value (Rindayatno, Fatur Rohma, et al., 2022; M. K. Sari, 2020). However, the application of these standards to non-wood biomass still requires a comprehensive evaluation approach to account for variations in biomass characteristics and to avoid biased quality assessments. This is particularly important because non-wood biomass often differs from woody biomass in mineral content, porosity, volatile matter, and combustion behavior.

Previous studies have shown that the quality of charcoal briquettes is influenced by biomass type and the plant parts used. Woody biomass generally produces briquettes with lower ash content and higher calorific value, whereas more porous biomass tends to exhibit faster burning rates, although this does not always correspond to higher energy efficiency (Martono et al., 2023; Nurhayati et al., 2022; L. Zhang et al., 2020). However, many existing studies still evaluate quality parameters separately and have not fully integrated physical and proximate characteristics within a unified evaluation framework, particularly for charcoal briquettes derived from sugar palm (*Arenga pinnata*) biomass waste. This limitation creates a need for a more integrated assessment that can identify both the strengths and limitations of each sugar palm plant part as a raw material for charcoal briquette production.

This study positions sugar palm (*Arenga pinnata*) vegetative waste as a non-timber forest product residue that can be evaluated as a standardized biomass material through an integrated approach to determine its technical feasibility and identify the most prospective plant parts for charcoal briquette production. The novelty of this study lies in two main aspects: first, the comparative analysis of different sugar palm plant parts, namely fronds, fruit stalks, and their mixture, which may produce distinct charcoal characteristics; and second, the integration of physical and proximate indicators within a unified quality evaluation framework to identify critical trade-offs among ignition ease, combustion stability, energy efficiency, and combustion residue.

By adopting SNI 01-6235-2000 as the main quality benchmark and complementing it with performance indicators relevant to non-wood biomass, this study is expected to provide a stronger scientific basis for selecting standardized sugar palm biomass materials and developing charcoal biobriquettes from local forestry residues within a circular economy framework (Bajwa et al., 2018; Hakim et al., 2024; Kpalo et al., 2020; Ngene et al., 2024; Saravanan et al., 2025; Widodo et al., 2021). This integrated approach is important because the feasibility of charcoal briquettes cannot be determined solely from calorific value, but must also consider moisture content, density, ash content, volatile matter, fixed carbon, combustion stability, and the ability of the material to meet relevant quality standards.

METHOD

This study employed an experimental approach using a quantitative research design. An experimental method is appropriate for examining the effects of specific treatments on response variables under controlled conditions. In this approach, the researcher deliberately manipulates the independent variable and observes the resulting changes in the dependent variables, while controlling other factors that may influence the research outcomes. This design enables stronger causal inference because the procedures are systematic, measurable, and reproducible. Therefore, the experimental approach was considered suitable for evaluating the effects of different sugar palm (*Arenga pinnata*) biomass residues on the physical properties, proximate composition, combustion performance, and charcoal yield of the resulting briquettes (D. P. Sari & Nugroho, 2023; Setiawan & Fitria, 2024).

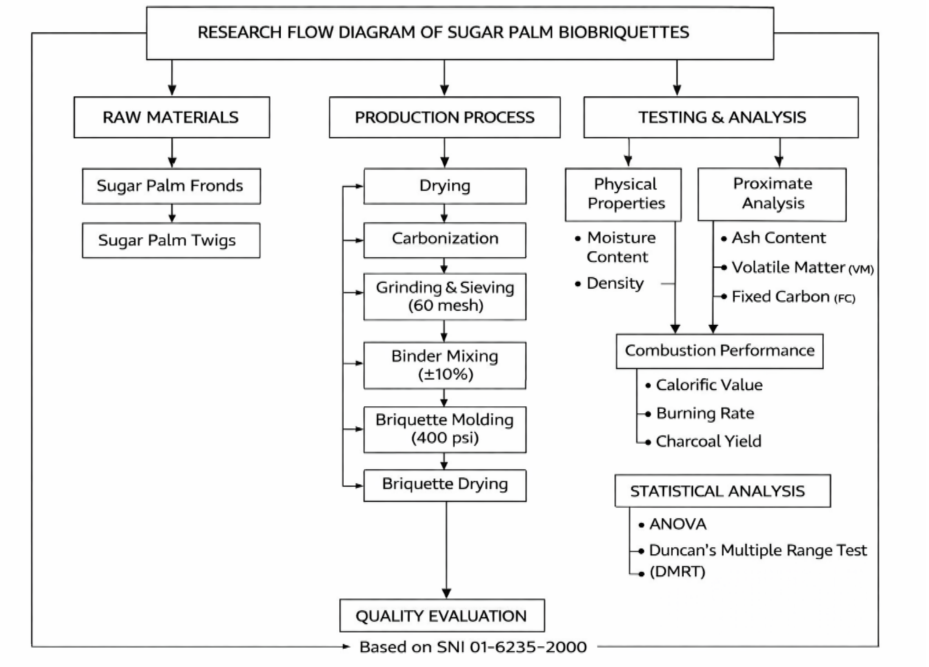

Figure 1. Research Flowchart

Charcoal briquette production was carried out using the drum kiln carbonization method at a controlled temperature of approximately 400°C, followed by briquette molding at a pressing pressure of 400 psi. The selected carbonization temperature is consistent with previous studies reporting that the optimal temperature range for carbonization using the drum kiln method is approximately 350–450°C (Erwin Junary et al., 2015; Rindayatno & Lewar D.O., 2017; Rindayatno, Wulandari, et al., 2022). A 10% maltodextrin binder was used as an environmentally friendly adhesive to improve particle bonding during briquette formation. The production process included raw material preparation, drying, carbonization, grinding and sieving to 60 mesh, binder mixing, briquette molding, and final drying before testing.

Figure 2. Manufacturing Process of Biobriquettes from Sugar Palm (*Arenga pinnata*) Waste

The quality of the charcoal briquettes was evaluated based on physical properties, proximate composition, combustion performance, and charcoal yield. The parameters measured included moisture content, density, ash content, volatile matter, fixed carbon, calorific value, burning rate, and charcoal yield. These parameters were selected to provide a comprehensive assessment of briquette quality because physical characteristics determine handling, storage, and ignition behavior, while proximate composition and combustion performance determine thermal efficiency and fuel suitability. The Indonesian National Standard SNI 01-6235-2000 for charcoal briquettes was used as the primary quality benchmark to evaluate product feasibility. The use of this standard ensures that the results are not only scientifically measurable but also technically relevant for the development of biomass-based charcoal briquettes as an alternative solid fuel.

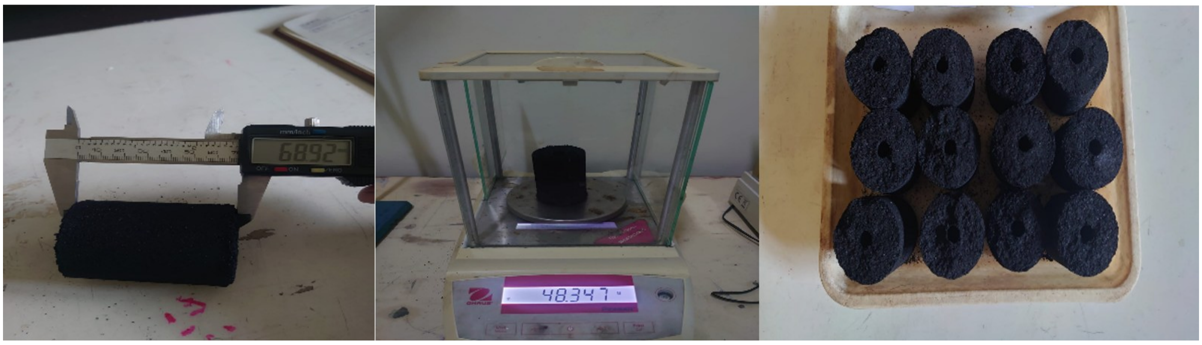

Figure 3. Testing Process of Sugar Palm (*Arenga pinnata*) Waste Biobriquettes

The study was arranged using a Completely Randomized Design (CRD) with a non-factorial structure. The single treatment factor was the type of sugar palm (*Arenga pinnata*) biomass residue used as the raw material for briquette production. This factor consisted of three treatment levels: briquettes produced from sugar palm fronds (P), briquettes produced from sugar palm fruit stalks (R), and briquettes produced from a mixture of sugar palm fronds and fruit stalks (C). Each treatment was replicated three times, resulting in a total of nine experimental units. The CRD was considered appropriate because all experimental units were assumed to be homogeneous, and the treatments could be assigned randomly. Therefore, the observed variation was primarily attributed to differences among the biomass treatments.

Table 1. Experimental Design

Type of Material	Test 1	Test 2	Test 3
P	P1	P2	P3
R	R1	R2	R3
C	C1	C2	C3

Note: P = sugar palm fronds; R = sugar palm fruit stalks; C = mixture of sugar palm fronds and fruit stalks.

The experimental data were analyzed statistically using analysis of variance (ANOVA) to determine the effect of biomass residue type on the observed quality parameters of the charcoal briquettes. When the ANOVA results indicated a statistically significant effect at $p < 0.05$, the analysis was followed by Duncan’s Multiple Range Test (DMRT) at a 95% confidence level to identify differences among treatments in more detail. This post hoc test was applied only to parameters showing significant treatment effects. Given the limited number of treatment groups in this study, additional testing using Tukey’s Honestly Significant Difference (HSD) test was not considered necessary. This statistical procedure was used to ensure that differences in briquette quality could be interpreted objectively based on the treatment effects.

