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THE EFFECT OF YAKISUGI FINISHING APPLICATION ON THE PHYSICAL AND MECHANICAL PROPERTIES OF RAJUMAS WOOD (*Duabanga moluccana*)

Pengaruh Aplikasi Finishing Yakisugi Terhadap Sifat Fisis dan Mekanis Kayu Rajumas (Duabanga Moluccana)

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ABSTRACT

This study aims to examine the influence of yakisugi surface charring treatment on the physical and mechanical properties of *Rajumas* wood (*Duabanga moluccana*). The method involved surface burning for 0 (control), 20, 40, and 60 seconds using a butane gas torch. Tests were conducted on moisture content, density, shrinkage, water absorption, thickness swelling, modulus of rupture (MoR), and modulus of elasticity (MoE). Statistical analysis using one-way ANOVA followed by Tukey's HSD test (α = 0.05) was performed to evaluate treatment effects. The results showed that burning duration affected both physical and mechanical properties of Rajumas wood. Longer burning durations improved dimensional stability by reducing moisture content, water absorption, and swelling; however, mechanical strength (MoR and MoE) tended to decrease at 60 seconds due to partial thermal degradation of cell wall polymers. Moderate exposure (20–40 seconds) provided an optimal balance between improved stability and acceptable strength retention. This study highlights the novel application of Yakisugi to a fast-growing tropical hardwood, offering a sustainable surface modification technique for enhancing durability and performance in non-structural wood applications.

Keywords: *Duabanga moluccana*; Thermal modification; Yakisugi

ABSTRAK

Penelitian ini bertujuan untuk mengetahui pengaruh perlakuan pembakaran permukaan teknik yakisugi terhadap sifat fisis dan mekanis kayu Rajumas (*Duabanga moluccana*). Metode penelitian dilakukan dengan pembakaran permukaan kayu selama 0 (kontrol), 20, 40, dan 60 detik menggunakan obor gas butana. Pengujian meliputi kadar air, kerapatan, penyusutan, daya serap air, pengembangan tebal, keteguhan patah (MoR), dan modulus elastisitas (MoE). Analisis statistik menggunakan one-way ANOVA yang dilanjutkan dengan uji lanjut Tukey's HSD (α = 0,05) untuk mengetahui pengaruh perlakuan. Hasil penelitian menunjukkan bahwa lama pembakaran berpengaruh terhadap sifat fisis dan mekanis kayu Rajumas. Pembakaran dengan durasi lebih lama meningkatkan stabilitas dimensi melalui penurunan kadar air, daya serap air, dan pengembangan tebal; namun kekuatan mekanis (MoR dan MoE) cenderung menurun pada pembakaran 60 detik akibat degradasi termal parsial pada polimer dinding sel. Perlakuan sedang (20–40 detik) memberikan keseimbangan optimal antara peningkatan stabilitas dimensi dan penurunan kekuatan yang masih dapat diterima. Penelitian ini menyoroti penerapan baru teknik Yakisugi pada kayu tropis cepat tumbuh, yang menawarkan metode modifikasi permukaan berkelanjutan untuk meningkatkan keawetan dan performa kayu pada aplikasi non-struktural.

Kata kunci: *Duabanga moluccana*; Modifikasi termal; Yakisugi

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A. INTRODUCTION

Indonesia possesses vast forest resources that provide an abundant supply of timber. Wood is one of the most frequently used materials for furniture, accounting for approximately 70% cellulose and 18–28% lignin (Lensufiie, 2008). It is widely preferred in furniture and handicrafts because of its flexibility compared to other materials (Seftianingsih, 2018). In addition to its strength, In addition to its strength, wood is valued in interior applications not only for its durability and aesthetic grain, but also for its natural texture and thermal comfort, which make it an ideal interior material. However, its performance can vary depending on dimensional stability and resistance to environmental changes.

The demand for wood as a construction material has also increased due to its eco-friendly characteristics and lower carbon emissions. According to Kuzman and Groselj (2012), engineered wood construction ranks as the top priority compared to solid wood, concrete, brick, and steel, owing to superior performance in load capacity, fire resistance, design, energy efficiency, cost, and overall quality. Despite these advantages, wood also has drawbacks, including flammability, dimensional instability, susceptibility to biological degradation, and non-uniformity that often results in defects (Fikriya 2020; Tanubrata 2015).

