



MATERIAL ENGINEERING IN THE FABRICATION OF CHARCOAL BRIQUETTES FROM SAGO TREE WASTE: PHYSICAL CHARACTERISTICS AND COMBUSTION PERFORMANCE EVALUATION

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Abstract: *This study aims to analyze the influence of material engineering on the physical characteristics and combustion performance of briquettes made from sago tree waste. Three compositions were tested, namely 90%:10%, 80%:20%, and 70%:30%, with equal mass in each composition. The physical characteristic tests of the briquettes included moisture content, ash content, volatile matter, fixed carbon, and calorific value. Meanwhile, combustion performance testing included burn rate and temperature at various time intervals. The results showed that the material engineering at the 80%:20% composition resulted in faster combustion, while the 90%:10% composition provided more stable and longer-lasting combustion. The 70%:30% composition showed slower but stable combustion, suitable for applications requiring a longer burn time. Overall, material engineering in the production of briquettes from sago tree waste has proven to have great potential as an efficient and environmentally friendly alternative fuel, with physical characteristics and combustion performance that can be adjusted to meet various renewable energy needs*

Keywords: *Charcoal Briquettes, Physical Characteristics, Combustion Performance*

Abstrak: Penelitian ini bertujuan untuk menganalisis pengaruh rekayasa material terhadap karakteristik fisik dan kinerja pembakaran briket yang terbuat dari limbah pohon sagu. Tiga komposisi yang diuji yaitu 90%:10%, 80%:20%, dan 70%:30%, dengan massa yang sama pada setiap komposisi. Pengujian karakteristik fisik briket meliputi kadar air, kadar abu, zat terbang, karbon terikat, dan nilai kalor. Sementara itu, pengujian kinerja pembakaran meliputi laju pembakaran dan suhu pada berbagai interval waktu. Hasil penelitian menunjukkan bahwa rekayasa material pada komposisi 80%:20% menghasilkan pembakaran yang lebih cepat, sedangkan komposisi 90%:10% memberikan pembakaran yang lebih stabil dan bertahan lebih lama. Komposisi 70%:30% menunjukkan pembakaran yang lebih lambat namun stabil, sehingga sesuai untuk aplikasi yang membutuhkan waktu bakar lebih panjang. Secara keseluruhan, rekayasa material dalam pembuatan briket dari limbah pohon sagu terbukti memiliki potensi besar sebagai bahan bakar alternatif yang efisien dan ramah lingkungan, dengan karakteristik fisik dan kinerja pembakaran yang dapat disesuaikan untuk memenuhi berbagai kebutuhan energi terbarukan.

Kata Kunci: Briket Arang; Karakteristik Fisik; Kinerja Pembakaran.

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INTRODUCTION

The escalating global demand for energy has intensified the pursuit of alternative fuel sources that are both environmentally benign and economically accessible. Biomass, encompassing agricultural residues, plantation by-products, and forestry waste, has emerged as one of the most promising feedstocks for solid fuel production. When processed into charcoal briquettes, biomass yields a fuel with substantially higher energy density than its raw counterpart while simultaneously contributing to waste valorization and cost reduction (Sunardi, 2019; Haurissa et al., 2025).

Indonesia harbors considerable reserves of sago palm (*Metroxylon sagu* Rottb.), a species predominant in the eastern provinces of Papua and Sulawesi. Although sago has historically been cultivated for its starchy pith as a dietary staple, the processing operations generate substantial quantities of lignocellulosic residues—including fronds, petioles, and bark—that are largely discarded or underutilized (Syam, 2025). Recent investigations indicate that these residues, following carbonization, possess physicochemical attributes that are well-suited for briquette fabrication (Khoirunsyah et al., 2024).

The functional quality of charcoal briquettes is governed by a set of interrelated physical parameters. Moisture content must be minimized to prevent energy dissipation during vaporization and to ensure efficient ignition. Bulk density influences the mechanical durability and specific energy content per unit mass. Ash content determines the extent of non-combustible residues generated, which affects both combustion efficiency and environmental cleanliness. Fixed carbon content governs the duration and steadiness of combustion, while calorific value provides a direct quantitative measure of the thermal energy released per unit mass (Muhammad, 2022; Alfian et al., 2024).