RESULTS AND DISCUSSION

Density

The density of charcoal briquettes produced from sugar palm biomass residues was relatively uniform across treatments, ranging from 0.35 to 0.36 g/cm³, with an overall average of 0.36 g/cm³. Briquettes produced from sugar palm fruit stalks (R) showed a slightly lower density than those produced from sugar palm fronds (P) and the mixture of fronds and fruit stalks (C). However, all treatments had density values below the SNI 01-6235-2000 requirement for charcoal briquettes (>0.60 g/cm³). This condition indicates that the briquettes produced in this study still had relatively high porosity, which may be influenced by raw material characteristics, particle size, compression pressure, binder type, and the uniformity of the molding process (Hendra & Darmawan, 2000; Yuliah et al., 2021).

Table 2. Average Density of Charcoal Briquettes (g/cm³)

Treatment	Test 1	Test 2	Test 3	Average
P	0.37	0.37	0.36	0.36
R	0.36	0.37	0.33	0.35

Treatment	Test 1	Test 2	Test 3	Average
C	0.36	0.36	0.37	0.36
Average				0.36

Note: P = sugar palm fronds; R = sugar palm fruit stalks; C = mixture of sugar palm fronds and fruit stalks.

Low density does not necessarily indicate poor combustion performance. Higher porosity can improve oxygen diffusion within the briquette structure, thereby facilitating ignition and increasing the burning rate, although it may reduce mechanical strength and shorten flame duration (Ajit Kaur et al., 2017; Y. Zhang et al., 2022). In this study, the effect of low density was partly compensated by the very low moisture content of the briquettes, allowing combustion to remain efficient. Several studies on non-wood biomass briquettes have also reported that densities below 0.40 g/cm³ may still be suitable for household applications that require rapid ignition. The lower density observed in the fruit stalk treatment was likely influenced by one replicate with a relatively low value, indicating that process-related factors such as compression pressure consistency, mixture homogeneity, binder distribution, and moisture content during molding and drying may have been more dominant than intrinsic differences in the raw materials (Ajit Kaur et al., 2017; Hendra & Darmawan, 2000; A. R. Putra et al., 2022).

These findings are consistent with previous studies showing that biomass briquette density tends to be low when compaction pressure and particle size are not optimized (Nurhayati et al., 2022; Prayoga et al., 2023; Sutrisno et al., 2021). Conversely, increasing compaction pressure, reducing particle size, and optimizing binder composition have been shown to increase briquette density up to 0.57 g/cm³, approaching the SNI 01-6235-2000 requirement. This confirms that density is strongly influenced by densification parameters and can still be improved through process optimization without necessarily changing the raw material (Rindayatno, Wulandari, et al., 2022).

Table 3. ANOVA Results for Density of Charcoal Briquettes

Source of Variation	Sum of Squares	df	Mean Square	F-value	Sig.
Treatment	0.000	2	0.000	0.867	0.467
Error	0.001	6	0.000		
Corrected Total	0.001	8			

The ANOVA results presented in Table 3 show that the type of sugar palm biomass residue did not have a significant effect on the density of charcoal briquettes ($p = 0.467$; $p > 0.05$). This indicates that the variation in density was more strongly controlled by production parameters, particularly the use of 60-mesh particles, 10% binder concentration, and 400 psi pressing pressure, rather than by differences among the biomass types (Putra et al., 2022; Rahman & Widodo, 2023). Therefore, further analysis using Duncan's Multiple Range Test (DMRT) was not required for this parameter. The relatively low density increased briquette porosity and facilitated ignition, but it may also reduce mechanical durability and flame duration. Accordingly, optimization of compaction pressure, particle size, and binder composition is needed to achieve a better balance between effective heating value, combustion stability, and mechanical strength (Ajit Kaur et al., 2017; S. Wulandari et al., 2025; Yuliah et al., 2021).

Moisture Content

Moisture content is one of the most important quality parameters in the evaluation of charcoal briquettes because it directly affects combustion efficiency, energy stability, ignition ease, and product durability during storage and distribution. Excessive moisture content can reduce the effective energy value of briquettes because part of the heat generated during combustion is used to evaporate water rather than to produce useful thermal energy. High moisture content may also slow ignition, reduce flame stability, and increase smoke emissions during combustion. Therefore, lower moisture content is generally preferred in charcoal briquettes, particularly when the product is intended for household and small-scale energy applications (S. Wulandari et al., 2025; Rahmadani & Fitria, 2022).

Table 4. Average Moisture Content of Charcoal Briquettes (%)

Treatment	Test 1	Test 2	Test 3	Average (%)
P	2.13	1.93	2.04	2.03
R	1.74	1.65	1.67	1.69
C	2.10	1.99	1.86	1.98
Average				1.90
SNI 01-6235-2000				≤8

Note: P = sugar palm fronds; R = sugar palm fruit stalks; C = mixture of sugar palm fronds and fruit stalks.

The results presented in Table 4 show that the moisture content of charcoal briquettes across all treatments ranged from 1.69% to 2.03%, with an overall average of 1.90%. These values are far below the maximum moisture content required by SNI 01-6235-2000, which is ≤8%. This indicates that the drying, carbonization, and post-molding drying processes were effective in reducing the water content of the briquettes. The moisture content obtained in this study can be classified as very low compared with typical biomass briquettes, which are commonly reported within the range of 3–7%. This condition reflects good process control and contributes positively to the thermal quality of the briquettes (Garcia et al., 2020; Kaliyan & Vance Morey, 2009). The consistently low moisture content is also associated with thermal dehydration during carbonization, in which free water and part of the bound water are released through the thermal degradation of lignocellulosic components (Chen et al., 2021).

Although the differences among treatments were relatively small, a clear pattern was observed. Briquettes produced from sugar palm fruit stalks (R) had the lowest moisture content, at 1.69%, while briquettes produced from sugar palm fronds (P) had the highest value, at 2.03%. The mixed treatment (C) showed an intermediate value of 1.98%. The lower moisture content in the fruit stalk treatment may be related to its denser and more compact structure, which can facilitate more efficient moisture removal during drying and carbonization (Sutrisno et al., 2021; Y. Zhang et al., 2022). In contrast, sugar palm fronds may have a more porous structure and a relatively higher hemicellulose fraction, making them more hygroscopic and more likely to retain residual moisture. Nevertheless, the moisture content of all treatments remained lower than values reported for several other biomass briquettes, such as rice straw–banana peel briquettes, which have been reported to contain approximately 4.22% moisture (Duangkham et al., 2023; T. Hidayat & Lestari, 2022; M. Rahman et al., 2020).

The intermediate moisture content observed in the mixed treatment suggests a balancing effect between the anatomical and physical characteristics of sugar palm fronds and fruit stalks. Blending biomass materials with different structural properties can produce moderate moisture characteristics without reducing technical feasibility. This finding is consistent with previous studies showing that biomass blending may improve the balance of briquette properties by combining the strengths of different raw materials (Nurhayati et al., 2022; Prasetyo et al., 2021). In this study, the very low moisture content contributed to improved ignition ease, higher effective calorific value, and more stable combustion because less energy was required for water evaporation during burning. As a result, carbon oxidation could proceed more efficiently with minimal latent heat loss (Antal & Grønli, 2003; Basu, 2018; Demirbas, 2017; L. Zhang et al., 2020).

Table 5. ANOVA Results for Moisture Content of Charcoal Briquettes

Source of Variation	Sum of Squares	df	Mean Square	F-value	Sig.
Treatment	0.211	2	0.105	11.836	0.008
Error	0.053	6	0.009		
Corrected Total	0.264	8			

The ANOVA results presented in Table 5 indicate that the type of sugar palm biomass residue had a significant effect on the moisture content of charcoal briquettes, as shown by a significance value of 0.008 ($p < 0.05$). This result confirms that differences in raw material type, namely sugar palm fronds, fruit stalks, and their mixture, produced statistically significant differences in moisture content. Therefore, further analysis using Duncan's Multiple Range Test (DMRT) was conducted to identify the specific differences among treatments. This statistical result supports the interpretation that moisture content is not only determined by the drying and carbonization process but also by the anatomical and chemical characteristics of the biomass used as raw material.

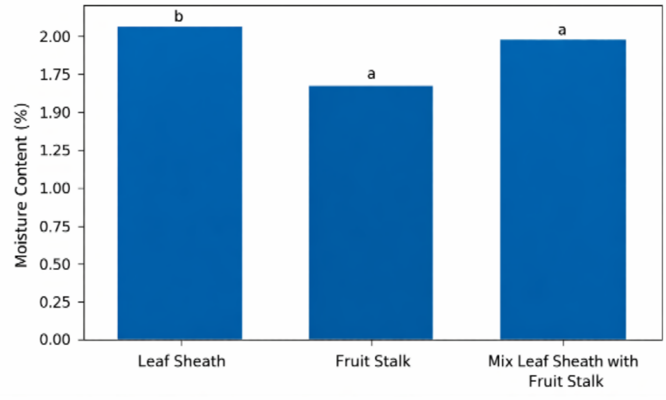

Figure 4. DMRT Results for Moisture Content of Charcoal Briquettes

The DMRT results shown in Figure 4 indicate that the fruit stalk treatment (R) belongs to group a and differs significantly from the frond treatment (P). Meanwhile, the mixed treatment (C) belongs to group b and is not significantly different from P, but differs significantly from R. This pattern confirms that the physical and anatomical characteristics of the raw materials influenced moisture release during drying and carbonization. The denser and more woody structure of fruit stalks, which may be associated with higher lignin content, likely facilitated more efficient water vapor diffusion and resulted in lower moisture content (Y. Zhang et al., 2022). In contrast, sugar palm fronds, which tend to be more porous and contain relatively higher hemicellulose fractions, are more hygroscopic and therefore more likely to retain residual moisture (Chen et al., 2021). The mixed treatment showed intermediate behavior, reflecting the combined contribution of both biomass materials (Prasetyo et al., 2021). Nevertheless, all treatments produced very low moisture content, below 5%, which is advantageous for achieving efficient and stable combustion and supports the potential use of sugar palm biomass residues as charcoal briquette raw materials (Garcia et al., 2020; Widodo et al., 2021; Kaur et al., 2023).