In recent decades, the supply of high-quality timber from natural forests has declined, while demand continues to grow, emphasizing the need for efficient utilization of fast-growing species (Fahrussiam *et al*. 2023a). Fast-growing timber species are favored because of their short harvesting cycles and availability, but they generally exhibit low density and inferior properties (Yunita *et al.* 2022). One such species is Rajumas (*Duabanga moluccana*), which is abundant in West Nusa Tenggara. Despite being classified in low strength and durability classes IV–V (Bonita 2015), Rajumas is considered strategic due to its local abundance, fast growth rate, and untapped potential for development through treatment and processing innovations. Its widespread availability makes it a viable candidate to reduce pressure on natural forests and improve the productivity of community forests. In Indonesia, approximately 85% of the 4000 species commonly cultivated in community forests fall into low durability classes (Oey 1990). This situation reduces utilization efficiency, as much harvested timber remains unused due to its poor quality and heterogeneity (Dumanauw 1984).

Wood preservation techniques are therefore essential to extend service life and improve performance. Among these, yakisugi traditional Japanese charring method offers a chemical-free, low-cost, and environmentally friendly solution. Compared to conventional preservation techniques such as chemical impregnation or surface coatings, Yakisugi provides enhanced resistance to decay and dimensional stability without introducing toxic substances. Its effectiveness, however, varies across wood species, depending on anatomical structure and chemical composition. Studies have shown that thermal treatment during charring alters lignin and hemicellulose content, influencing hydrophobicity, resistance to fungi, and surface hardness (Esteves & Pereira 2009; Hill 2006). For instance, hardwoods and softwoods exhibit different pyrolysis responses, which affects the depth and uniformity of the char layer (Nakamura *et al.* 2021). Therefore, a better understanding of the charring mechanism and wood chemistry under pyrolysis is crucial for optimizing its application. This technique improves resistance to termites, fungi, and weathering, while also enhancing aesthetic qualities (Ebner *et al.* 2021). However, its effects vary: *yakisugi* treatment on pine wood has been shown to improve dimensional stability, particularly by reducing thickness swelling by up to 56% after 30 seconds of surface charring, but also causes reductions of approximately 17% in modulus of elasticity (MoE) and modulus of rupture (MoR) (Fahrussiam *et al.* 2023b).

Given the abundance but low natural durability of Rajumas, this study investigates the effect of *yakisugi* finishing on its physical and mechanical properties. The research aims to evaluate whether this modification can enhance the performance of Rajumas, thereby supporting its wider use in furniture and construction applications.

While the Yakisugi method has been explored in various temperate wood species, its application to tropical fast-growing species like Rajumas (*Duabanga moluccana*) remains underreported. Most previous studies focus on general performance outcomes, without linking specific burning durations to dimensional and mechanical properties in species with low natural durability. This study contributes novel insights by systematically evaluating the effects of three charring depths on both physical (e.g., moisture content, swelling, shrinkage) and mechanical parameters (MoE and MoR), using Rajumas as a representative tropical hardwood. The findings aim to fill a gap in sustainable wood modification techniques for underutilized community forest species in Indonesia.

B. METHODS

This study was conducted at the Wood Technology Laboratory, Faculty of Agriculture, University of Mataram. The main material used was Rajumas wood (*Duabanga moluccana*), a fast-growing species originating from community forests in West Nusa Tenggara. The tools and equipment included a gas torch for the *yakisugi* process, digital calipers, analytical balance, oven, desiccator, water container, and a Universal Testing Machine (UTM) for mechanical testing.

Sample Preparation

Wood logs were processed into test specimens according to ASTM D143 standards for physical and mechanical testing. A total of 84 specimens were prepared and conditioned at room temperature to achieve equilibrium moisture content prior to testing. The specimens were divided into three groups: 3 × 3 × 3 cm (36 samples) for physical tests of moisture content, specific gravity, and density; 2.5 × 2.5 × 2.5 cm (24 samples) for shrinkage and thickness swelling; and 1.7 × 1.7 × 40 cm (24 samples) for mechanical tests determining modulus of elasticity (MOE) and modulus of rupture (MOR). Four Yakisugi treatments were applied control (0 seconds) and burning for 20, 40, and 60 seconds, each with three replications, where each replication represented the specimens per parameter as shown in Table 1. Thus, a total of 60 specimens were used for physical tests and 24 specimens for mechanical tests.