Natural binders, particularly tapioca starch, are widely adopted in briquette manufacturing to enhance inter-particle cohesion and mechanical integrity. Beyond improving structural stability, tapioca starch aligns with sustainability objectives since it is bio-based, biodegradable, and readily available from agricultural production chains (Haurissa et al., 2025). Prior studies have demonstrated that appropriate binder incorporation can improve compressive strength and dimensional stability of briquettes during the combustion cycle (Rezki et al., 2025).

The carbonization process profoundly affects the fixed carbon fraction of the resulting biochar, which directly correlates with calorific potential. A higher fixed

carbon content translates to prolonged and more energetically dense combustion. Research further suggests that controlled pyrolysis of sago tree residues can elevate charcoal quality to levels competitive with briquettes derived from rice husks or coconut shells—both of which are established reference biomass fuels in the Indonesian context (Alfian et al., 2024; Ichsan et al., 2025).

Combustion performance testing—encompassing calorific value measurement, burn duration profiling, and emission characterization—is indispensable for assessing the practical suitability of briquettes as marketable alternative fuels. Studies by Yusuf and Sari (2022) and Budiarto (2023) have established that high calorific value coupled with combustion stability constitutes the principal quality benchmarks for commercially viable biomass briquettes. Despite the growing body of literature on biomass briquettes, systematic investigations specifically addressing the physical characterization and combustion performance of sago palm waste briquettes remain sparse in both the Indonesian and international scientific communities (Ichsan et al., 2025). This knowledge gap underscores the necessity for rigorous empirical studies capable of establishing evidence-based guidelines for sago-derived briquette production (Rezki et al., 2025).

The present study aims to comprehensively evaluate the physical characteristics and combustion performance of charcoal briquettes fabricated from sago tree waste. The investigation specifically examines key physical parameters—including moisture content, bulk density, ash content, and calorific value—and assesses combustion behavior in terms of thermal stability and emission profiles. The findings are expected to contribute meaningfully to the advancement of biomass-based renewable energy in Indonesia, particularly in sago-abundant regions.

METHODS

Materials and Equipment

The experimental apparatus comprised a briquette-forming press, a laboratory drying oven, a Type-K thermocouple assembly, a 0.1-gram precision analytical balance, and various instrumentation for physical and combustion characterization. The primary raw material consisted of sun-dried and mechanically shredded sago palm frond waste, which was subsequently subjected to controlled carbonization to yield the charcoal feedstock. Tapioca starch was employed as a natural binder to enhance inter-particle adhesion and mechanical strength of the fabricated briquettes.

Briquette Fabrication Procedure

The fabrication process was conducted in three sequential stages:

1. **Raw Material Preparation:** Dried sago frond waste was carbonized under controlled conditions to produce a homogeneous charcoal feedstock. The carbonization temperature and duration were maintained consistently across all batches to minimize variability in char quality.
2. **Mixing and Compaction:** The charcoal was ground to a uniform particle size and blended with tapioca starch binder at predetermined mass ratios. The admixture was subsequently compacted using a cylindrical press die with a diameter of 3 cm and a length of 5 cm, yielding briquettes of standardized geometry and mass.
3. **Drying:** Freshly formed briquettes were oven-dried at 70°C for 24 hours to reduce residual moisture content. This drying step ensured dimensional stability and optimal combustion readiness prior to testing.

Physical Characterization and Combustion Performance Testing

Correlation analysis was performed to elucidate the relationships among ash content, moisture content, volatile matter, fixed carbon, calorific value, and combustion performance. All analyses conducted using standardized proximate analysis protocols.

Experimental Design

A Completely Randomized Design (CRD) was adopted to govern experimental variability. Three binder-to-charcoal mass ratios were investigated: 90%:10%, 80%:20%, and 70%:30% (charcoal:binder, w/w). Each experimental treatment was replicated three times to ensure data reproducibility and statistical reliability. Comparative analysis across treatment groups was conducted to elucidate the effect of compositional variation on briquette quality and combustion behavior.