Ash Content

Ash content refers to the inorganic mineral residue remaining after the complete combustion of briquettes at high temperatures. This parameter represents the non-combustible fraction of the fuel and is commonly used as an important indicator of biomass fuel quality. In charcoal briquettes, high ash content is generally undesirable because it can reduce effective calorific value, lower combustion efficiency, increase combustion residue, and contribute to slag formation during burning. Therefore, briquettes with lower ash content are usually considered to have better fuel quality, especially for household and small-scale applications that require cleaner and more efficient combustion. In this study, ash content was evaluated to determine the effect of sugar palm biomass type on mineral residue accumulation after combustion (S. Wulandari et al., 2025).

Table 6. Average Ash Content of Charcoal Briquettes (%)

Treatment	Test 1	Test 2	Test 3	Average (%)
P	11.4	11.2	12.0	11.53
R	7.8	7.7	7.9	7.80
C	6.2	6.4	5.9	6.17
Average				8.50

Treatment	Test 1	Test 2	Test 3	Average (%)
SNI 01-6235-2000				≤8

Note: P = sugar palm fronds; R = sugar palm fruit stalks; C = mixture of sugar palm fronds and fruit stalks.

As shown in Table 6, the ash content of charcoal briquettes derived from sugar palm biomass residues ranged from 6.17% to 11.53%, with an overall average of 8.50%. These results indicate that raw material composition strongly influenced the accumulation of inorganic residue in the briquettes. Briquettes produced from sugar palm fronds (P) had the highest ash content, at 11.53%, and did not meet the SNI 01-6235-2000 requirement of ≤8%. In contrast, briquettes produced from fruit stalks (R) had an ash content of 7.80%, while briquettes produced from the mixture of fronds and fruit stalks (C) had the lowest ash content, at 6.17%. Both R and C treatments met the SNI requirement, although the mixed treatment showed the best performance for this parameter.

The higher ash content in sugar palm frond briquettes may be associated with the greater accumulation of inorganic minerals in the frond structure, such as silica, alkali metals, and alkaline earth elements, which are non-volatile and remain as residue after carbonization and combustion. In contrast, fruit stalks generally contain lower mineral fractions, resulting in lower ash formation during combustion (Jenkins et al., 2018; Saputro et al., 2020; Vassilev et al., 2013). The lowest ash content observed in the mixed treatment suggests that blending fronds with fruit stalks reduced the overall inorganic fraction through a mineral dilution effect. This finding indicates that biomass blending can be a practical strategy to improve ash-related quality without requiring additional chemical treatment.

The ash values obtained in this study are consistent with previous findings showing that biomass materials with higher mineral content, such as oil palm empty fruit bunches and rice husks, tend to produce higher ash content. Conversely, biomass materials with lower mineral content, such as corn cobs and coconut shell-based mixtures, generally produce lower ash levels (T. Hidayat et al., 2021; A. R. Putra et al., 2018; Suryani et al., 2021). The lower ash content in the mixed treatment supports the view that combining biomass materials with different mineral characteristics can improve briquette quality. This result is also consistent with studies reporting that biomass blending can reduce the inorganic fraction and improve the balance of briquette properties (T. Hidayat et al., 2021; Prasetyo et al., 2021).

From a technical perspective, lower ash content contributes positively to combustion performance because it increases the effective energy fraction of the briquette, improves flame stability, and reduces the risk of slagging and deposition in the combustion chamber. Lower ash content also minimizes non-combustible residue, making briquettes more efficient and cleaner during use (Antal & Grønli, 2003; Chen et al., 2021; Demirbas, 2017; Kaur et al., 2023; Saidur et al., 2020). Therefore, the mixture of sugar palm fronds and fruit stalks can be considered the most favorable treatment for ash content because it produced the lowest value and clearly met the SNI 01-6235-2000 standard. However, fruit stalk briquettes also met the standard and should not be excluded as a technically feasible raw material.

Table 7. ANOVA Results for Ash Content of Charcoal Briquettes

Source of Variation	Sum of Squares	df	Mean Square	F-value	Sig.
Treatment	45.407	2	22.703	276.122	0.000
Error	0.493	6	0.082		
Corrected Total	45.900	8			

The ANOVA results presented in Table 7 show that the type of sugar palm biomass residue had a highly significant effect on the ash content of charcoal briquettes, as indicated by a significance value of 0.000 ($p < 0.05$). The F-value of 276.122 confirms that differences among raw materials, namely sugar palm fronds, fruit stalks, and their mixture, resulted in statistically significant differences in ash content. This finding demonstrates that the mineral composition and anatomical characteristics of each sugar palm biomass component directly influenced the amount of ash residue produced after combustion. Therefore, further analysis using Duncan's Multiple Range Test (DMRT) was conducted to identify the specific differences among treatments.

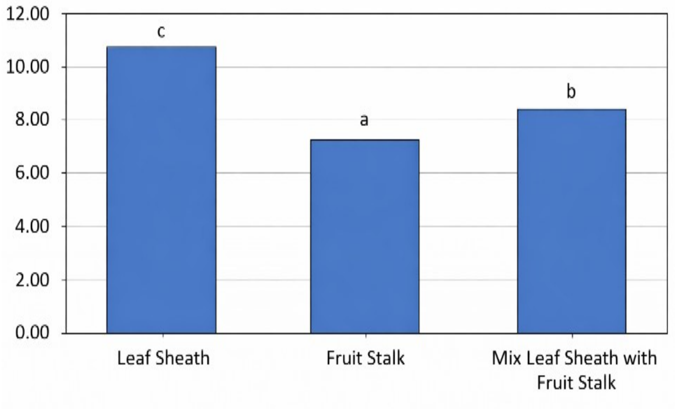

Figure 5. DMRT Results for Ash Content of Charcoal Briquettes

The DMRT results shown in Figure 5 indicate that all three treatments differed significantly at the 95% confidence level. The treatment groups followed the order: fruit stalks (a) < mixture of fronds and fruit stalks (b) < fronds (c). This means that briquettes produced from sugar palm fronds had the highest ash content, while briquettes produced from fruit stalks had lower ash content, and the mixed treatment showed an intermediate value. The high ash content in frond-based briquettes may be attributed to higher levels of structural inorganic minerals, such as silica, calcium, and potassium, which are non-volatile and remain as residue after carbonization or combustion (Saidur et al., 2020; Vassilev et al., 2013). In contrast, the lower ash content in fruit stalk briquettes reflects their relatively lower mineral content and higher combustible fraction. The mixed treatment remained significantly different from both individual treatments, indicating that biomass blending produced a measurable mineral dilution effect and effectively reduced the ash fraction without additional chemical processing (S. Hidayat et al., 2019; Prasetyo et al., 2021).

Calorific Value

Calorific value is a key indicator of charcoal briquette quality because it represents the amount of heat energy released during combustion. A higher calorific value indicates better fuel efficiency and greater competitiveness of briquettes as an alternative solid fuel. This parameter is mainly influenced by fixed carbon content, while it is negatively affected by moisture and ash content. Volatile matter also contributes to initial combustion characteristics because it supports ignition and early flame development. Therefore, calorific value should not be interpreted as a stand-alone parameter, but rather as the result of interactions among fixed carbon, volatile matter, moisture content, ash content, and the quality of the carbonization process (F. T. Wulandari & Lestari, 2025).

Table 8. Average Calorific Value of Charcoal Briquettes (cal/g)

Treatment	Test 1	Test 2	Test 3	Average
P	5,883	6,062	6,011	5,985
R	5,416	5,442	5,403	5,420
C	5,339	5,617	5,470	5,475
Average				5,627
SNI 01-6235-2000				≥5,000

Note: P = sugar palm fronds; R = sugar palm fruit stalks; C = mixture of sugar palm fronds and fruit stalks.

As shown in Table 8, the calorific value of charcoal briquettes ranged from 5,420 to 5,985 cal/g, with the order P > C > R. All treatments exceeded the minimum requirement of SNI 01-6235-2000, which is ≥5,000 cal/g. This result indicates that charcoal briquettes produced from sugar palm biomass residues are technically feasible as alternative solid fuels based on their energy content. The highest calorific value was observed in briquettes produced from sugar palm fronds (P), while the lowest value was found in briquettes produced from fruit stalks (R). The mixed treatment (C) showed an intermediate calorific value. Compared with other biomass briquettes, which commonly have calorific values within the range of approximately 4,800–5,700 cal/g, the values obtained in this study can be considered competitive and reflect good thermal quality (Duangkham et al., 2023; Prayoga et al., 2023).