Table 1. Experimental Design

Treatment	Burning Time (s)	Replication
P1	0 (control)	U1, U2, U3
P2	20	U1, U2, U3
P3	40	U1, U2, U3
P4	60	U1, U2, U3

Yakisugi Treatment

The yakisugi process consisted of surface burning using a GSF 1093 gas torch, fueled by butane gas with a medium flame intensity setting. The flame was directed at a fixed distance of 40 mm from the specimen surface, positioned on a horizontal platform during burning. The process was conducted under ambient laboratory conditions of approximately 31 °C temperature and 75% relative humidity. Burning durations were 20, 40, and 60 seconds, while control specimens received no burning. Although the actual surface temperature was not measured directly, this is acknowledged as a limitation that may contribute to variability in thermal exposure. The burning was performed manually, without mechanical assistance to control motion speed or flame angle, which is also recognized as a source of potential variation affecting treatment uniformity. After burning, the specimens were cleaned using a wire brush, followed by wiping with tissue until no black ash residue appeared on the tissue surface. The cleaning process was considered complete once the wood grain became visible and the surface displayed a uniform dark brown tone, indicating the removal of loose charcoal and stable exposure of the modified layer.

Physical Properties

Physical properties were tested to evaluate fundamental characteristics of Rajumas wood that influence its dimensional stability and utilization. All specimens were pre-conditioned at room temperature to achieve equilibrium moisture content prior to testing. The parameters included:

Moisture content is defined as the percentage of water present in the wood relative to its oven-dry weight (Mori *et al.* 2025). Specimens were weighed in the air-dry condition (BKU in g), oven-dried at 103 ± 2 °C for 24 h, then cooled for 15 30 min in a desiccator and reweighed periodically until two consecutive weights, indicating constant mass.

$$\%MC = \left(\frac{BKU-BKT}{BKT}\right) \times 100 \quad (1)$$

Where, BKU is air-dry weight (g), BKT is oven-dry weight (g).

Density was determined from the air-dry mass and corresponding air-dry volume of the specimen (Simpson, 1993):

$$\text{Density } (g/cm^3) = \frac{BKU}{VKU} \quad (2)$$

Where, BKU is air-dry weight (g), VKU is air-dry volume (cm^3).

Specific gravity was measured by water displacement method using a beaker and balance (Johansson *et al.* 2003):

$$\text{Specific gravity} = \frac{W}{V},\ V = B-A \quad (3)$$

Where, W is specimen weight (g), A is weight of beaker with water (g), B is weight of beaker + water + specimen (g).

Dimensional swelling was measured volumetrically to determine the extent of wood expansion after immersion in water for 24 h and measuring dimensional changes (Miyoshi *et al.* 2017):

$$\%\text{Swelling} = \left(\frac{D_0 - D_a}{D_0}\right) \times 100 \quad (4)$$

Where, D_0 is final dimension (cm^3), D_a is initial dimension (cm^3).

Shrinkage was measured volumetrically as the percentage reduction in wood volume from air-dry to oven-dry condition at 103 ± 2°C (Johansson & Ormarsson, 2009):

$$\%\text{Shrinkage} = \left(\frac{D_a - D_0}{D_a}\right) \times 100 \quad (5)$$

Where, D_a is initial dimension (cm^3), D_0 is final oven-dry dimension (cm^3).

Mechanical Properties

Mechanical properties were tested to assess wood strength and performance under load (Ishimaru *et al.* 2001), following ASTM D143-05 standards, all specimens were conditioned to a consistent equilibrium moisture content before testing. 12 specimens were used for MoE testing and 12 specimens were used for MoR testing, while all specimens were free from visible defects, any defective specimen will excluded from testing. The test using a Universal Testing Machine (UTM) under three-point bending configuration, with a 35 cm span and a loading speed of 5 mm/min. Specimens were loaded flatwise. The machine automatically stopped when the first crack occurred.

$$\text{MoE (kgf/cm}^2\text{)} = \frac{\Delta P.L^3}{4\Delta Y.b.h^3} \quad (6)$$

Where, ΔP is the load within the proportional limit (N), L is the span length (mm), ΔY is the deflection at the proportional limit (mm), b is the specimen width (mm), and h is the specimen thickness (mm).

