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Optimization of Biomass Briquettes from Red Meranti (Shorea Leprosula Miq.) and Betung Bamboo (Dendrocalamus Asper) for Sustainable Energy Production

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ABSTRACT

Charcoal briquettes produced from lignocellulosic biomass represent a renewable alternative to fossil fuels for household cooking and small-scale energy use. This study assessed the influence of raw material composition on the physical, mechanical, and chemical characteristics of briquettes made from red meranti (Shorea leprosula Miq.) wood waste and betung bamboo (Dendrocalamus asper). A Completely Randomized Design with five treatment ratios—100% red meranti, 75:25, 50:50, 25:75, and 100% bamboo—was applied with five replications for density, moisture content, compressive strength, volatile matter, ash content, and fixed carbon, and three replications for calorific value. Results showed that 100% red meranti briquettes had the highest calorific value (6647.91 cal/g) and fixed carbon content (68.18%). The 75% red meranti + 25% bamboo treatment exhibited the most balanced performance, with good density, compressive strength, moderate ash content, and high calorific value (6288.60 cal/g). Increasing bamboo proportion improved density and volatile matter but lowered calorific value. Overall, red meranti-dominant briquettes provide superior energy quality, while mixed compositions offer a balanced alternative for sustainable domestic fuel production from local biomass resources

INTRODUCTION

Growing global energy demand and the need to reduce greenhouse gas emissions have intensified the search for renewable energy sources. Biomass-based solid fuels, particularly charcoal briquettes, are increasingly recognized for their renewability, carbon neutrality potential, and suitability for household and small-scale industrial applications (IEA, 2023). Briquetting improves biomass energy density, handling, storage, and combustion stability compared to raw materials (Sarker et al., 2022).

In tropical regions, wood-processing residues and bamboo waste are abundant but underutilized. Red meranti (Shorea leprosula Miq.), a commercially important hardwood, generates substantial waste and contains high lignin levels that enhance fixed carbon formation and calorific value after carbonization (Zhang et al., 2021). Betung bamboo (Dendrocalamus asper), a fast-growing species with short harvest cycles, offers strong renewable potential, though its higher cellulose and hemicellulose contents affect thermal degradation and volatile release during pyrolysis (Chen et al., 2022).

Since briquette quality depends heavily on feedstock composition (Lichinga et al., 2023), this study aims to identify the optimal meranti–bamboo mixing ratio to produce high-quality renewable briquettes.

Charcoal: Definition and Production

Charcoal is a carbon-rich fuel produced through biomass pyrolysis under limited oxygen, increasing fixed carbon and calorific value (Seboka, 2025). It is widely used for cooking, industrial reduction, and briquette production due to high energy density and low emissions (Parthipan, 2025). Typically carbonized at 400–700°C (Iswara et al., 2023), red meranti and betung bamboo were processed in a drum kiln, then crushed and sieved for uniform particle size (Maryono et al., 2024).

Charcoal Briquettes: Definition and Production

Charcoal briquettes are densified fuels made by compressing charcoal powder with binders, improving handling and combustion stability (Lichinga et al., 2023). Densification increases energy density and burn efficiency. Production includes carbonization, crushing, drying, mixing, molding, pressing, and final drying below 8% moisture. Tapioca starch is widely used as a natural binder due to strong adhesion and low environmental impact (Seboka, 2025; Aldillah et al., 2024; Rahman et al., 2020).

Factors Affecting Briquette Properties

Briquette quality is influenced by biomass type, particle size, binder concentration, pressure, and moisture (Lichinga et al., 2023). High-lignin biomass improves strength and fixed carbon (Zhang et al., 2021). Key indicators include density, moisture, volatile matter, ash, fixed carbon, strength, and calorific value (Iswara et al., 2023; Parthipan, 2025), with >5000 cal/g considered good (Seboka, 2025; Maryono et al., 2024).