The relatively high calorific values obtained in this study were primarily supported by the fixed carbon fraction formed during carbonization. Fixed carbon represents the energy-rich solid residue that contributes to sustained combustion, whereas moisture and ash reduce effective combustion energy because they do not contribute directly to heat release. Moisture consumes part of the heat for evaporation, while ash represents the non-combustible mineral fraction remaining after combustion (Antal & Grønli, 2003; Demirbas, 2017; Prasetyo et al., 2021). In this study, the very low moisture content of all treatments helped support high effective calorific values. However, differences in ash content and fixed carbon among treatments contributed to variation in calorific value, particularly the superior value observed in frond-based briquettes.

The balance among fixed carbon, volatile matter, and ash content is an important determinant of final calorific value. Volatile matter can support initial ignition and rapid energy release during early combustion, but excessive volatile matter may reduce clean combustion efficiency because part of the energy can be lost through gases and smoke. In contrast, higher fixed carbon content contributes to more stable and sustained heat release during the char combustion phase. Therefore, optimal carbonization conditions are required to increase fixed carbon while reducing moisture and undesirable volatile components, thereby improving calorific value and overall thermal efficiency (Basu, 2018; L. Zhang et al., 2020; Chen et al., 2021; Shen et al., 2022).

Overall, the calorific values of 5,420–5,985 cal/g confirm that charcoal briquettes derived from sugar palm biomass residues have strong potential for household and small- to medium-scale energy applications. Even though the densification process has not yet been fully optimized, the briquettes still demonstrated good thermal performance and exceeded the SNI calorific value requirement. This finding indicates that sugar palm fronds, fruit stalks, and their mixture can be further developed as sustainable biomass fuels, provided that carbonization and briquetting conditions are optimized to improve other quality parameters, particularly ash content, volatile matter, fixed carbon, and density (Rindayatno et al., 2022; F. T. Wulandari & Lestari, 2023).

Table 9. ANOVA Results for Calorific Value of Charcoal Briquettes

Source of Variation	Sum of Squares	df	Mean Square	F-value	Sig.
Treatment	582,350.000	2	291,175.000	30.931	0.001
Error	56,482.000	6	9,413.667		
Corrected Total	638,832.000	8			

The ANOVA results presented in Table 9 indicate that the type of sugar palm biomass residue had a statistically significant effect on the calorific value of charcoal briquettes, as shown by an F-value of 30.931 and a significance value of 0.001 ($p < 0.05$). These results confirm that differences in raw material type, namely sugar palm fronds, fruit stalks, and their mixture, significantly influenced the amount of heat energy generated by the briquettes. Therefore, the anatomical and chemical characteristics of each sugar palm plant part played an important role in determining the thermal quality of the resulting charcoal briquettes. Since the treatment effect was significant, further analysis using Duncan’s Multiple Range Test (DMRT) was conducted to identify specific differences among treatments.

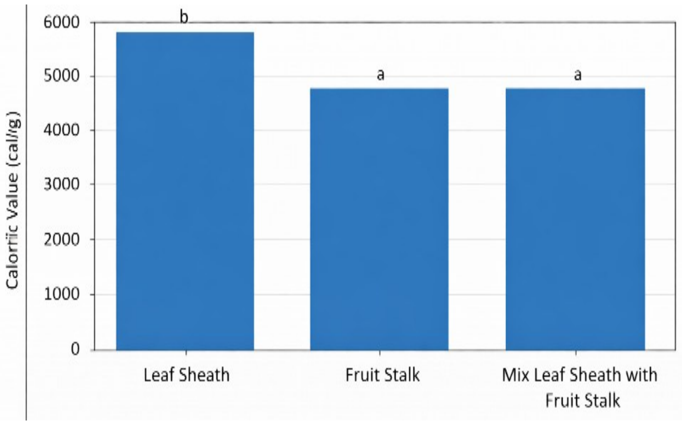

Figure 6. DMRT Results for Calorific Value of Charcoal Briquettes

Based on Figure 6, briquettes produced from sugar palm fronds exhibited the highest calorific value and were significantly different from briquettes produced from fruit stalks and the mixed material. The DMRT grouping showed that frond-based briquettes belonged to group b, while fruit stalk and mixed briquettes belonged to group a. This result confirms that raw material type significantly influenced the energy quality of the briquettes. The superior performance of frond-based briquettes may be associated with their higher fixed carbon content and greater lignification, which contribute to the formation of a more stable and energy-dense aromatic carbon structure during carbonization. In contrast, fruit stalk-based briquettes, which may contain relatively higher cellulose and hemicellulose fractions, tend to undergo more intensive devolatilization, resulting in lower fixed carbon content and reduced calorific value. These findings are consistent with previous studies reporting a positive relationship between lignin or fixed carbon content and the calorific value of biomass-derived charcoal (Mencareli et al., 2022).

Volatile Matter

Volatile matter content is an important parameter in determining the quality of charcoal briquettes because it influences ignition ease, combustion stability, and the potential formation of smoke and gaseous emissions. Volatile matter is released during biomass heating under oxygen-limited conditions as a result of the thermal degradation of hemicellulose, cellulose, and part of the lignin fraction. Therefore, its content is strongly influenced by the type and chemical composition of the raw material used for briquette production (Antal & Grønli, 2003; Basu, 2018). In general, higher volatile matter content promotes faster ignition because more combustible gases are released during the early stage of combustion. However, excessive volatile matter may reduce combustion stability and increase smoke emissions, whereas lower volatile matter content tends to produce more stable and sustained combustion (Chen et al., 2021; L. Zhang et al., 2020).

Table 10. Average Volatile Matter Content of Charcoal Briquettes (%)

Treatment	Test 1	Test 2	Test 3	Average (%)
P	23.5	25.6	23.8	24.3
R	37.3	37.3	35.9	36.8
C	33.9	33.2	33.3	33.5
Average				31.5
SNI 01-6235-2000				<15

Note: P = sugar palm fronds; R = sugar palm fruit stalks; C = mixture of sugar palm fronds and fruit stalks.

As shown in Table 10, the volatile matter content of charcoal briquettes varied among treatments, ranging from 24.3% to 36.8%, with an overall average of 31.5%. The lowest volatile matter content was found in briquettes produced from sugar palm fronds (P), at 24.3%, followed by the mixture of fronds and fruit stalks (C), at 33.5%. The highest volatile matter content was observed in briquettes produced from sugar palm fruit stalks (R), at 36.8%.

According to SNI 01-6235-2000, the maximum allowable volatile matter content for charcoal briquettes is <15%. Therefore, none of the treatments in this study met the SNI requirement for volatile matter content. This result indicates that the carbonization process still needs to be optimized, particularly to reduce the remaining volatile fraction in the briquettes.

The relatively high volatile matter content can be explained by the characteristics of non-wood biomass, which generally contains higher proportions of thermally reactive cellulose and hemicellulose than woody biomass. These components decompose more easily during carbonization and release volatile compounds in the form of gases, vapors, and tar fractions (Antal & Grønli, 2003; Basu, 2018). In addition, carbonization at moderate temperatures may not fully convert organic fractions into stable fixed carbon, thereby leaving a relatively high volatile fraction in the final briquette product (Chen et al., 2021; L. Zhang et al., 2020). Although the values obtained in this study did not comply with SNI standards, they remain comparable to those reported for several non-wood biomass briquettes. Such briquettes may still be applicable for household use because their higher volatile matter can support easier ignition. However, further optimization of carbonization temperature and residence time is required to reduce volatile matter content and improve compliance with national quality standards (Kaur et al., 2023; Sukarta et al., 2022).

The lower volatile matter content in frond-based briquettes (P) may be associated with higher lignification and a greater contribution of thermally stable lignin. Lignin decomposes over a wider temperature range and tends to promote the formation of stable carbon structures during carbonization, thereby reducing the release of volatile compounds. This condition supports more stable combustion and lower smoke emission potential compared with materials containing higher cellulose and hemicellulose fractions (Antal & Grønli, 2003; Azizah et al., 2021; Chen et al., 2021; Stelte et al., 2012). In contrast, sugar palm fruit stalks (R) produced the highest volatile matter content, likely because they contain a higher proportion of cellulose and hemicellulose, which degrade at lower temperatures and release larger amounts of volatile compounds. Consequently, briquettes produced from fruit stalks may ignite more easily but tend to have less stable combustion and higher emission potential (Basu, 2018; Yang et al., 2007).

The mixed treatment (C) showed an intermediate volatile matter content, indicating that blending fronds with fruit stalks can partially reduce the high volatile fraction associated with fruit stalks. However, the volatile matter content of the mixed briquettes remained much higher than the SNI threshold, suggesting that biomass blending alone is insufficient to meet the standard unless it is supported by improved carbonization conditions. Therefore, controlling volatile matter in sugar palm charcoal briquettes should involve both adjustment of the raw material composition and optimization of carbonization temperature, heating duration, and residence time. This approach is necessary to increase fixed carbon formation, reduce residual volatile compounds, and improve the combustion stability of non-wood biomass briquettes (Kaur et al., 2023; Martono et al., 2023).

