

ENHANCED PROPERTIES AND DURABILITY OF RATTAN USING JERNANG, TEAK LEAF EXTRACT, AND RATTAN VINEGAR

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ENHANCED PROPERTIES AND DURABILITY OF RATTAN USING JERNANG, TEAK LEAF EXTRACT, AND RATTAN VINEGAR. Rattan is a non-timber forest product with high export potential and economic value. The use of natural dyes from processing waste and plant materials provides an environmentally friendly alternative for rattan coloring while increasing product value. This study aimed to evaluate rattan processing waste and teak leaves as sources of natural dyes to improve rattan quality and durability. Dyes were extracted using maceration and ultrasound-assisted extraction with water as the solvent and evaluated based on yield and color stability. The selected dye was applied through vacuum impregnation at 50 cmHg for 30 min, followed by pressure impregnation at 7 kgf/cm² for 2 h, using citric acid as a mordant. Treated rattan was evaluated for color change, physical and mechanical properties, and functional groups using Fourier transform infrared spectroscopy (FTIR). The best treatment was coated with rattan vinegar at 25% and 50% (w/v) and tested against dry-wood termites and powder-post beetles. Ultrasound-assisted extraction produced higher yields of 10.64% from rattan processing waste and 15.90% from teak leaves, with greater color stability against ultraviolet exposure and oxidizing agents than maceration. Vacuum-pressure impregnation produced noticeable color changes and generally improved physical and mechanical properties with increasing dye concentration. ED-U-30 showed a 33.85% decrease in ΔE after leaching. ED-U-30 combined with 50% rattan vinegar resulted in the lowest weight losses from dry-wood termites (1.76%) and powder-post beetles (1.25%). The combined application of natural dyes and rattan vinegar improved rattan quality and durability.

Keywords: durability, impregnation, maceration, natural dyes, rattan vinegar, ultrasound-assisted extraction.

PENINGKATAN SIFAT DAN KEAWETAN ROTAN MENGGUNAKAN JERNANG, EKSTRAK DAUN JATI, DAN ASAP CAIR ROTAN. Rotan sebagai hasil hutan bukan kayu yang memiliki potensi ekspor dan nilai ekonomi tinggi. Penggunaan pewarna alami dari limbah pengolahan dan bahan nabati dapat menjadi alternatif pewarnaan yang lebih ramah lingkungan serta meningkatkan nilai produk rotan. Penelitian ini bertujuan mengevaluasi potensi limbah pengolahan jernang dan daun jati sebagai sumber pewarna alami untuk meningkatkan kualitas dan keawetan rotan. Ekstraksi pewarna dilakukan menggunakan metode maserasi dan ultrasound-assisted extraction (UAE) dengan air sebagai pelarut. Ekstrak dievaluasi berdasarkan rendemen dan stabilitas warna. Pewarna terbaik diaplikasikan pada rotan melalui impregnasi vakum pada 50 cmHg selama 30 menit yang dilanjutkan dengan tekanan 7 kgf/cm² selama 2 jam menggunakan asam sitrat sebagai mordant. Rotan hasil impregnasi diuji perubahan warna, sifat fisik dan mekanis, serta gugus fungsi menggunakan Fourier transform infrared spectroscopy (FTIR). Perlakuan terbaik kemudian dilapisi asap cair rotan pada konsentrasi 25% dan 50% (b/v), diuji terhadap rayap kayu kering dan kumbang bubuk kayu. Hasil menunjukkan UAE menghasilkan rendemen lebih tinggi, yaitu 10,64% dari limbah pengolahan jernang dan 15,90% dari daun jati, serta menghasilkan warna yang lebih stabil terhadap ultraviolet dan oksidator dibandingkan maserasi. Impregnasi vakum-tekan menghasilkan perubahan warna yang nyata serta secara umum memperbaiki sifat fisik dan mekanis rotan seiring peningkatan konsentrasi pewarna. Perlakuan ED-U-30 menunjukkan penurunan ΔE sebesar 33,85% setelah pelindian. Kombinasi ED-U-30 dengan asap cair rotan 50% menghasilkan kehilangan bobot terendah, yaitu 1,76% akibat serangan rayap kayu kering serta 1,25% akibat kumbang bubuk kayu. Penggunaan pewarna alami bersama asap cair rotan berpotensi meningkatkan kualitas, nilai, sekaligus keawetan rotan.

Kata kunci: Idasap cair, impregnasi, keawetan, maserasi, pewarna alami, ultrasonikasi.