Biomass Sources for Briquettes

Red meranti (Shorea leprosula Miq.) is a dense, high-lignin hardwood producing charcoal with high fixed carbon and calorific value, with abundant residues from industry (Aldillah et al., 2024). Betung bamboo (Dendrocalamus asper) is fast-growing; though higher in volatiles, it improves briquette density and strength (Chen et al., 2022). Tapioca starch acts as a natural binder (Aldillah et al., 2024).

Research Gap

Limited research has systematically investigated hardwood–bamboo composite briquettes to optimize calorific value, mechanical strength, and combustion stability, constraining the advancement of sustainable, high-performance fuels for domestic and small-scale industrial applications.

METHODS

Raw Material Preparation

Red meranti (Shorea leprosula Miq.) sawmill waste and betung bamboo (Dendrocalamus asper) residues were collected based on their availability and briquette potential (Haryanto et al., 2022). Materials were cleaned, cut (2–5 cm), and air-dried to 10–12% moisture. Carbonization was performed in a drum kiln at 500°C for 2 hours under limited oxygen (Rahman et al., 2020). Charcoal was cooled, crushed, and sieved to 0.5–1 mm to ensure uniformity affecting density and strength (Putra &

Widodo, 2021), then oven-dried at 105°C. Powders were blended by treatment ratio, mixed with 10% tapioca binder, pressed at 40 bar ≈ 580.15 psi for 10 minutes, oven-dried, and conditioned before testing (Rindayatno et al., 2025).

Experimental Design

A Completely Randomized Design (CRD) was applied with five treatment combinations based on the ratio of red meranti to bamboo:

Table 1. Treatments Combinations Based on the Ratio of Red Meranti to Bamboo

Treatment	Composition
A	100% red meranti
B	75% red meranti + 25% bamboo
C	50% red meranti + 50% bamboo
D	25% red meranti + 75% bamboo
E	100% bamboo

Five replications were conducted for density, moisture content, compressive strength, volatile matter, ash content, and fixed carbon, while calorific value was tested in three replications to account for variability.

Parameters Measured

Table 2. The Following Parameters Were Evaluated Using Standard Methods:

Parameter	Method / Standard	Unit
Density	Geometric method: mass / volume	g/cm^3
Moisture content	Oven-drying at 105°C for 24 h (ASTM D4442)	%
Compressive strength	Universal testing machine (ASTM E9)	kg/cm^2
Volatile matter	ASTM E872 / proximate analysis	%
Ash content	ASTM D1102 / combustion at 750°C	%
Fixed carbon	By difference from proximate analysis	%
Calorific value	Bomb calorimeter (ISO 1928)	cal/g

These parameters reflect the fuel quality, combustion behavior, and mechanical properties essential for practical applications (Sari et al., 2023; Parthipan, 2025).

RESULTS AND DISCUSSION

The following section presents the comprehensive results of physicochemical and mechanical quality evaluations conducted to assess the performance characteristics of the produced charcoal briquettes.

Table 3. Evaluation of Quality Parameters of Charcoal Briquettes

Charcoal Briquettes Quality Parameters	Treatments				
	A	B	C	D	E
Density (g/cm^3)	0.48	0.49	0.52	0.57	0.61
Moisture content (%)	5.64	6.10	6.60	1.02	7.55
Compressive strength (kg/cm^2)	13.42	13.44	13.47	13.56	13.88
Volatile matter content (%)	23.36	26.92	27.60	29.50	29.42
Ash content (%)	8.46	8.00	3.44	5.20	7.69
Fixed carbon content (%)	68.18	65.08	68.96	65.30	62.88
Calorific value (cal/gr)	6647.91	6288.60	5941.04	5494.89	4660.72

The physicochemical and mechanical properties of the charcoal briquettes varied across treatments A–E, indicating the influence of formulation or processing conditions on product quality. Density increased progressively from 0.48 g/cm^3 (Treatment A) to 0.61 g/cm^3 (Treatment E), suggesting improved compaction and particle bonding in later treatments. A similar upward trend was observed in compressive strength, which ranged from 13.42 to 13.88 kg/cm^2, indicating relatively consistent mechanical integrity with slight enhancement at higher densities.