MoR indicates maximum bending strength at failure. Testing was conducted under the same loading setup until rupture, and maximum load was recorded (Hussin Binti Raja, 2023):

$$\text{MoR (kgf/cm}^2\text{)} = \frac{3P.L}{2b.h^2} \quad (7)$$

Where, P is the maximum load at failure (N), L is the span length (mm), b is the specimen width (mm), and h is the specimen thickness (mm).

Data Analysis

The results of physical and mechanical property tests were tabulated and analyzed statistically using One-Way ANOVA to determine significant differences among treatments (Table 2). When significant effects were found, Tukey's HSD at the 5% level was applied. Statistical processing was conducted using SPSS v29, while preliminary tabulation was performed with Microsoft Excel.

Table 2. Analysis of Variance Equation

Source of Variation	Degree of Freedom (df)	Sum of Square (SS)	Mean Square (MS)	F-ratio
Treatment	k – 1	$SST = \sum_{i=1}^{k} n_i(\bar{x}_i - \bar{x})^2$	$MST = \frac{SST}{k-1}$	$FStat = \frac{MST}{MSE}$
Error	N – k	$SSE = \sum_{i=1}^{k} (n_i - 1)Si^2$	$MSE = \frac{SSE}{N-k}$	

C. RESULTS AND DISCUSSION

Physical properties of wood describe the response of the material to external factors such as water, heat, electricity, or light. The physical properties examined in this study include moisture content, density, specific gravity, swelling, and shrinkage. Testing was carried out according to standard procedures for each parameter, with a total of 60 samples.

Moisture content refers to the percentage of water in green wood relative to oven-dry weight. Table 3 shows variations after burning treatment: control (P0) 9.12%, P1 10.12%, P2 3.97%, and the lowest in P3 with 2.11%. All treatments met the requirements of SNI 7973:2013, which stipulates a maximum of 19%. Although P1 exhibited a slight increase in moisture content compared to the control, a substantial reduction was observed at longer burning durations (P2 and P3), suggesting that only deeper surface charring effectively reduces moisture retention. Pyrolysis damages hygroscopic structures and forms charcoal with high porosity but lower water uptake capacity (Kymäläinen *et al.* 2017). Heat treatment also reduces hydroxyl groups in cell walls, leading to increased hydrophobicity, reduced water absorption, and enhanced dimensional stability (Abdillah *et al.* 2020). ANOVA results (p-value = 0.504) indicate no significant differences among treatments ($\alpha = 0.05$). Tukey's test also shows all treatments share the same symbol ("a"), meaning different burning times (20, 40, 60 s) do not significantly affect moisture content. However, the initial increase at P1 may result from temporary surface rehydration or measurement variation, while the overall trend reflects decreasing moisture content with longer burning durations.

Table 3. Mean Values of Physical Properties of Rajumas Wood for Each Treatment

Parameter	N	P0	P1	P2	P3	p-value (Sig.)
% MC	12	9.12 a	10.12 a	3.97 a	2.11 a	0.50
Density (g/cm^3)	12	0.58 b	0.49 a	0.51 a	0.53 ab	0.06
Specific gravity	12	0.06 b	0.06 a	0.05 a	0.05 a	0.02*
% Swelling	12	3.55 a	4.87 a	4.47 a	2.38 a	0.58
% Shrinkage	12	6.65 c	4.91 b	5.83 bc	2.91 a	0.00*

where: n = number of samples; abc = Tukey's test symbols at $\alpha = 0.05$; a = no significant difference; b = significant difference with a & c; ab = partial significance; bc = partial significance; F = ANOVA significance p-value. P0 = control, P1 = 20 s burning, P2 = 40 s burning, P3 = 60 s burning.