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I. INTRODUCTION

Rattan is a valuable non-timber forest product with significant potential as a raw material for furniture and handicrafts. The largest producer in the world in terms of rattan production is Indonesia, which contributes about 85% of the world's total production, or 690,000 tons per year (Kemenperin, 2024). Indonesia is home to about 350 rattan species. In relation to the 13 reported rattan genera in the world, there are 10 types that are indigenous to Indonesia, thus making the country among the world's centers of rattan diversity (Jasni et al., 2012). Among these types, mandola rattan (*Calamus oxleyanus*), naturally found in the tropical forests of Sumatra and Kalimantan, is known for its excellent structural qualities. It is noted for its larger diameter, relatively short internode length, smooth texture, and creamy to light brown color (Karipalai et al., 2019). As such, the mandola rattan is a high-grade material that can be effectively used as structures in the manufacture of furniture especially chair, table, and sofa frames (Putri et al., 2016). Despite its usefulness, rattan is viewed as having a dull color (Rowell, 2005) and poor durability (Satiti et al., 2017).

According to Chowdhary (2024), rattan furniture design should also align with color and aesthetics to meet customers' needs. Apart from increasing visual appeal of the product, the coloration is an important stage of the finishing since it adds great market value to the rattan items. Synthetic dyes are primarily used in rattan furniture finishing because they offer bright, durable colors, easy application, and affordable prices (Paryanto et al., 2012). The use of spray finishing and dyeing with synthetic dyes helped Hartanto and Rudyanto (2017) to obtain a wide range of colors. However, there are serious concerns associated with the use of synthetic dyes since they often contain carcinogenic and allergenic substances (Komarawidjaja, 2016). While they were regulated in some industries, they are still widely used in rattan finishing since there is no better alternative yet. Therefore,

researchers have focused on plant-based natural dyes as an environmentally friendly replacement of synthetic dyes.

Natural dyes are mainly derived from roots, bark, leaves, flowers, and plant shells (Yuniati et al., 2024). A promising natural dye source for rattan is jernang, a deep-red resin (dragon blood resin) coating the fruit of rattan species in the genus *Daemonorops*. Jernang has long been used as a natural coloring agent and an active ingredient in medicinal and cosmetic products (Mahlinda et al., 2020; Sari et al., 2022). However, its processing waste (JPW) remains severely underutilized, as it is currently used primarily as fertilizer (Waluyo, 2008). The red color of JPW indicates a high residual content of active resin pigments. Extraction of JPW by decoction using water at a temperature of 96–98 °C still produces jernang in the form of a red extract, with a yield of approximately 5.15% (Emha, 2020). This yield value is considerably lower than that of jernang extract obtained through the traditional processing of *Daemonorops acehensis* Rustiarni fruit by the Acehnese community, which reaches 12.15% (Waluyo, 2013). Redness of jernang is due to the presence of flavonoids, especially nondracorhodin and nondracorubin (Asra et al., 2021). Likewise, teak leaves, considered agricultural waste, have shown potential as sources of natural dye. According to Charoensit et al. (2021), teak leaf extract is composed of anthraquinones, which have different color characteristics such as tectoleafquinone (red), anthracteone (orange) (Lacret et al., 2011), and tectoquinone (yellow) (Bhuyan et al., 2005). It can be seen from the studies that jernang and teak leaves are among the best candidates for natural dye, which can help in decreasing the dependence on rattan.

The pigmented compounds must be extracted from the plant source in order to be able to serve as natural dyes. Some of the methods used for extracting the pigment compounds from the teak leaves and jernang include decoction and boiling (Emha, 2020; Wiyono and Kartikawati, 2017). The process

involves subjecting the materials to heat at a temperature of 96-98 °C, in order to accelerate the dissolution of the water-soluble compounds. While traditional methods of extracting compounds from teak leaves and jernang have proven to be effective in many instances, exposure to extremely high temperatures leads to thermal degradation of compounds such as anthocyanins and flavonoids. Besides, traditional techniques require long extraction periods and a considerable amount of solvents. In addition, traditional extraction methods pose the risk of thermal degradation of thermolabile compounds (Azizi et al., 2023). To avoid heat-induced degradation, maceration can be used at room temperature, although it requires long extraction periods, filtration, and evaporation. Maceration is easy, inexpensive, and appropriate for thermolabile compounds because it does not use any heat (Ghozali et al., 2023). As an alternative, ultrasound-assisted extraction (UAE) provides an efficient, eco-friendly method in which the use of ultrasonic waves generates. The yield pattern derived using UAE has been observed to be similar to the results reported by Sukandar et al. (2022). Nonetheless, there have been no studies about the integration of processes of natural-dye extraction, rattan dyeing, and preservation after that, despite individual study conducted on these areas. Such aspects have been individually studied in several recent international researches. The research performed by Vespignani et al. (2023) was related to wood dyeing using environmentally friendly technology. In contrast, Lee et al. (2022) focused on using pyroligneous acid for wood preservation through vacuum-pressure impregnation. However, no research has examined the use of these three technologies together.