Table 11. ANOVA Results for Volatile Matter Content of Charcoal Briquettes

Source of Variation	Sum of Squares	df	Mean Square	F-value	Sig.
Treatment	252.447	2	126.223	181.471	0.000
Error	4.173	6	0.696		
Corrected Total	256.620	8			

The ANOVA results presented in Table 11 show that the type of sugar palm biomass residue had a highly significant effect on the volatile matter content of charcoal briquettes, as indicated by a significance value of 0.000 ($p < 0.05$). This result confirms that differences among sugar palm fronds, fruit stalks, and their mixture significantly influenced the amount of volatile compounds remaining in the briquettes after carbonization. The high F-value also indicates that raw material characteristics played a strong role in determining volatile matter content. Since the treatment effect was significant, further analysis using Duncan's Multiple

Range Test (DMRT) was conducted at a 95% confidence level to identify specific differences among treatments.

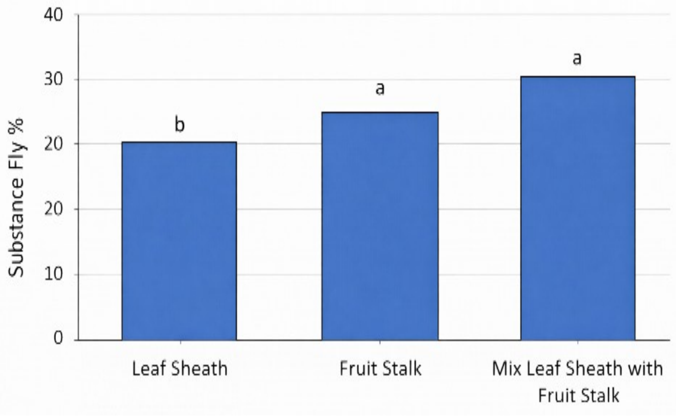

Figure 7. DMRT Results for Volatile Matter Content of Charcoal Briquettes

The DMRT results presented in Figure 7 indicate that the volatile matter content differed among the treatments. Briquettes produced from sugar palm fronds had the lowest volatile matter content, reflecting a higher degree of lignification and the formation of more stable aromatic carbon residues during carbonization. In contrast, briquettes produced from fruit stalks had the highest volatile matter content, indicating a greater contribution of cellulose and hemicellulose fractions, which decompose more readily and release more volatile compounds. The mixed treatment showed intermediate behavior, consistent with the combined contribution of fronds and fruit stalks. Mechanistically, these results support the view that biomass composition strongly influences volatile release, char formation, and combustion behavior during carbonization and subsequent burning (Antal & Grønli, 2003; Chen et al., 2021; Collard & Blin, 2014; Lu & Gu, 2022; Yang et al., 2007).

Fixed Carbon

Fixed carbon is the solid carbon fraction remaining after moisture, volatile matter, and ash have been removed during proximate analysis. This parameter is one of the most important indicators of charcoal briquette quality because it reflects the proportion of stable carbon that contributes to sustained combustion. Unlike volatile matter, which is released rapidly during the early stage of burning, fixed carbon dominates the slower char combustion phase and supports longer flame duration, better heat retention, and improved thermal efficiency. Therefore, briquettes with higher fixed carbon content are generally considered more suitable for applications requiring stable and sustained heat release. In biomass-derived charcoal briquettes, fixed carbon content is strongly affected by raw material composition, carbonization temperature, residence time, and the extent of devolatilization during the carbonization process (Basu, 2018; Chen et al., 2021; L. Zhang et al., 2020).

Table 12. Average Fixed Carbon Content of Charcoal Briquettes (%)

Treatment	Test 1	Test 2	Test 3	Average (%)
P	65	63	64	64.00
R	55	55	56	55.33
C	60	60	61	60.33
Average				59.89
SNI 01-6235-2000				>65

Note: P = sugar palm fronds; R = sugar palm fruit stalks; C = mixture of sugar palm fronds and fruit stalks.

As shown in Table 12, the fixed carbon content of charcoal briquettes ranged from 55.33% to 64.00%, with the order P > C > R. Briquettes produced from sugar palm fronds (P) showed the highest fixed carbon content, at 64.00%, followed by briquettes produced from the mixture of fronds and fruit stalks (C), at 60.33%. The lowest fixed carbon content was found in briquettes produced from sugar palm fruit stalks (R), at 55.33%. According to SNI 01-6235-

2000, the minimum fixed carbon content required for charcoal briquettes is >65%. Therefore, none of the treatments fully met the SNI requirement, although the frond-based briquettes approached the standard most closely. This result indicates that sugar palm fronds have better potential for producing charcoal briquettes with more stable combustion characteristics than fruit stalks and mixed materials.

The higher fixed carbon content in frond-based briquettes may be associated with greater lignification and more effective char formation during carbonization. Lignin is thermally more stable than cellulose and hemicellulose, and it tends to form denser carbonaceous residues when exposed to heat under limited oxygen conditions. In contrast, cellulose and hemicellulose decompose more readily into volatile compounds, gases, and tar, which can reduce the remaining fixed carbon fraction in the final charcoal product (Basu, 2018; Yang et al., 2007). This explains why fruit stalk-based briquettes, which may contain a relatively higher proportion of thermally reactive cellulose and hemicellulose, showed the lowest fixed carbon content. The mixed treatment exhibited an intermediate value because it reflected the combined contribution of the two biomass components.

The differences in fixed carbon content among treatments are consistent with previous studies showing that anatomical structure and chemical composition strongly influence carbonization outcomes and proximate characteristics of biomass briquettes. Biomass materials with higher lignin content and more stable carbon-forming fractions generally produce charcoal with higher fixed carbon, whereas materials with higher volatile-forming components tend to produce lower fixed carbon after carbonization (A. Putra et al., 2022; A. Rahman & Widodo, 2023). In this study, the relatively high volatile matter content, particularly in fruit stalk and mixed briquettes, indicates that carbonization was not yet sufficient to convert a larger proportion of organic material into stable fixed carbon. The intermediate fixed carbon content in the mixed treatment also suggests that biomass blending can moderate raw material characteristics, although it may not be sufficient to meet the SNI requirement without further process optimization (A. Putra et al., 2022; Wulandari F. T. et al., 2024).

In general, these findings are in line with the literature, which reports that fixed carbon content increases in biomass with higher lignin content and lower ash or volatile fractions, particularly under optimized carbonization conditions. Conversely, non-wood biomass with relatively high mineral content or incomplete devolatilization may show lower fixed carbon content, thereby reducing its ability to sustain long and stable combustion (Demirbas, 2017; Kaur et al., 2023). Therefore, sugar palm fronds appear to be the most promising raw material for producing charcoal briquettes with better combustion stability and thermal performance. Meanwhile, briquettes derived from fruit stalks require further optimization of carbonization temperature and residence time to enhance devolatilization, reduce volatile matter, and increase fixed carbon content toward the national quality standard (Basu, 2018; L. Zhang et al., 2020).

Table 13. ANOVA Results for Fixed Carbon Content of Charcoal Briquettes

Source of Variation	Sum of Squares	df	Mean Square	F-value	Sig.
Treatment	113.556	2	56.778	102.200	0.000
Error	3.333	6	0.556		
Corrected Total	116.889	8			

The ANOVA results presented in Table 13 show that the type of sugar palm biomass residue had a highly significant effect on the fixed carbon content of charcoal briquettes, as indicated by a significance value of 0.000 ($p < 0.05$). This result confirms that differences among sugar palm fronds, fruit stalks, and their mixture significantly influenced the formation of fixed carbon during carbonization. The high F-value indicates that raw material type played a strong role in determining the fixed carbon fraction of the resulting briquettes. Since fixed carbon is closely related to combustion stability and heat retention, this statistical finding supports the interpretation that the selection of sugar palm plant parts is important for improving the energy performance of charcoal briquettes. Therefore, further analysis using

Duncan’s Multiple Range Test (DMRT) was conducted to identify specific differences among treatments.

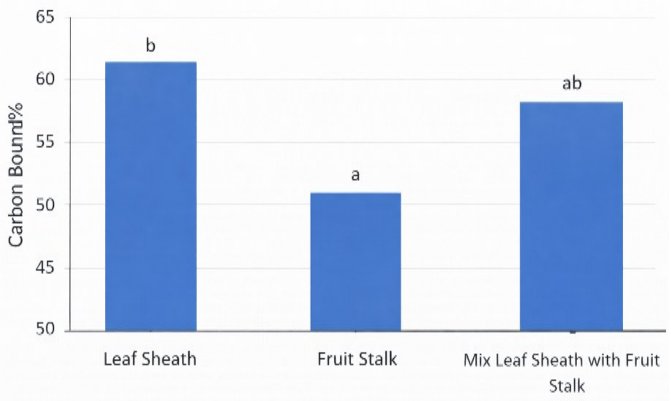

Figure 8. DMRT Results for Fixed Carbon Content of Charcoal Briquettes

The DMRT results presented in Figure 8 indicate that frond-based briquettes had the highest fixed carbon content, while fruit stalk-based briquettes had the lowest value. The mixed treatment showed an intermediate fixed carbon content, reflecting the combined characteristics of fronds and fruit stalks. These differences are consistent with the role of lignocellulosic composition during carbonization. More lignified biomass, such as sugar palm fronds, tends to form denser and more stable aromatic carbon structures, resulting in higher fixed carbon content (Antal & Grønli, 2003; Basu, 2018). In contrast, fruit stalks, which are relatively richer in cellulose and hemicellulose, release more volatile compounds during carbonization and consequently produce lower fixed carbon content (Basu, 2018; Yang et al., 2007). Higher fixed carbon content is also associated with more stable and longer-lasting combustion, which supports the superior thermal performance of frond-based briquettes (Chen et al., 2021; L. Zhang et al., 2020).