Moisture content ranged from 1.02% to 7.55%, with Treatment D exhibiting the lowest value, which is favorable for combustion efficiency and storage stability. Volatile matter content was relatively high across all treatments (23.36–29.50%), potentially indicating incomplete carbonization. Ash content showed notable variation, with the lowest value observed in Treatment C (3.44%), suggesting lower mineral residue and potentially cleaner combustion characteristics.

Fixed carbon content ranged between 62.88% and 68.96%, with Treatment C showing the highest value. Conversely, calorific value exhibited a decreasing trend from Treatment A (6647.91 cal/g) to Treatment E (4660.72 cal/g), suggesting that increasing density and volatile matter may be associated with reduced energy content. Overall, Treatment C appears to present a balanced combination of relatively high fixed carbon, low ash content, and acceptable calorific value, indicating comparatively favorable fuel characteristics among the treatments.

Table 4. Analysis of Variance (ANOVA) Assessing the Influence of Treatment on the Physicochemical and Mechanical Properties of Charcoal Briquettes

Charcoal Briquettes Quality Parameters	Error	Treatments	
	Mean Square	Mean Square	F-Count
Density[(a)]	0.0001	0.013	131.898**
Moisture content[(a)]	0.077	3.567	46.248**
Compressive strength[(a)]	1.574	0.179	0.144^{ns}
Volatile matter content[(a)]	0.818	10.427	12.745**
Ash content[(a)]	1.77	32.44	18.363**
Fixed carbon content[(a)]	0.867	6.215	7.168**
Calorific value[(b)]	3480.6	1,778,381	510.947**

Notes: (a) = 5 replications =F-table 5%= 2.866; 1% = 4.431

(b) = 3 replications = F-table 5%=3.478; 1%= 5.994

** = very significantns = non significant

The ANOVA results indicate that material composition significantly affected most charcoal briquette quality parameters. Density, moisture content, volatile matter, ash content, fixed carbon, and calorific value showed highly significant differences ($p < 0.01$), as F-count values exceeded the critical F-table values. These findings confirm that biomass blending substantially influences physicochemical and thermal characteristics. Similar trends have been reported in recent studies highlighting the role of biomass composition in determining briquette performance (Gupta et al., 2021; Li et al., 2022). In contrast, compressive strength was not significantly affected, suggesting that mechanical properties may be more influenced by processing conditions than feedstock ratio alone.

Table 5. Comparison of Research Results with SNI 01-6235-2000 Standard

Parameter	SNI 01-6235-2000 Requirement	Research Results	Compliance Status
Density (g/cm³)	—	0.48–0.61	*No specific SNI requirement*
Compressive strength (kg/cm²)	—	13.42-13.88	*No specific SNI requirement*
Moisture content (%)	≤ 8	1.02–7.55	Compliant
Volatile matter (%)	≤ 15	23.36–29.50	Not compliant
Ash content (%)	≤ 8	3.44–8.46	Partially compliant
Fixed carbon (%)	≥ 77	62.88–68.96	Not compliant
Calorific value (cal/g)	≥ 5000	4660.72–6647.91	Treatment-dependent

The quality characteristics of the produced charcoal briquettes were evaluated against the Indonesian National Standard SNI 01-6235-2000. The results indicate that the moisture content of all treatments (1.02–7.55%) complied with the maximum allowable limit of 8%, demonstrating adequate drying and storage conditions. Similarly, the calorific value of treatments A–D (5494.89–6647.91 cal/g) exceeded the minimum requirement of 5000 cal/g, indicating acceptable energy performance, although treatment E (4660.72 cal/g) fell below the standard threshold. Ash content (3.44–8.46%) was generally within or near the maximum limit of 8%, with slight deviations in certain treatments. However, volatile matter content (23.36–29.50%) significantly exceeded the maximum allowable level of 15%, while fixed carbon content (62.88–68.96%) remained below the minimum requirement of 77%. These findings suggest that although the briquettes exhibit satisfactory moisture and, in some cases, calorific properties, optimization of the carbonization process is necessary to reduce volatile compounds and enhance fixed carbon content to achieve full compliance with SNI standards.