Natural dyes have the potential to improve the appearance of rattan, but the problem here is the inability of natural dyes to hold their colors since the colors are easily lost (Vespignani et al., 2023). In order to solve this problem, it is necessary to use a mordant such as citric acid, which will react with -OH groups in the cellulose to form covalent

bonds, hence increasing the bonding ability of the substrate and dye (Bogoriani, 2011). The use of the citric acid mixture was found to be more effective in maintaining its color for ten washing cycles in the color fastness test as explained by Dafiq et al. (2025). This issue can be addressed with faster methods such as vacuum impregnation (Augustina et al. 2024), which significantly reduces dyeing time and improves effectiveness. According to the research carried out by Nguyen et al. (2018), the vacuum-pressure method proved to have an impressive impact on dyeing, penetration, and color changes, especially for the samples dyed at 1000 kPa with pressure time of 120 minutes. Besides color fastness, rattan is very vulnerable to biodeterioration from fungi and drywood beetles. The novelty of this study is the integration of three sequential treatment stages in a single rattan system: (1) UAE extraction of natural dyes from jernang processing waste and teak leaves, (2) combination of natural dyes with citric-acid-assisted vacuum-pressure impregnation of rattan for coloration, and (3) rattan-vinegar post-preservation for protection against drywood termites and powderpost beetles. Therefore, a preservation treatment is essential to enhance durability (Hamdi, 2012). One promising approach is applying rattan vinegar as a coating material, as it contains phenolic compounds and tar that are toxic to insects (Hossain et al. 2013), thereby offering potential to improve rattan resistance to biodeteriorating agents. The low concentration of liquid smoke used may cause low preservative retention in wood; therefore, Fakkar et al. (2023) determined that the minimum percentage of liquid smoke should be around 25%. Therefore, this study aimed to compare maceration and UAE to identify an efficient and stable natural-dye extraction method, characterize rattan after vacuum-pressure dye impregnation, and evaluate changes in color, physical and mechanical properties, and functional groups. The study also assessed the effects of rattan-vinegar post-treatment on the resistance of the optimally dyed rattan to drywood termites and powderpost beetles.

II. MATERIAL AND METHOD

A. Materials

The research was conducted from February 2024 to March 2025. Extraction and durability testing of rattan were conducted at the Non-Timber Forest Products Laboratory and the Termite Laboratory, Department of Forest Products, Faculty of Forestry and Environment, IPB University. Other experiments were performed at the Integrated Laboratory of Bioproducts (ILaB), Research Center for Biomass and Bioproducts, National Research and Innovation Agency (BRIN), Cibinong, Bogor. Mandola rattan (*Calamus oxleyanus*) sourced from Cirebon, Indonesia, with a length of 5 cm, and oven-dried at 103 ± 2 °C for 24 h before use. Teak leaves (young leaves) were sourced from the National Research and Innovation Agency (BRIN), Cibinong, Bogor, Indonesia, and the jernang processing waste (JPW) was sourced from Aceh, Indonesia. All chemicals used in this study were commercially available. Citric acid was obtained from a Merck distributor, and distilled water was obtained from a commercial supplier. Rattan vinegar was obtained from the Integrated Forest Products Laboratory, Bogor, Indonesia.

B. Methods

1. Raw Material Preparation

The jernang processing waste (JPW) was ground into powder with a 40-60 mesh particle size. Teak leaves (D) were cut into small pieces. The moisture content of the powder was determined by weighing approximately 2 g (initial weight), drying it in an oven at 103 ± 2 °C for 24 h until a constant oven-dry weight was reached, and repeating the process three times (triplicate analysis, $n=3$).

2. Natural Dye Extraction, Extract Color Stability, and Rattan Color Evaluation

Extraction was done using maceration and ultrasound-assisted extraction (UAE) with water as the solvent. Maceration was performed at room temperature for 24 h, while UAE

was conducted at 40 Hz for 30 min. For each extraction, 300 g of sample (JPW powder or teak leaves with known moisture content of 19.64% and 8.64%) was mixed with 1500 mL of water, and the process was repeated three times. The filtrate was then evaporated at 40–60 °C using a rotary evaporator. Two milliliters of filtrate were utilized to calculate the concentration of the extract through the drying process in 103 ± 2 °C, while the rest of the solution was dried in 40–60 °C and acted as a source of the natural dye material. Extraction yield was calculated using the calculation of Kusuma & Aprileili (2022). This yielded four different extracts, as outlined in Table 1 below.