Data Analysis

All data from physical and combustion testing were subjected to descriptive statistical analysis to characterize the distributional profile of each measured parameter. Pearson correlation analysis was employed to quantify associations among ash content, moisture content, fixed carbon, calorific value, and combustion performance indices. Hypothesis testing was conducted to determine whether inter-compositional differences significantly influenced briquette quality, employing an alpha level of 0.05 as the threshold for statistical significance.

RESULT AND DISCUSSION

Physical Characterization of Briquettes

The proximate analysis results for charcoal briquettes produced from sago tree waste are summarized in Table 1. The data reveal consistent trends across the three compositional variants and highlight the suitability of sago-derived briquettes as alternative solid fuels.

Table 1. Proximate Analysis Results for Sago Tree Waste Charcoal Briquettes

No	Test Parameter	Unit	10% Binder	20% Binder	30% Binder
1	Moisture Content	%	3,47	3,58	3,09
2	Ash Content	%	13,82	16,48	14,30
3	Volatile Matter	%	4,42	5,19	5,55
4	Fixed Carbon	%	78,29	74,76	77,07
5	Calorific Value	Cal/g	4157,28	3181,646	3093,639

1. Moisture Content

Moisture content values ranged from 3.09% to 3.58% across all tested compositions. These low values are indicative of highly efficient drying and confirm that the briquettes are well-suited for direct combustion without incurring substantial energy losses attributable to moisture vaporization. Low moisture content also enhances ignition reliability and storage stability. These values are consistent with acceptable thresholds for biomass briquettes intended for domestic and small-scale industrial applications.

2. Ash Content

Ash content exhibited moderate variation, ranging from 13.82% (90%:10%) to 16.48% (80%:20%). While these values marginally exceed the ideal threshold of $\leq 10\%$ commonly cited in briquette quality standards, they remain within acceptable bounds for applications where combustion cleanliness is not a critical constraint. The elevated ash content in the 80%:20% composition may be attributed to residual inorganic compounds contributed by the increased binder fraction. Reducing inorganic impurities in the raw material during preprocessing could potentially lower ash content in future production runs.

3. Volatile Matter

Volatile matter content ranged from 4.42% to 5.55%, increasing proportionally with binder concentration. Higher volatile matter content facilitates rapid ignition by

releasing combustible gases at comparatively low temperatures, thereby reducing the activation energy required for combustion initiation. The 80%:20% and 70%:30% compositions demonstrated marginally elevated volatile matter fractions relative to the 90%:10% composition, which correlates with their observed tendency for faster initial flame propagation during combustion testing.

4. Fixed Carbon

Fixed carbon content was consistently high across all compositions, ranging from 74.76% to 78.29%. Fixed carbon constitutes the primary combustible fraction that sustains thermal output during steady-state combustion. The 90%:10% composition yielded the highest fixed carbon content (78.29%), followed by 70%:30% (77.07%) and 80%:20% (74.76%). These values are favorable for applications requiring extended and stable heat generation, such as industrial kilns, food processing facilities, and prolonged space heating.

5. Calorific Value

Calorific values ranged from 3,093.64 Cal/g (70%:30%) to 4,157.28 Cal/g (90%:10%), with the 80%:20% composition yielding an intermediate value of 3,181.65 Cal/g. The inverse relationship between binder concentration and calorific value reflects the dilutive effect of the non-carbonaceous tapioca starch on the overall energy density of the briquette matrix. Nonetheless, all compositions demonstrated calorific values that are energetically competitive with conventional biomass fuels, confirming the economic and technical viability of sago-derived briquettes as renewable energy carriers.

Performance Evaluation

Combustion performance was assessed by monitoring temperature profiles at two measurement points, namely T1 and T2, over a ten-minute interval for each compositional variant. This approach was designed to evaluate the thermal behavior and stability of the combustion process under different material compositions. Temperature data were recorded continuously at both points to capture variations in heat distribution and combustion intensity throughout the testing period. The use of two measurement points allowed for a more comprehensive understanding of how heat propagates within the sample and how consistent the combustion process remains over

time. Each compositional variant was tested under the same experimental conditions to ensure comparability and reliability of the results. The collected data were then analyzed to identify trends, peak temperatures, and fluctuations that indicate combustion efficiency. Through this method, the study provides insights into the influence of material composition on combustion characteristics, highlighting which variants demonstrate more stable and efficient thermal performance during the combustion process.