Burning Rate

Burning rate describes the rate at which briquette mass is consumed during combustion and is closely related to energy efficiency, flame stability, and combustion duration. This parameter is influenced by several factors, including density, porosity, fixed carbon content, moisture content, ash content, and the carbon structure formed during carbonization (Garcia et al., 2020; Kaliyan & Vance Morey, 2009). Mechanistically, higher porosity or lower density can enhance oxygen (O_2) diffusion within the briquette matrix, thereby increasing the burning rate. In contrast, higher fixed carbon content and more stable aromatic carbon structures tend to slow down mass consumption during combustion and support longer flame duration (Kaur et al., 2023; Shen et al., 2022). Therefore, a lower burning rate generally indicates more stable and sustained combustion, which is desirable for household and small- to medium-scale energy applications (Y. Zhang et al., 2022).

Table 14. Average Burning Rate of Charcoal Briquettes (g/min)

Treatment	Test 1	Test 2	Test 3	Average (g/min)
P	0.05	0.04	0.04	0.04
R	0.06	0.05	0.05	0.05
C	0.05	0.05	0.05	0.05
Average				0.05

Note: P = sugar palm fronds; R = sugar palm fruit stalks; C = mixture of sugar palm fronds and fruit stalks.

As shown in Table 14, the burning rate of charcoal briquettes ranged from 0.04 to 0.05 g/min. Briquettes produced from sugar palm fronds (P) had the lowest burning rate, at 0.04 g/min, while briquettes produced from fruit stalks (R) and the mixture of fronds and fruit stalks (C) showed slightly higher values, at approximately 0.05 g/min. Although the differences among treatments were relatively small, this pattern suggests that raw material characteristics may still contribute to differences in mass consumption during combustion. Compared with several previous studies reporting burning rates in the range of 0.06–0.12 g/min, the values obtained in this study are relatively low, indicating longer burning duration and potentially better thermal efficiency (Martono et al., 2023; Nurhayati et al., 2022; Prayoga et al., 2023; Rindayatno et al., 2022).

The relatively low burning rate observed in frond-based briquettes can be associated with their higher fixed carbon content. Fixed carbon represents the solid carbon residue that burns gradually during the char combustion phase and plays an important role in maintaining flame stability. Briquettes with higher fixed carbon content generally exhibit slower and more stable burning because the combustion process is dominated by aromatic carbon structures that are more resistant to rapid oxidation. In contrast, lower fixed carbon content is often associated with higher volatile matter and greater porosity, which may accelerate combustion through increased oxygen diffusion and more intensive oxidation (Antal & Grønli, 2003; Basu, 2018; Chen et al., 2021; Li et al., 2022). This explains why briquettes made from sugar palm fronds, which showed relatively higher fixed carbon content, had the lowest burning rate and better flame stability than those made from fruit stalks and mixed materials (Demirbas, 2017; Kaur et al., 2023; L. Zhang et al., 2020).

Overall, the burning rate performance of sugar palm charcoal briquettes in this study can be considered competitive for applications requiring stable and sustained combustion. SNI 01-6235-2000 does not specify a numerical standard for burning rate; therefore, this parameter is generally evaluated comparatively and interpreted in relation to fixed carbon content, flame stability, and thermal efficiency based on existing literature (Sutrisno et al., 2021). The low burning rate of 0.04–0.05 g/min indicates that sugar palm biomass briquettes have potential as solid fuels with relatively long combustion duration. However, further optimization of carbonization conditions, particularly temperature and residence time, remains important to increase fixed carbon content, reduce excessive volatile matter, and improve the combustion performance of non-wood biomass charcoal briquettes.

Table 15. ANOVA Results for Burning Rate of Charcoal Briquettes

Source of Variation	Sum of Squares	df	Mean Square	F-value	Sig.
Treatment	0.000	2	0.000	3.500	0.098
Error	0.000	6	0.000		
Corrected Total	0.000	8			

The ANOVA results presented in Table 15 indicate that the type of sugar palm biomass residue did not have a statistically significant effect on the burning rate of charcoal briquettes, as shown by a significance value of 0.098 ($p > 0.05$). Therefore, further analysis using Duncan's Multiple Range Test (DMRT) was not required for this parameter. The burning rate values were relatively uniform across treatments, ranging narrowly from 0.04 to 0.05 g/min, indicating that the observed differences were not large enough to be statistically significant. From a mechanistic perspective, this uniformity is reasonable because the briquettes had similarly low moisture content, relatively comparable density, and sufficient calorific value, resulting in comparable oxygen diffusion through pore structures and similar carbon oxidation rates during combustion (Garcia et al., 2020; Kaliyan & Vance Morey, 2009).

Functionally, the low and stable burning rate observed in all treatments indicates more efficient combustion and longer flame duration, making these briquettes suitable for household and small- to medium-scale applications (Y. Zhang et al., 2022). The overall thermal performance of sugar palm charcoal briquettes was supported by their high calorific values, ranging from 5,420 to 5,985 cal/g, and their relatively stable burning rates of 0.04–0.05 g/min. Nevertheless, the combustion performance was still influenced by proximate characteristics, particularly fixed carbon, volatile matter, and ash content. Fixed carbon contributed positively to flame stability, whereas excessive ash and volatile matter could reduce combustion efficiency. Therefore, optimization of carbonization conditions remains necessary to balance proximate parameters and further enhance the energy performance of charcoal briquettes derived from sugar palm biomass residues.

Charcoal Yield

Charcoal yield is an important parameter in evaluating the efficiency of the carbonization process because it shows the proportion of charcoal produced from the initial biomass weight. In biomass carbonization, yield is strongly influenced by raw material characteristics, especially moisture content, lignocellulosic composition, mineral content, and the thermal stability of the biomass components. Materials with higher lignin content generally produce higher char yield because lignin has a more aromatic and thermally stable structure than cellulose and hemicellulose. In contrast, cellulose and hemicellulose are more easily degraded into volatile compounds, gases, and tar during carbonization, which can reduce the amount of solid charcoal residue formed. Therefore, charcoal yield can be used as an indicator of both raw material suitability and the effectiveness of the carbonization process.

Table 16. Charcoal Yield of Sugar Palm (*Arenga pinnata*) Biomass Residues

Material	**Initial Biomass Weight (kg)**	**Charcoal Weight (kg)**	**Yield (%)**
Sugar palm fronds	10.0	2.12	21.2
Sugar palm fruit stalks	8.0	2.00	25.0
Mixture of fronds and fruit stalks	7.5	1.50	20.0

As shown in Table 16, sugar palm fronds with an initial biomass weight of 10.0 kg produced 2.12 kg of charcoal, corresponding to a yield of 21.2%. Sugar palm fruit stalks produced the highest yield, with 8.0 kg of initial biomass generating 2.00 kg of charcoal, equivalent to 25.0%. Meanwhile, the mixture of fronds and fruit stalks produced the lowest yield, with 7.5 kg of initial biomass producing 1.50 kg of charcoal, equivalent to 20.0%. These results indicate that charcoal yield varied among raw material types, reflecting differences in the physical and chemical characteristics of sugar palm biomass during the carbonization process.

The higher yield observed in fruit stalks may be associated with their lower moisture content and more compact biomass structure, which can support more efficient char formation during carbonization. In general, biomass with lower initial moisture content requires less energy for water evaporation and may retain a greater proportion of solid residue after pyrolysis. In addition, lignin plays an important role in char formation because its aromatic and thermally stable structure contributes to the formation of greater carbon-rich residues. Conversely, cellulose and hemicellulose are more readily decomposed into gases and tar, which reduces the final charcoal yield (T. Hidayat & Lestari, 2022; Ristori et al., 2020). This interpretation is supported by previous studies reporting that palm-based and other agricultural biomass materials contain lignocellulosic components that strongly influence briquette and charcoal characteristics (Imraan et al., 2024; Zalfiany et al., 2024).

The charcoal yield range obtained in this study, namely 20.0–25.0%, can be considered competitive compared with other lignocellulosic biomass materials, which are commonly reported to produce charcoal yields of approximately 18–30%, depending on biomass type, initial moisture content, carbonization temperature, and residence time (Maryono et al., 2021; Mulyana et al., 2023). Although charcoal yield is not specifically regulated in SNI 01-6235-2000, it remains technically important because it reflects the efficiency of raw material conversion into charcoal. A higher yield is generally favorable from a production perspective because it indicates better mass retention after carbonization. However, yield should not be interpreted separately from quality parameters such as fixed carbon, volatile matter, ash content, and calorific value, because high yield does not always guarantee superior fuel quality.

From a carbonization perspective, charcoal yield is closely related to the thermal degradation behavior of lignocellulosic components. Higher lignin content and more stable carbon-forming fractions tend to increase char yield, whereas more intensive degradation of cellulose and hemicellulose not only reduces yield but may also increase the volatile matter fraction in the final product (Antal & Grønli, 2003; Basu, 2018; Yang et al., 2007). Therefore, the yield values obtained in this study suggest that sugar palm biomass residues have acceptable carbonization efficiency, but the process still requires optimization to improve both yield and proximate quality. This is particularly important because several quality parameters, such as volatile matter and fixed carbon, had not fully met the SNI standard in the previous sections.