Table 1. Sample code and description of the extract

Codes	Descriptions
EJ-M	Jernang waste with the maceration method
EJ-U	Jernang waste with the UAE method
ED-M	Teak leaves with the maceration method
ED-U	Teak leaves with the UAE method

The color stability of the extracts was analyzed in triplicate ($n=3$) by UV-Visible Spectrophotometer using the method of Kurniati et al. (2012), in a wavelength range of 200-600 nm. The extract solutions were made by dissolving 30 g of extract in 150 mL of distilled water. Color stability was analyzed according to the absorbance variation caused by certain conditions such as sunlight exposure, pH level, and oxidizing agents. In the sunlight condition, 10 mL of extract solution was put in a test tube and exposed to direct sunlight for 3 hours; absorbance was taken every hour. In the pH condition, the extract solutions were varied by adding buffer to get pH 2, 3, 5, and 8, then the absorbance of each solution was taken. In oxidizing agent condition, 10 mL of solution was added to 1 mL of 30% H₂O₂. The absorbance was recorded at 0 h, 3 h, 4

h, and 5 h of oxidant exposure. Based on the extraction yield and color stability analysis, the most appropriate extract from each source was selected.

3. Rattan Impregnation

The natural dyes were prepared from the EJ and ED extracts based on extraction yield and color stability. The concentrations of dyes were determined by conducting some initial experiments prior to the actual experiment. Concentrations below 15% (w/v) produced insufficient color intensity on the rattan surface, whereas concentrations above 30% (w/v) produced saturation without meaningful improvements in color depth or stability. The final design therefore used two factors: extract type (jernang processing-waste extract and teak leaf extract) and extract concentration (15% and 30% w/v), with 5% citric acid (w/v) added as a mordant (Table 2). Rattan samples, 5 cm long with an average diameter of 2 cm, were dried at 103 ± 2 °C until a constant oven-dry weight (W1) was reached. The samples were immersed in the natural-dye impregnation solution and placed in an impregnation chamber under vacuum (50 cmHg for 30 min), followed by pressure (7 kgf/cm² for 2 h). After impregnation, the samples were dried again at 103 ± 2 °C until a constant oven-dry weight (W2) was achieved. The impregnation process was conducted at room temperature (approximately 25–27 °C).

Rattan Color Measurement and Leaching Test

Rattan color was measured using a color reader (Konica Minolta CR-10+) before and after the leaching test to evaluate color stability. The leaching test was performed by immersing

the samples in hot water and heating them in a water bath at 40 °C for 3 h. After treatment, the samples were drained and dried at room temperature. Color change was evaluated by comparing the samples' L*, a*, and b* values before and after soaking, following the method of Muflihati et al. (2014).

4. Physical and Mechanical Properties of Rattan

The samples were evaluated for physical and mechanical properties, including moisture content, density, natural-dye uptake as weight percent gain (WPG), bulking coefficient (BC), and liquid uptake (LU), and hardness, following Augustina et al. (2024). A total of 10 rattan samples were used for each treatment.

5. FTIR Testing

The functional groups of rattan were analyzed using Fourier Transform Infrared Spectroscopy (FTIR) to identify potential chemical changes after treatment. The spectra were recorded in the mid-infrared region from 4000 to 400 cm⁻¹, averaging 32 scans at a resolution of 4 cm⁻¹ to ensure a reliable signal-to-noise ratio (Solihat et al., 2022).

6. Durability Testing of Rattan

To determine the optimal natural dye formulation for subsequent durability testing, a multi-criteria decision scoring matrix was established based on physical and mechanical performance metrics. Six target parameters were evaluated: moisture content, density, weight percent gain (WPG), bulking coefficient (BC), liquid uptake (LU), and hardness. Based on the characterization results of rattan impregnated with the best formula using the scoring method—showing superior physical and mechanical properties—the samples

Table 2. Sample code and description of rattan impregnation

Codes	Descriptions
K	Rattan untreated/no coloration
EJ-U-15	Coloration of rattan with 15% concentration of jernang waste extract
EJ-U-30	Coloration of rattan with 30% concentration of jernang waste extract
ED-U-15	Coloration of rattan with 15% concentration of teak leaves extract
ED-U-30	Coloration of rattan with 30% concentration of teak leaves extract

were subsequently subjected to preservation treatment using rattan-vinegar (RV) solutions at concentrations of 25% and 50% (w/v). Durability testing against drywood termites was conducted over 12 weeks following SNI 7207-2014, with a slight modification in which the termites were placed not on the longest surface of the rattan but instead on one of its ends (BSN 2014), while resistance to powderpost beetles was evaluated over three months, referring to the method of Febrianto et al. (2014). The same six criteria and 1–3 scoring scale were applied consistently to all formulations as a study-specific comparative decision matrix; no independent external validation of the scoring matrix was performed. Both drywood-termite and powderpost-beetle durability assessments were performed under controlled laboratory conditions. For durability testing, K denotes untreated rattan; ED-U-30 and EJ-U-30 denote rattan colored with 30% teak-leaf and jernang-waste extracts obtained by UAE, respectively. RV denotes rattan vinegar, and RV25 and RV50 indicate post-treatment with 25% and 50% (w/v) rattan-vinegar solutions. Thus, ED-U-30+RV25, EJ-U-30+RV25, ED-U-30+RV50, and EJ-U-30+RV50 denote the corresponding combined coloration and rattan-vinegar treatment.