Wood density is the mass per unit volume expressed in g/cm^3. Table 3 indicates density decreased after burning, with the lowest in P1 (0.49 g/cm^3). Thermal degradation reactions contribute to density changes (Hakkou *et al.* 2005). Increased temperature reduces cellulose polymerization but increases crystallinity (Romagnoli 2017), as less ordered molecules degrade preferentially (Sivonen *et al.* 2002). Similar findings by Šeda (2021) show short-duration heat treatments only slightly reduced surface density (4.5–8.2%), while exposure at 200°C for 20 min caused reductions of 15.5–33.5%. ANOVA (p-value = 0.063) suggests no significant difference across treatments, although Tukey's test marks P1 differently from P0, indicating some treatment effect at shorter burning durations.

Specific gravity is a measure of mass-to-volume ratio, indicating wood compactness and strength. Based on Table 3, Specific gravity decreased with longer burning times: P0 = 0.064, P1 = 0.061, P2 = 0.057, and the lowest in P3 = 0.056. ANOVA (p-value = 0.027) confirms significant differences at $\alpha = 0.05$. Tukey's test shows P0 differs significantly from all treated groups (P1–P3), confirming that burning duration has a strong influence on reducing wood specific gravity.

Swelling is the dimensional increase in wood due to water uptake. Values varied between 4.87% (P1) and 2.38% (P3). Although trends were observed, ANOVA (p-value = 0.584) showed no significant differences among treatments.This phenomenon is linked to hydrophobic, cross-linked, but porous char layers formed above 300°C. Water penetrates microcracks in charred surfaces, increasing localized swelling (Šeda 2021). However, overall statistical analysis showed no significant differences across treatments.

Shrinkage is the dimensional reduction due to water loss when drying. Table 3 shows shrinkage decreases with longer burning: P0 = 6.65%, P1 = 4.91%, P2 = 5.83%, and lowest in P3 = 2.91%. ANOVA (F = 0.002) indicates significant differences ($\alpha = 0.05$). Tukey's test shows P0 differs significantly from P1–P3. Shrinkage reduction is attributed to water removal during burning and subsequent pyrolysis of hemicellulose and lignin (Chowdhury *et al.* 2005). The process causes microcracks in S1–S2 cell wall layers, producing char, gas, vapor, and tar. High shrinkage is also related to large microfibril angles in the S2 layer (Shmulsky & Jones 2019).

The MoE measures wood stiffness, indicating its ability to resist deformation under load. A higher MoE suggests greater rigidity, making the wood more suitable for structural applications. As shown in Table 4, MoE values exhibited a decreasing trend with longer burning durations: P0 (control) = 13,239.0 kgf/cm^2, P1 = 13,323.3 kgf/cm^2, P2 = 11,660.4 kgf/cm^2, and P3 = 10,276.7 kgf/cm^2. Despite this decline, all values still exceeded the minimum requirement of 7,500 kgf/cm^2 according to JAS 234:2007 (Wulandari 2024). The observed reduction is attributed to partial thermal degradation, which affects bonding integrity and cell wall structure (Bal 2014). Candelier *et al.* (2016) also reported that MoE and MoR decrease with increased thermal modification intensity. Although ANOVA results (p-value = 0.121) indicate no statistically significant differences ($\alpha = 0.05$), Tukey's's test shows that P3 differs from P0 and P1, suggesting that extended surface burning weakens stiffness to some extent. Importantly, because Yakisugi primarily modifies the outermost wood layers, the internal core structure likely retains most of its mechanical integrity, especially at shorter burning durations (P1–P2). This explains why the decrease in MoE is moderate and still within acceptable structural standards.

Table 4. Mean Values of Mechanical Properties of Rajumas Wood for Each Treatment

Parameter	N	P0	P1	P2	P3	p-value (Sig.)
MoE	8	13,239 b	13,323.3 b	11,660.4 ab	10,276 a	0.121
MoR	8	83.07 b	81.19 b	69.93 a	66.20 a	0.065

where*:* n = number of samples; abc = Tukey test symbols at α = 0.05; F = ANOVA significance value. P0 = control, P1 = 20 s burning, P2 = 40 s burning, P3 = 60 s burning.