Charcoal yield can still be improved through process optimization, particularly by controlling carbonization temperature and residence time. Maintaining the carbonization temperature within an optimal range of approximately 350–450°C is important because excessively high temperatures can accelerate devolatilization and reduce the amount of solid char remaining after pyrolysis (M. Rahman et al., 2020). At the same time, insufficient carbonization may leave excessive volatile matter in the briquettes and reduce fixed carbon formation. Therefore, future optimization should aim to achieve a balance between maintaining adequate charcoal yield and improving proximate quality, especially by increasing fixed carbon and reducing volatile matter.

In practical terms, these findings highlight the potential of sugar palm biomass residues as efficient raw materials for charcoal and biobriquette production. The yield values indicate that sugar palm fronds, fruit stalks, and their mixture can be converted into charcoal at a technically acceptable level, while their calorific values also support their use as alternative solid fuels. Among the tested materials, fruit stalks produced the highest charcoal yield, whereas fronds showed better performance in terms of fixed carbon and calorific value. This means that material selection should consider both production efficiency and final briquette quality. The use of sugar palm residues also supports the broader utilization of local biomass resources and community-based energy transition initiatives, in line with renewable energy development and agricultural waste valorization efforts (Ministry of Energy and Mineral Resources of the Republic of Indonesia, 2022; Prabowo et al., 2023).

CONCLUSION

This study confirms that vegetative residues of sugar palm (*Arenga pinnata*) have strong potential to be developed as raw materials for charcoal biobriquettes derived from non-wood biomass. All treatments produced high calorific values, ranging from 5,420 to 5,985 cal g^{-1}, and very low moisture content, ranging from 1.69% to 2.03%. These values complied with the requirements of SNI 01-6235-2000, indicating that sugar palm biomass residues can support efficient and stable combustion performance. The differences among plant parts significantly affected the main proximate parameters, particularly ash content, volatile matter, and fixed carbon content, which directly determine flame characteristics, combustion stability, and the thermal performance of the briquettes.

Among the tested materials, briquettes produced from sugar palm fronds showed the best thermal performance, as indicated by the highest fixed carbon content, the highest calorific value, and the lowest burning rate. These characteristics reflect more stable and controlled combustion. Meanwhile, briquettes produced from the mixture of fronds and fruit stalks showed the most balanced quality profile, particularly because this treatment produced the lowest ash content and met the SNI requirement for ash content. Although several proximate parameters, especially volatile matter and fixed carbon, did not fully meet the SNI standards for charcoal briquettes, these limitations are largely process-dependent and can be improved through optimization of carbonization temperature, residence time, particle size, binder composition, and densification pressure.

Therefore, charcoal biobriquettes derived from sugar palm biomass residues are promising for further development as alternative solid fuels within a circular economy and sustainable energy transition framework. The utilization of these locally available residues can increase the value of non-wood biomass waste while supporting community-based renewable energy development. Future studies should focus on optimizing carbonization and briquetting conditions to improve fixed carbon content, reduce volatile matter, increase density, and ensure more consistent compliance with national briquette quality standards.

RECOMMENDATION

Further research is recommended to optimize the production process of sugar palm (*Arenga pinnata*) charcoal biobriquettes, particularly by improving carbonization temperature, residence time, particle size, binder composition, and densification pressure. These process variables are important because several quality parameters, especially density, volatile matter, and fixed carbon content, have not fully met the SNI 01-6235-2000 requirements, although the briquettes already showed promising calorific value, low moisture content, and stable burning performance. Future studies should also examine different mixing ratios between sugar palm fronds and fruit stalks to obtain a more balanced quality profile with lower ash content, higher fixed carbon, and better combustion stability. In addition, mechanical properties, emission characteristics, storage durability, and user-scale performance should be further evaluated to strengthen the technical feasibility of these briquettes for household and small- to medium-scale energy applications. Pilot-scale production and economic analysis are also needed to support the practical development of sugar palm biomass residues as locally available renewable solid fuels within a circular bioenergy framework.

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AUTHOR CONTRIBUTIONS STATEMENT

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Febriana Tri Wulandari	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓		✓	
Aluh Nikmatullah		✓				✓		✓	✓	✓	✓	✓		
Sitti Latifah	✓		✓				✓	✓					✓	
Hayati		✓			✓	✓		✓			✓	✓		

CONFLICT OF INTEREST STATEMENT

The authors declare that there is no conflict of interest.

DATA AVAILABILITY

The data that support the findings of this study can be obtained from the corresponding author upon reasonable request.

REFERENCES

Aminah, D., Fatriani, & Ariyati, H. (2020). Sifat fisik dan kimia pelepah aren (*Arenga pinnata* Merr) untuk bahan baku alternatif pulp dan kertas. *Jurnal Sylva Sciencteae, 3*(3), 460–465.

Antal, M. J., & Grønli, M. (2003). The art, science, and technology of charcoal production. *Industrial & Engineering Chemistry Research, 42*(8), 1619–1640. https://doi.org/10.1021/ie0207919

Azizah, N. N., Maryanti, R., & Nandiyanto, A. B. D. (2021). Optimal design and techno-economic analysis for corncob particles briquettes: A literature review of the utilization of agricultural waste and analysis calculation. *Applied Science and Engineering Progress, 14*(4), 656–669.

Bajwa, D. S., Peterson, T., Sharma, N., Shojaeiarani, J., & Bajwa, S. G. (2018). A review of densified solid biomass for energy production. *Renewable and Sustainable Energy Reviews, 96*, 296–305. https://doi.org/10.1016/j.rser.2018.07.040

Basu, P. (2018). *Biomass gasification, pyrolysis and torrefaction* (1st ed., Vol. 3). Elsevier. https://doi.org/10.1016/C2016-0-04056-1

Chen, W. H., Peng, J., & Bi, X. T. (2021). A state-of-the-art review of biomass torrefaction, densification and applications. *Renewable and Sustainable Energy Reviews, 4*, 847–866.

Collard, F.-X., & Blin, J. (2014). A review on pyrolysis of biomass constituents: Mechanisms and composition of the products obtained from the conversion of cellulose, hemicelluloses and lignin. *Renewable and Sustainable Energy Reviews, 38*, 594–608. https://doi.org/10.1016/j.rser.2014.06.013

Demirbas, A. (2017). *Waste management, waste resource facilities and waste conversion processes*. Elsevier.

Duangkham, S., Phrompitak, S., & Rattanadecho, P. (2023). Fuel properties and combustion performance of agricultural biomass briquettes. *Energy Reports, 9*, 1245–1256.

Fachry, A. R., Indah, S. T., Yudha, D. A., & Najamuddin, J. (2020). *Teknik pembuatan briket campuran eceng gondok dan batubara sebagai bahan bakar alternatif bagi masyarakat pedesaan*. Universitas Sriwijaya.

Garcia, R., Gil, M. V., Rubiera, F., & Pis, J. J. (2020). Biomass briquetting and combustion behavior. *Fuel Processing Technology, 199*, 106252.

Hakim, L., Suryani, A., & Pranoto, P. (2024). Utilization waste plant sugar palm as biocharcoal raw material. *Journal Energy Renewable Indonesia, 13*(1), 45–55.

Hendra, D., & Darmawan, S. (2000). Sifat fisik dan kimia briket arang kayu. *Jurnal Penelitian Hasil Hutan, 18*(1), 21–28.

Hidayat, S., Askar, A., & Fauzi, A. (2019). Kualitas briket arang dari campuran limbah kayu sengon dan tempurung kelapa dengan variasi tekanan kempa. *Jurnal Penelitian Hasil Hutan, 37*(2), 125–136.

Hidayat, T., & Lestari, S. (2022). Characteristics thermal briquettes biomass mixture waste agriculture. *Journal Technology Industry Agriculture, 32*(1), 77–85.

Hidayat, T., Nugroho, A., & Wibowo, A. (2021). Effect of proximate composition on heating value of biomass briquettes. *Energy Procedia, 158*, 123–130.

IEA. (2024). *CO_2 emissions in 2023*. International Energy Agency.

IEA. (2025). *World energy outlook 2025*. International Energy Agency.

Imraan, I., Maryanti, R., & Nandiyanto, A. B. D. (2024). Production of briquettes from Indonesia agricultural biomass waste by using pyrolysis process and comparing the characteristics. *Communications in Science and Technology, 8*(1), 43–50.

IPCC. (2022). *Climate change 2022: Mitigation of climate change*. Cambridge University Press.

Jenkins, B. M., Baxter, L. L., & Miles, T. R. (2018). Combustion properties of biomass. *Fuel Processing Technology, 54*, 17–46.

Junary, E., Pane, J. P., & Herlina, N. (2015). Pengaruh suhu dan waktu karbonisasi terhadap nilai kalor dan karakteristik pada pembuatan bioarang berbahan baku pelepah aren (*Arenga pinnata*). *Jurnal Teknik Kimia USU, 4*(2), 46–53.

Kaliyan, N., & Morey, R. V. (2009). Factors affecting strength and durability of densified biomass products. *Biomass and Bioenergy, 33*(3), 337–359. https://doi.org/10.1016/j.biombioe.2008.08.005

Kaur, A., Roy, M., & Kundu, K. (2017). Densification of biomass by briquetting: A review. *International Journal of Recent Scientific Research, 8*(10), 20561–20568.

Kaur, G., Singh, A., & Sharma, R. (2023). Effect of density and porosity on combustion behavior of biomass briquettes. *Renewable Energy, 201*, 1231–1242.