C. Analysis

The extract yield and color characteristics were statistically analyzed using a two-factor completely randomized design (CRD)

(Rahmawati and Erina, 2020), with raw material type (jernang/J and teak leaves/D) and extraction method (maceration and UAE) as factors. Extract color stability was analyzed using a three-factor CRD for each stability test, with raw material type (jernang processing waste and teak leaves), extraction method (maceration and UAE), and test level/exposure period as factors. The third factor comprised four levels for each test: pH 2, 3, 5, and 8; UV exposure at 0, 1, 2, and 3 h; and oxidant exposure at 0, 3, 4, and 5 h. The characteristics of rattan impregnated with natural dyes—including color, physical, and mechanical properties—were analyzed using a one-factor CRD, with natural dye formulation as the factor. Statistical significance was evaluated at $p < 0.05$. Before the analysis of variance (ANOVA), the assumptions of normality and homogeneity of variance were tested. Where significant main or interaction effects were detected ($p < 0.05$), Duncan's Multiple Range Test (DMRT) was conducted for post-hoc pairwise comparisons. The optimal dyeing formulation for rattan was determined using a scoring method based on moisture content, density, and natural dye uptake (WPG, BC, and LU). A score of 1 indicated poor performance, 2 indicated good performance, and 3 indicated very good performance. The best formula was determined from the total points. Data on rattan durability against termites and powder-

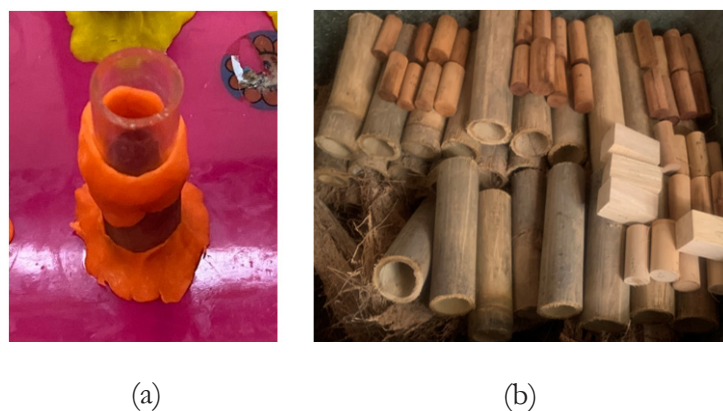


Figure 1. Durability-test setup: (a) funnel placement on one end of the rattan specimen for drywood-termite testing; (b) rattan samples placed in bamboo culms infested with powderpost beetles for powderpost-beetle testing

post beetles were statistically analyzed using a one-factor Completely Randomized Design (CRD), with treatment formulation as the factor and seven levels: K, ED-U-30, EJ-U-30, ED-U-30+RV25, EJ-U-30+RV25, ED-U-30+RV50, and EJ-U-30+RV50. All statistical analyses were conducted using RStudio (Lusiana & Mahmudi 2021), while FTIR results were analyzed descriptively. Raw-material moisture content, extraction yield, extract color stability, and extract color characterization were determined in triplicate ($n = 3$), whereas physical, mechanical, and impregnation-property measurements used 10 rattan specimens per treatment. Before ANOVA and DMRT, normality and homogeneity of variance were tested, and the data met these assumptions.

III. RESULT AND DISCUSSION

A. Appearance, Yield, and Color Stability of Natural Dye Extracts

The plant source and extraction method significantly influenced the appearance, yield, and color stability of the natural dye extracts. Sambodo et al. (2022) reported a notably high extract yield of 33.09% (w/w) from teak leaves (*Tectona grandis*), attributed to the thin leaf structure and the efficient dissolution of bioactive compounds via 70% ethanol maceration. In contrast, Sari and Handika (2020) observed that dragon's blood resin extracted from *Daemonorops draco* had a comparatively low maximum yield of 20.02% in 100% ethanol extraction because of its more compact resin structure and less porous tissues. In addition to this, results by Sulaiman et al. (2020) also demonstrate that small-sized jernang fruits and the use of more powerful solvents (ethanol-chloroform) increase extract yield.