The MoR reflects wood's bending strength, representing the maximum stress it can withstand before fracture. As seen in Table 4, MoR values decreased with longer burning times: P0 = 83.07 kgf/cm², P1 = 81.19 kgf/cm², P2 = 69.93 kgf/cm², and lowest in P3 = 66.20 kgf/cm². The reduction trend suggests structural weakening due to thermal degradation. Although ANOVA results (p-value = 0.065) show no significant differences among treatments, Tukey's test indicates P3 differs from P0 and P1, confirming that longer exposure weakens bending strength. This decline is likely caused by thermal degradation of hemicellulose and partial depolymerization of lignin and cellulose, which compromise structural integrity. In addition, thermal stress and microcracking near the char boundary may initiate localized weaknesses that reduce load-bearing performance (Ibáñez *et al.* 2023). However, at shorter burning durations (P1 and P2), the formation of a thin char layer may contribute to surface densification and thermal shielding effects, maintaining MoR values relatively close to the control. This implies that moderate Yakisugi treatment can balance durability improvement with mechanical performance retention, particularly when applied within controlled exposure limits. The mechanical degradation observed in this study is closely linked to thermal decomposition of cell wall polymers, particularly hemicellulose, which contributes significantly to load-bearing capacity. High temperatures during surface charring (180–220 °C) induce softening of lignin and decomposition of hemicellulose in the outer layers, disrupting hydrogen bonding and reducing the cohesion of the secondary wall matrix (Kačíková *et al.* 2013; Candelier *et al.* 2016). These reactions increase mechanical anisotropy by weakening transverse stiffness, thus lowering MoE and increasing brittleness, as reflected in reduced MoR values. Although the char layer formed through Yakisugi is confined to the surface, it affects stress distribution and failure initiation points. Similar findings were reported by Ibáñez *et al.* (2023), where localized burning led to carbohydrate loss and mechanical decline in *Pinus taeda* and *Eucalyptus bosistoana*. Compared to these temperate species, this study provides evidence on the structural response of *Duabanga moluccana*, a fast-growing tropical hardwood that remains underrepresented in the thermal treatment literature.

Despite the reduction in bending strength, all MoR values in this study remained above 66 kgf/cm², suggesting that moderately charred Rajumas still satisfies basic performance thresholds. Therefore, Yakisugi-treated Rajumas may remain suitable for non-structural applications such as paneling, interior finishing, or decorative components, where enhanced dimensional stability and durability are prioritized over high strength. These findings highlight the potential of surface modification to upgrade low-durability tropical species for broader material applications, especially in community forest utilization contexts.

D. CONCLUSION

This study concluded that yakisugi surface charring significantly affects the physical and mechanical properties of Rajumas wood (*Duabanga moluccana*). Notably, increasing the burning duration reduced moisture content and shrinkage, indicating improved dimensional stability. However, it also led to declines in density, specific gravity, MoE, and MoR, particularly at 60 seconds of exposure. While ANOVA results showed no statistically significant differences in MoE and MoR, Tukey's's test identified a significant decrease at longer durations, likely due to thermal degradation of hemicellulose and cellulose. The highest MoE value (13,323.3 kgf/cm²) exceeded the minimum requirement of 7,500 kgf/cm² for structural applications, as specified by JAS 234:2007, suggesting partial suitability for light structural use depending on application requirements. Although MoR values decreased with longer burning durations, they remained within a reasonable range, but no official benchmark was cited to verify structural classification for bending strength. These findings suggest that controlled yakisugi treatment particularly at moderate durations can enhance the dimensional performance of fast-growing tropical wood species with minimal compromise to strength. Nonetheless, the method presents trade-offs, while surface charring improves durability and water resistance, it may reduce mechanical strength if over-applied. Future research should investigate longer-term durability, optimize charring depth relative to species anatomy, and expand application scenarios, especially for non-structural or decorative uses in humid tropical environments.

AUTHOR'S DECLARATION

- Conflicts of Interest: None.
- We here by confirm that all the Figures and Tables in the manuscript are ours.
- No animal studies are present in the manuscript.
- No human studies are present in the manuscript.
- No potentially identified images or data are present in the manuscript.

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