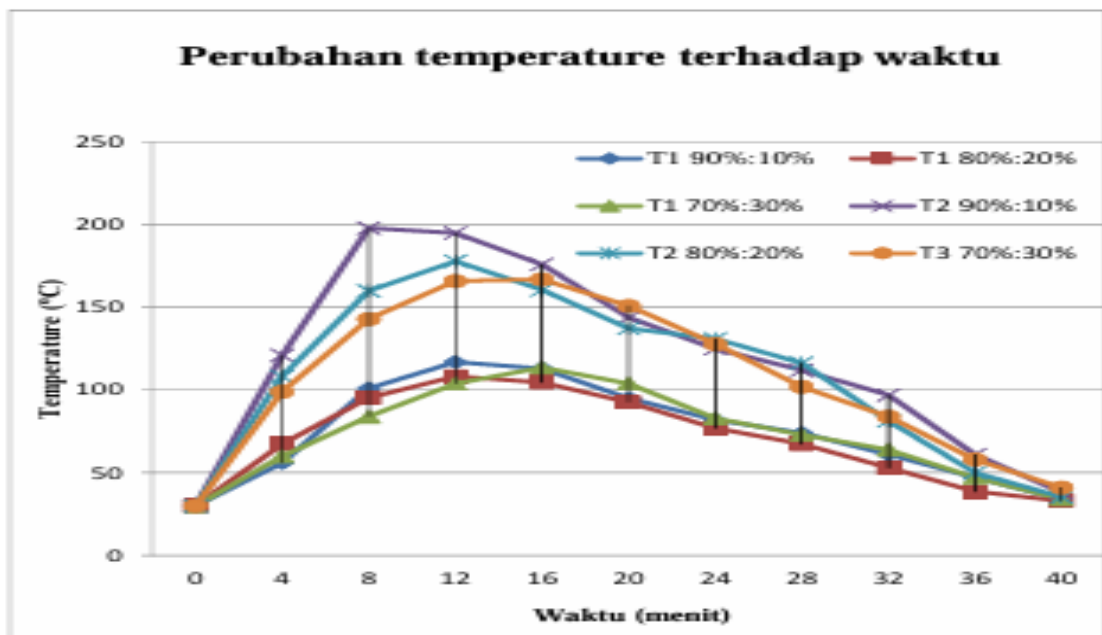


Figure 1. Temperature vs. Time Profile for Each Briquette Composition

1. Comparative Burn Rate and Temperature Analysis

For the 90%:10% composition, the recorded temperature at T1 and T2 during the first minute was 30°C and 36.5°C, respectively. By the tenth minute, T1 had risen to 123°C and T2 to 154°C, reflecting a gradual but sustained combustion trajectory. This composition exhibited the most thermally stable profile, which is advantageous for applications requiring prolonged and controllable heat output. The 80%:20% composition demonstrated notably accelerated combustion dynamics, with initial temperatures of 58°C (T1) and 62.5°C (T2) recorded within the first minute—substantially higher than the other compositions. By the tenth minute, T1 reached 145°C and T2 150°C, indicating superior heat generation efficiency over short timeframes. This composition is particularly suitable for applications necessitating rapid thermal response and high instantaneous heat flux. The 70%:30% composition

exhibited the most gradual combustion behavior. Initial temperatures were comparable to the 90%:10% composition (30°C at T1 and 36.5°C at T2), but by the tenth minute, T1 reached only 106°C and T2 116°C. Despite this slower thermal progression, the combustion remained stable throughout the observation period, making this composition well-adapted to scenarios requiring sustained, low-intensity heat over extended durations.