Interaction between raw materials and extraction methods towards the yield of the extract was highly significant ($p < 0.05$). Duncan's test showed that there was a highly significant difference between the four extracts derived from the different raw materials with

different extraction methods. The maximum extract yield was recorded by ED-U, followed by ED-M, EJ-U, and EJ-M (Table 3). The results show that UAE is a more efficient extraction technique than maceration for both raw materials. Familasari et al. (2023) also noted the same trend in their study. This is due to the cavitation energy of UAE, which creates micro-solvent bubbles that break down the cell walls (Budiastra et al., 2020). The ultrasonic waves lead to the generation of bubbles followed by implosive collapse in the liquid solvent, resulting in the creation of microjets and high-pressure shearing force. The force helps in breaking the rigid lignocellulosic cell walls of teak leaves and jernang waste, enabling solvent penetration and rapid mass transfer of intracellular polyphenols without the need for a long-time heating process. As a result, heat-labile chromophores like flavonoids and anthocyanins are successfully extracted without any damage due to heat, maintaining their chemical stability and resistance against UV and photochemical oxidation. This explanation aligns well with the results of Tiwari (2015) and Linares and Rojas (2022), who found that cavitation helps prevent oxidation of thermolabile pigments during green extraction. This explanation supports the recently published international UAE studies which reported that acoustic cavitation enhances solvent penetration and effective diffusivity, facilitates mass transfer of pigments, and may help in avoiding prolonged thermal exposure (Linares and Rojas, 2022; Thakur et al., 2022). The EJ-M yield obtained in this study (Table 3) was higher than that reported by Emha (2020) using the decoction method (5.15%). The lower yield from decoction is likely due to the high temperatures (96–98 °C) used, which can damage or volatilize thermolabile compounds (Anwar et al., 2025), thereby reducing extract yield (Asendy et al., 2018). Nonetheless, the yields in this study were still lower than that of rattan fruit extract obtained by traditional extraction methods (12.15%) (Waluyo, 2013). The ED-U yield achieved here using UAE with water as the solvent was 15.90%, lower than

the 19.69% reported by Budiman et al. (2020) using the same raw material and method but with ethanol as the solvent. This difference highlights the strong influence of solvent type on extraction yield (Satriawan and Wijaya, 2023).

The interaction between the raw material and the extraction method influenced the L^* , a^* , and b^* values ($p < 0.05$). Based on Duncan's Multiple Range Test, there were no significant differences in L^* , a^* , and b^* values between jernang extracts obtained via maceration (EJ-M) and those obtained via UAE (EJ-U); however, both differed significantly from teak leaf

extracts obtained via either maceration (ED-M) or UAE (ED-U) (Table 4). The L^* values of EJ ranged from 17.31 to 18.88, indicating low lightness, whereas ED showed higher L^* values of 34.42 to 36.89. All a^* values were positive, confirming a red component in both extracts; the red component was greater for ED (35.93 to 39.05) than for EJ (17.21 to 17.27). Positive b^* values indicated a yellow component, which was also greater for ED (38.09 to 38.26) than for EJ (17.11 to 17.92). Higher positive L^* values indicate greater lightness (Muflihati et al., 2014). Because Table 4 reports the absolute CIELAB coordinates of independent extract samples

Table 3. Yield of natural dye extracts

Extraction Methods	Raw Materials	
	Jernang extract yield (%)	Teak leaf extract yield (%)
Maceration	8.81±0.25 ^a	12.04±0.51 ^b
UAE	10.64±0.67 ^{ab}	15.90±0.17 ^c

Notes: Values are reported as mean $\pm$ SD. Different lowercase superscript letters indicate significant differences according to Duncan's Multiple Range Test (DMRT) at $\alpha = 0.05$.

Table 4. CIELAB color characteristics of natural dye extracts

Color characterization of Extracts	Jernang Extract		Teak leaves Extract	
	Maceration	UAE	Maceration	UAE
Name of Color	<i>Maroon</i>	<i>Maroon</i>	<i>Dark Red</i>	<i>Fire Brick</i>
L^*	17.31±0.89 ^a	18.88±0.73 ^a	34.42±0.59 ^b	36.89±0.56 ^b
a^*	17.27±2.79 ^a	17.21±1.81 ^a	39.05±0.39 ^b	35.93±1.53 ^b
b^*	17.11±0.27 ^a	17.92±0.40 ^a	38.09±0.15 ^b	38.26±1.25 ^b

Notes: Values are reported as mean $\pm$ SD. Different lowercase superscript letters within the same row indicate significant differences according to Duncan's Multiple Range Test (DMRT) at $\alpha = 0.05$.

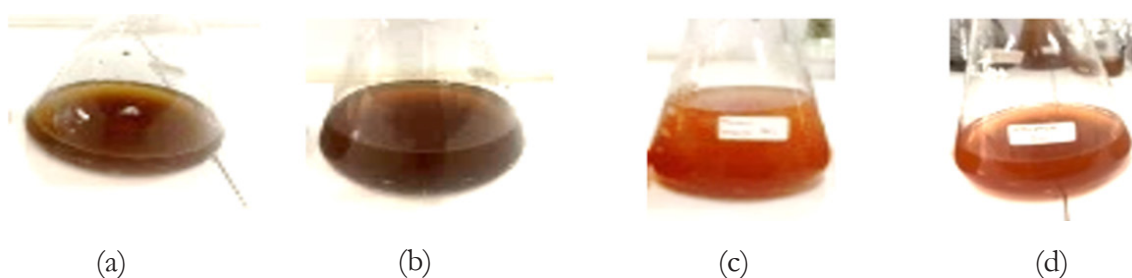


Figure 2. Appearance of natural dye extracts: (a) macerated jernang processing-waste extract; (b) UAE jernang processing-waste extract; (c) macerated teak leaf extract; (d) UAE teak leaf extract.

without a predefined reference color, ΔE was not calculated for this extract-comparison table. Overall color change (ΔE) was calculated for the rattan before and after leaching and is reported in Table 6. The similar CIELAB profiles obtained by maceration and UAE indicate that the mild UAE conditions did not cause a major shift in extract color (Figure 2).