Density

The density of charcoal briquettes increased with higher bamboo content, ranging from 0.48 g/cm³ (Treatment A, 100% red meranti) to 0.61 g/cm³ (Treatment E, 100% bamboo) (Table 1). Higher bamboo content enhanced compaction due to finer particle texture and better packing behavior, consistent with biomass densification theory (Kaliyan & Morey, 2009; Sarker et al., 2022). Densities above 0.50 g/cm³ are considered suitable for tropical commercial briquettes (Rahman et al., 2020).

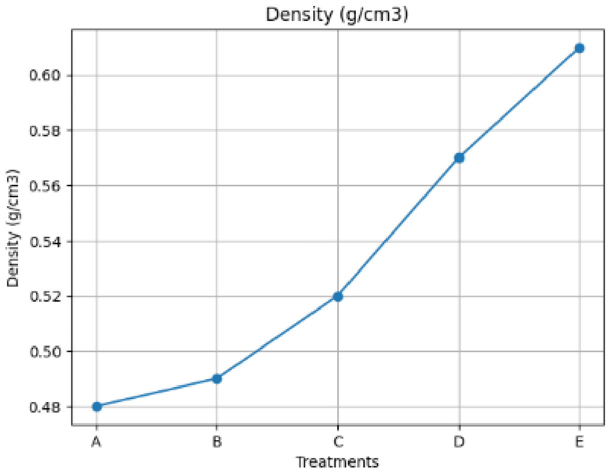

Figure 1. Effect of Treatment Variation on the Density of Charcoal Briquettes

Moisture Content

Moisture content ranged from 5.64% to 7.55%, slightly increasing with bamboo ratio (Table 1). Bamboo's hygroscopic nature and higher cellulose content likely contribute to this trend (Chen et al., 2022). Moisture levels below 8% meet standard biofuel requirements and support efficient ignition (Sarker et al., 2022). Excess moisture can reduce calorific value and increase smoke emissions (IEA, 2023).

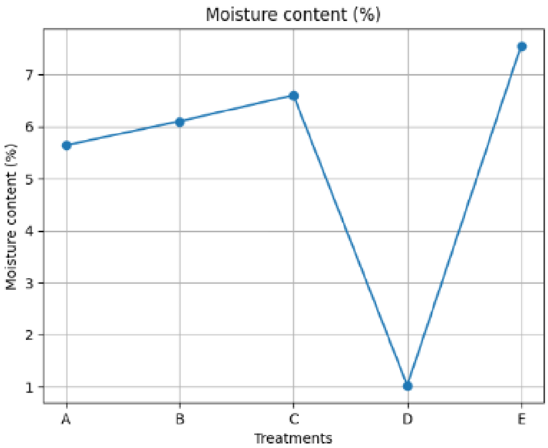

Figure 2. Variation in Moisture Content of Charcoal Briquettes Across Different Treatments

Compressive Strength

Compressive strength increased slightly from 13.42 kg/cm^2 (A) to 13.88 kg/cm^2 (E) (Table 3). Bamboo-rich briquettes showed better mechanical resistance, likely due to fibrous interlocking enhancing particle bonding. Mechanical strength correlated positively with density and binder effectiveness (Putra & Widodo, 2021). Adequate strength is crucial to prevent cracking and powdering during handling and storage (Lichinga et al., 2023).

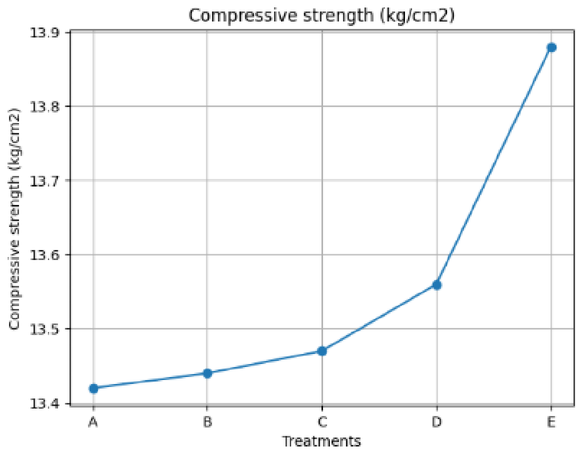

Figure 3. Variation in Compressive Strength of Charcoal Briquettes Under Different Treatments