2. Mass Loss Analysis

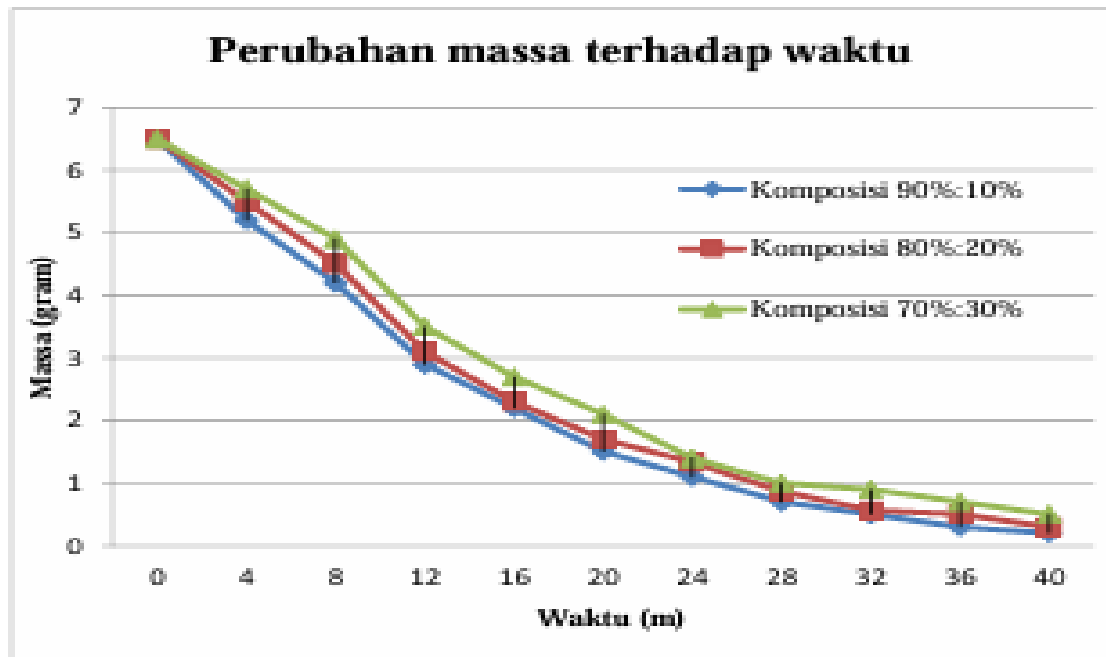


Figure 2. Mass Loss vs. Time During Combustion for Each Composition

As illustrated in Figure 2, the rate of mass loss during combustion was highest for the 90%:10% composition, corroborating its elevated calorific value and more intense thermal output. Conversely, the 70%:30% composition exhibited the slowest mass depletion rate, consistent with its lower calorific value and more gradual combustion profile. The 80%:20% composition demonstrated an intermediate mass loss trajectory, offering a balanced combination of combustion speed and thermal endurance.

The observed relationship between temperature evolution and mass loss across compositions confirms that calorific value is a primary determinant of combustion intensity. Compositions with higher fixed carbon content and calorific value—particularly the 90%:10% blend generated greater thermal energy per unit time, as evidenced by the steeper temperature gradients and accelerated mass reduction relative to higher-binder formulations.

CONCLUSION

This study systematically evaluated the physical characteristics and combustion performance of charcoal briquettes fabricated from sago tree waste across three binder-to-charcoal compositional ratios. The principal conclusions are as follows:

1. Sago tree waste charcoal briquettes exhibit strong potential as efficient and environmentally sustainable alternative fuels, with physical and combustion properties that are adjustable through compositional optimization.
2. The highest calorific value was recorded for the 90%:10% composition (4,157.28 Cal/g), while the lowest was observed for the 70%:30% composition (3,093.64 Cal/g), reflecting the dilutive influence of the binder on energy density.
3. The 80%:20% composition yielded the most rapid and energetically efficient combustion onset, making it suitable for applications demanding quick thermal response.
4. The 90%:10% composition provided the most stable and sustained combustion profile, supported by the highest fixed carbon content (78.29%), and is therefore recommended for uses requiring long-duration heat generation.
5. The 70%:30% composition, despite slower combustion dynamics, maintained consistent thermal output over extended periods, rendering it appropriate for low-intensity, long-duration heating applications.

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