B. Color Stability

Color stability and intensity are important factors that determine a product's attractiveness and quality, as they not only enhance visual appeal but also increase consumer acceptance and market competitiveness. In natural-based materials such as rattan and wood products, inconsistent coloration may reduce perceived quality, whereas durable and vibrant hues indicate better performance and durability of the dyeing treatment (Loppies et al., 2020). The analysis of variance showed that neither the interaction between extract type and pH value nor the effect of each factor significantly influenced the absorbance (Figure 3). The extracts contained flavonoid and anthocyanin compounds, which are more stable under acidic conditions (Simanjuntak et al., 2014).

Observations of color stability in jernang waste extract and teak leaf extract revealed that ultraviolet exposure caused pigment degradation in the maceration method, as indicated by decreasing absorbance, fading color, and clearer appearance with more prolonged exposure. The three-factor ANOVA showed a significant interaction among raw material type, extraction method, and exposure period under UV exposure ($p < 0.05$). DMRT was therefore applied to the 16 raw-material $\times$ extraction-method $\times$ exposure-period combinations. The macerated extracts showed time-dependent changes in absorbance, with ED-M showing the clearest decline; in contrast, EJ-U and ED-U retained the same DMRT group (d) across all exposure times, indicating no significant change within the UAE extracts during the 3-h UV test (Figure 4). Rundubelo et al. (2019) also reported that protracted ultraviolet exposure increases pigment degradation, decreases absorbance, and causes color fading due to the decomposition of anthocyanin compounds.

Degradation by oxidizing agents (Figure 5) further showed that H_2O_2 accelerated pigment photodegradation, as its reactive groups broke down pigment molecules, leading to

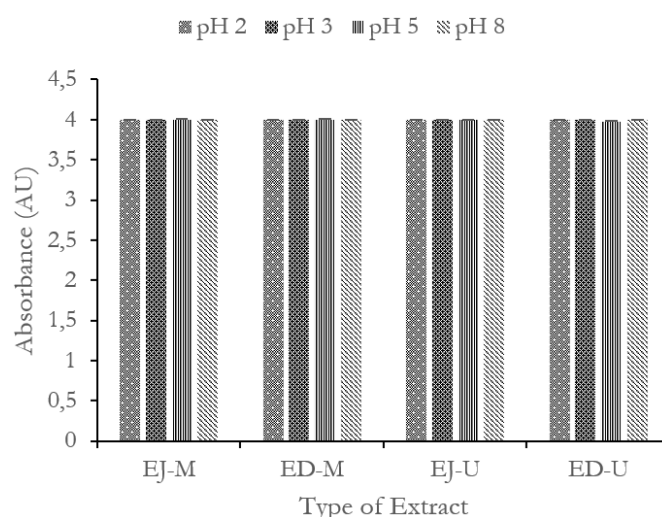


Figure 3. Effect of pH on the color stability of the natural dye extracts base on absorbance. EJ-M = jernang extract obtained by maceration; ED-M = teak leaf extract obtained by maceration; EJ-U = jernang extract obtained by UAE; ED-U = teak leaf extract obtained by UAE.

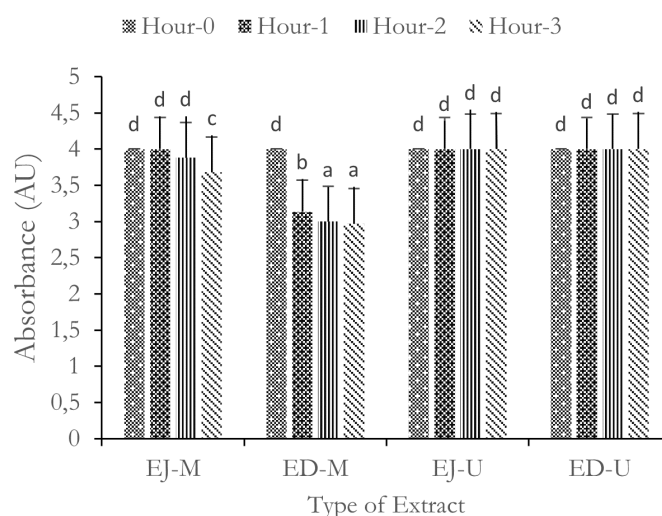


Figure 4. Effect of ultraviolet exposure on the color stability of the natural dye extracts base on absorbance. EJ-M = jernang extract obtained by maceration; ED-M = teak leaf extract obtained by maceration; EJ-U = jernang extract obtained by UAE; ED-U = teak leaf extract obtained by UAE. Different letters above the bars indicate significant differences according to Duncan's multiple range test at the 5% significance level.