Volatile Matter

Volatile matter increased from 23.355% (A) to 29.504% (D), indicating greater bamboo-derived volatile fractions. During pyrolysis, hemicellulose and cellulose decompose at lower temperatures (200–350 °C) than lignin (250–500 °C), releasing more volatiles (Yang et al., 2007; Chen et al., 2022). Higher volatile content enhances ignition and flame development but may elevate smoke and particulate emissions if not balanced by sufficient fixed carbon (Zhang et al., 2021). Therefore, moderate volatile levels provide a better balance between ignition ease, combustion stability, and overall fuel performance.

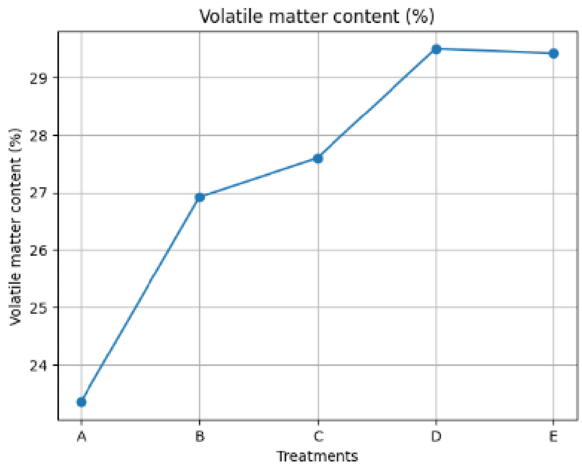

Figure 4. Effect of Treatment Variation on the Volatile Matter Content of Charcoal Briquettes

Ash Content

Ash content varied significantly, with the lowest value in Treatment C (3.439%). Ash, the inorganic residue after combustion, affects heat transfer efficiency and stability (Vassilev et al., 2010). High ash may form insulating deposits, reducing efficiency and increasing slagging, whereas low ash improves thermal performance. Higher ash in meranti-dominant briquettes may relate to inherent mineral composition and species variability (Sari et al., 2023). The 50:50 blend likely diluted mineral content, reducing inorganic fractions. These results emphasize compositional control to minimize ash-related constraints and enhance fuel performance.

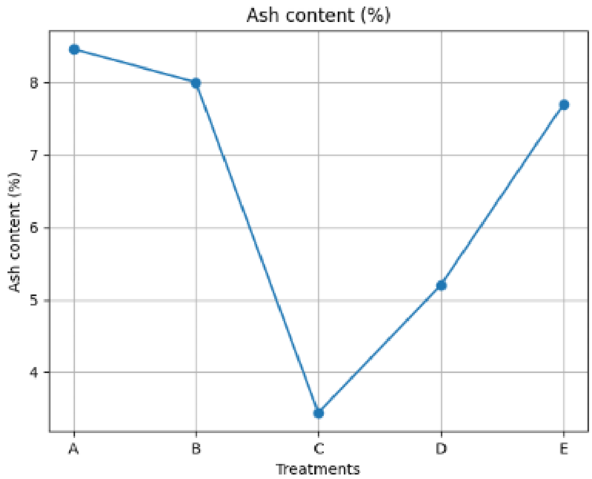

Figure 5. Variation in Ash Content of Charcoal Briquettes Across Different Treatments

Fixed Carbon

Treatments C (68.955%) and A (68.183%) showed the highest fixed carbon. Fixed carbon sustains heat release and prolongs combustion as the solid residue after devolatilization (Demirbaş, 2004). Hardwood-derived char, rich in lignin, forms stable aromatic carbon structures during carbonization, increasing thermal stability and fixed carbon (Zhang et al., 2021). This higher fixed carbon positively correlates with calorific value, highlighting biomass composition's role in energy quality.