Kpalo, S. Y., Zainuddin, M. F., & Rahman, A. (2020). Briquetting of agricultural residues for energy use. *Renewable and Sustainable Energy Reviews, 127*, 10987.

Li, X., Zhang, Y., Wang, Q., & Chen, H. (2022). Proximate characteristics and thermal degradation behavior of lignocellulosic biomass briquettes. *Fuel, 322*, 124176.

Lu, J., & Gu, X. (2022). Influence of volatile matter on char combustion. *Fuel, 324*, 124566.

Martono, B., Nurhayati, N., & Pratiwi, R. (2023). Performance of mixed biomass briquette. *Journal of Cleaner Production, 385*, 135673.

Maryono, M., Alwi, M. F., & Yani, A. (2021). Aromatherapy charcoal briquettes from coconut shell (*Cocos nucifera*) with the addition of local orange peel and agarwood powder. *RJOAS: Russian Journal of Agricultural and Socio-Economic Sciences, 10*(11), 195–202.

Mencareli, A., Ranzi, E., & Faravelli, T. (2022). Role of lignin in char formation and heating value. *Energy & Fuels, 36*(14), 7685–7695.

Ministry of Energy and Mineral Resources of the Republic of Indonesia. (2022). *Indonesia energy outlook 2022*.

Mulyana, D., Putra, A. R., & Kurniawan, A. (2023). Yield and quality of charcoal from lignocellulosic biomass. *Biomass Conversion and Biorefinery, 13*, 4121–4132.

Ngene, F., Obi, O. F., & Okoye, C. O. (2024). Integrated evaluation of charcoal briquette quality. *Fuel, 352*, 128812.

Nurhayati, N., Sutrisno, S., & Prayoga, D. (2022). Combustion performance of non-wood biomass briquettes. *Energy Source, 44*(4), 1021–1033.

Obi, O. F., Akubuo, C. O., & Okonwo, W. I. (2021). Proximate properties as indicators of briquette performance. *Renewable Energy, 185*, 1034–1043.

Prabowo, A., Maryanti, R., & Nandiyanto, A. B. D. (2023). Review: Production of briquette from agricultural waste. *ASEAN Journal of Science and Engineering, 3*(2), 163–174.

Prasetyo, D. J., Rahman, A., & Widodo, T. W. (2021). Effect of biomass blending on briquette quality. *Journal Forest Products Technology, 14*(3), 201–211.

Prayoga, D., Sutrisno, S., & Nurhayati, N. (2023). Combustion characteristics of low-density biomass briquettes. *Case Studies in Thermal Engineering, 41*, 102564.

Putra, A., Suryaningsih, S., & Prayoga, R. (2022). Characterization of lignocellulosic biomass briquettes and their combustion properties. *Heliyon, 8*(3), 91233.

Putra, A. R., Nugroho, Y. S., & Widodo, T. W. (2018). Characteristics of charcoal briquettes from agricultural residues. *IOP Conference Series: Earth and Environmental Science*, 012045.

Putra, A. R., Nugroho, Y. S., & Widodo, T. W. (2022). Optimization of biomass briquette densification. *Bioresource, 17*(1), 456–470.

Rahmadani, S., & Fitria, R. (2022). Pengaruh konsentrasi perekat terhadap karakteristik briket arang limbah kulit pinang (*Areca catechu* L.). *Jurnal Teknologi Pertanian, 11*(2), 85–94.

Rahman, A., & Widodo, T. W. (2023). Statistical analysis of biomass briquette properties. *Journal Statistics Applied, 7*(2), 99–108.

Rahman, M., Hasan, M., & Islam, M. (2020). Effect of biomass type on proximate and ultimate analysis of briquettes. *Energy Reports, 6*(1), 215–221.

Rindayatno, F. R., & Fahmi, A. N. (2022). Charcoal briquette quality analysis based on composition palm oil (*Elaeis guineensis* Jacq) midrib charcoal powder with sugar palm (*Arenga pinnata* Merr) midrib charcoal powder. *Jurnal Multidisiplin Madani (MUDIMA), 2*(6), 2879–2894.

Rindayatno, & Lewar, D. O. (2017). Kualitas briket arang berdasarkan komposisi campuran arang kayu ulin (*Eusideroxylon zwageri* Teijsm. & Binn.) dan kayu sengon (*Paraserianthes falcataria* (L.) Nielsen). *Jurnal Hutan Tropika, 1*(1), 39–48.

Rindayatno, M., Wulandari, D., & Kurniawan, A. (2022). Pressure optimization in charcoal briquetting. *Fuel Processing Technology, 231*, 107238.

Ristori, A., Spinelli, R., & Magagnotti, N. (2020). Char yield from lignocellulosic biomass. *Biomass and Bioenergy, 141*, 105704.

Saidur, R., Islam, M. R., Mohammed, H. A., & Hasanuzzaman, M. (2020). Potential of biomass as a renewable energy source for sustainable applications: A review on charcoal briquettes production. *Renewable and Sustainable Energy Reviews, 124*(1), 109–121.

Sanyang, M. L., Sapuan, M. S., Jawaid, M., Ishak, M. R., & Sahari, J. (2016). Recent developments in sugar palm (*Arenga pinnata*)-based biocomposites and their potential industrial applications: A review. *Renewable and Sustainable Energy Reviews, 54*, 533–549.

Saputro, D. D., Rusdiyanto, R., & Rohman, N. (2020). Karakteristik briket arang campuran limbah serbuk gergaji kayu jati dan tempurung kelapa. *Jurnal Kompetensi Teknik, 12*(1), 1–8.

Saravanan, A., Kumar, P. S., & Vo, D. V. N. (2025). Circular bioeconomy and biomass waste valorization. *Bioresource Technology, 388*, 129632.

Sari, D. P., & Nugroho, A. (2023). Quantitative experimental methods in applied research. *Quantitative Experimental Methods in Applied Research, 12*(2), 101–110.

Sari, M. K. (2020). *Kualitas briket arang berdasarkan komposisi campuran arang dari kayu meranti merah (Shorea sp.) dengan tempurung kelapa (Cocos nucifera L.)*. Universitas Lambung Mangkurat.

Setiawan, A., & Fitria, L. (2024). Experimental research design in energy studies. *Journal Methodology Research, 8*(1), 15–24.

Shen, D., Xiao, R., & Gu, S. (2022). Structure-reactivity relationship of biomass char. *Fuel, 307*, 121789.

Stelte, W., Sanadi, A. R., Shang, L., Holm, J. K., Ahrenfeldt, J., & Henriksen, U. B. (2012). Fuel pellets from biomass: The importance of lignin. *Biomass and Bioenergy, 35*(1), 337–346.

Suryani, S., Amelia, R., & Putri, M. E. (2021). Karakteristik mutu briket arang dari limbah kulit durian (*Durio zibethinus*) dengan variasi konsentrasi perekat tepung tapioka. *Jurnal Teknologi Pertanian, 10*(1), 45–53.

Sutrisno, S., Nurhayati, N., & Prayoga, D. (2021). Effect of compaction pressure on briquette density. *Journal Energy and Environment, 17*(2), 65–73.

Vassilev, S. V., Baxter, D., Andersen, L. K., & Vassileva, C. G. (2013). An overview of the chemical composition of biomass ash. *Fuel, 105*, 19–39.

Widodo, T. W., Prasetyo, D. J., & Nugroho, Y. S. (2021). Evaluation of Indonesian charcoal briquette standards. *Journal Standardization, 23*(1), 95–104.

Wulandari, F. T., & Lestari, S. (2023). Karakteristik mutu briket arang dari campuran limbah kayu kemiri dan tempurung kelapa. *Jurnal Penelitian Hasil Hutan, 14*(1), 45–56.

Wulandari, F. T., & Lestari, S. (2025). Karakteristik fisik dan kimia briket arang dari campuran limbah bambu dan tempurung kelapa dengan variasi komposisi perekat. *Jurnal Penelitian Hasil Hutan, 43*(1), 12–20.

Wulandari, F. T., Lestari, D., Fahrussiam, F., Ningsih, R. V., & Raehnayati. (2024). Karakteristik sifat fisika briket arang tempurung kelapa dan bongkol jagung. *Jurnal Hutan Lestari, 12*(1), 49–62.

Wulandari, S., Fernandez, R., Yuwita, F., & Sidik, G. (2025). Analisis briket arang kulit kopi robusta dengan variasi konsentrasi perekat tepung tapioka sebagai bahan bakar alternatif. *Agroteknika, 8*(2), 263–275.

Yang, H., Yang, R., Chen, H., Lee, D. H., & Zheng, C. (2007). Characteristics of hemicellulose, cellulose and lignin pyrolysis. *Fuel, 86*(13), 1781–1788.

Yuliah, Y., Sugiarti, E., & Sapei, A. (2021). Karakteristik briket arang dari limbah pengolahan kayu dan tempurung kelapa. *Jurnal Teknik Pertanian Lampung, 10*(2), 235–244.

Zalfiany, R., Sukarta, I. N., & Ayuni, N. P. (2024). Evaluation and characterization of charcoal briquettes using damar binder for sustainable energy. *Journal of Applied Engineering and Technological Science, 5*(2), 1120–1132.

Zhang, L., Xu, C., & Champagne, P. (2020). Overview of biomass combustion and char properties. *Renewable and Sustainable Energy Reviews, 124*, 109875.

Zhang, Y., Chen, Y., & Li, B. (2022). Effect of porosity on combustion performance of biomass briquettes. *Energy, 239*, 122122.