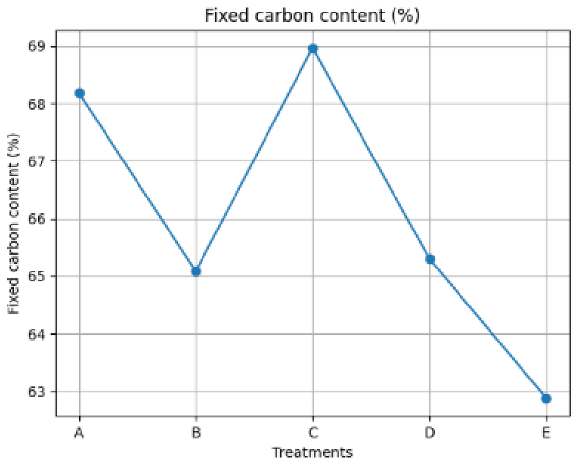

Figure 6. Effect of Treatment Variation on the Fixed Carbon Content of Charcoal Briquettes

Calorific Value

Calorific value declined from 6647.91 cal/g (A) to 4660.72 cal/g (E) as bamboo proportion increased. Higher values in meranti briquettes relate to greater fixed carbon and lower volatile matter, as fixed carbon directly enhances heat release (Demirbaş, 2004; IEA, 2023). Increasing bamboo raised volatile content and reduced fixed carbon, lowering energy output. However, values above 4500 cal/g remain acceptable for domestic cooking in Indonesia (Rahman et al., 2020), indicating bamboo-dominant briquettes retain practical potential.

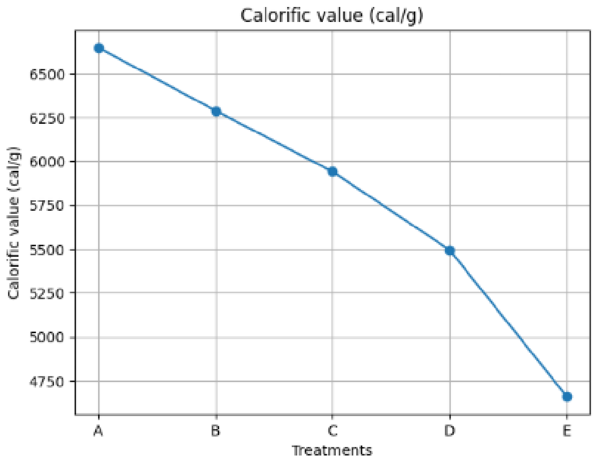

Figure 7. Effect of Treatment Variation on the Calorific Value of Charcoal Briquettes

Overall Performance Evaluation

Although Treatment A yielded the highest calorific value and fixed carbon content, Treatment B (75% meranti + 25% bamboo) exhibited a more balanced performance profile when both thermal and mechanical properties are considered. This formulation demonstrated adequate density (0.494 g/cm³), good compressive strength (13.442 kg/cm²), moderate ash content (7.999%), and a relatively high calorific value (6288.60 cal/g).

From a fuel optimization perspective, performance cannot be assessed solely on the basis of maximum energy output. Mechanical durability, ignition behavior, and combustion cleanliness are equally critical parameters, as they collectively determine handling stability, combustion efficiency, and end-user practicality (Lichinga et al., 2023). Therefore, a multi-criteria evaluation provides a more comprehensive assessment of briquette quality than calorific value alone.

Accordingly, 100% meranti briquettes are more suitable for applications prioritizing maximum energy yield, whereas the 75:25 meranti–bamboo blend represents a pragmatic compromise between structural integrity and thermal performance. These findings underscore the strategic importance of biomass blending in tailoring briquette characteristics to specific performance requirements, thereby contributing to the advancement of sustainable bioenergy systems in tropical regions.

CONCLUSION

This study shows that biomass composition strongly influences charcoal briquette quality. While 100% red meranti produced the highest calorific value and fixed carbon content, optimal performance depends not only on energy output but also on mechanical strength, density, and ash content. The 75% meranti + 25% bamboo blend provided the most balanced characteristics, combining good structural integrity with high thermal performance. Therefore, biomass blending is an effective strategy to optimize briquette quality and support sustainable bioenergy development.

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