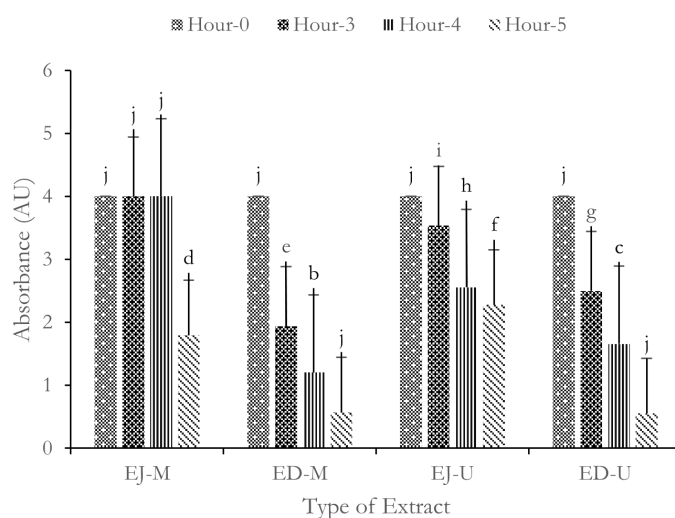


Figure 5. Effect of oxidant exposure on the color stability of the natural dye extracts base on absorbance. EJ-M = jernang extract obtained by maceration; ED-M = teak leaf extract obtained by maceration; EJ-U = jernang extract obtained by UAE; ED-U = teak leaf extract obtained by UAE. Different letters above the bars indicate significant differences according to Duncan's multiple range test at the 5% significance level.

discoloration or fading (Rosamah et al., 2013). The three-factor ANOVA likewise showed a significant interaction among raw material type, extraction method, and exposure period under oxidant exposure ($p < 0.05$). DMRT across the 16 raw-material $\times$ extraction-method $\times$ exposure-period combinations

showed significant time-dependent changes in absorbance, as indicated by changes in statistical groupings across exposure times (Figure 5). Based on yield and color stability, the UAE method was identified as the most effective extraction technique for producing EJ and ED for natural dye formulation. According

to Linares and Rojas (2022), in anthocyanin extraction, the UAE method showed superior features, including more efficient solvent use (acidified water and ethanol), pH stability, and optimal solvent viscosity to preserve pigment mass

C. Physical and Mechanical Properties of Dyed Rattan

The physical and mechanical properties of impregnated rattan, including moisture content, density, natural dye absorption (WPG, LU, BC), and hardness, are summarized in Table 5. Analysis of variance (ANOVA) showed that the impregnation treatment did not significantly affect the moisture content (MC) of the rattan ($p > 0.05$). The moisture content of rattan ranges from 9.77% to 12.52%, which is within the acceptable limit for rattan ($\leq 14\%$) as specified by SNI 7208 (2017). The results also indicated that the density of impregnated rattan increased compared to the control and rose with higher extract concentrations (Table 5).

Analysis of variance (ANOVA) showed that the impregnation treatment had no significant effect ($p > 0.05$) on the density of the rattan, resulting in no requirement for further Duncan's multiple range post-hoc testing (Table 5). Nevertheless, a numerical increase in bulk density (from 0.49 g/cm³ in the control to 0.75–0.86 g/cm³ in impregnated samples). A density value above 0.25 g/cm³ indicates that rattan is suitable for industrial applications

(Yang et al., 2020; Hadi et al., 2013).

Analysis of variance (ANOVA) test showed that the impregnation process had a significant effect on the WPG, LU, and BC of rattan ($p < 0.05$). Duncan's Multiple Range Test (DMRT) analysis (Table 5) showed that the WPG of ED-U-15% ($51.10 \pm 2.91\%$) was significantly smaller compared to EJ-U-15% ($67.25 \pm 6.14\%$) and EJ-U-30% ($78.53 \pm 11.50\%$), whereas ED-U-30% had the highest WPG value ($97.15 \pm 19.61\%$) and differed significantly from other treatments. The LU of ED-U-15% ($72.07 \pm 13.06\%$) was significantly smaller compared to EJ-U-15% ($89.63 \pm 12.50\%$), EJ-U-30% ($93.67 \pm 8.13\%$) and ED-U-30% ($97.93 \pm 16.94\%$). There was no significant difference between EJ-U-15%, EJ-U-30%, and ED-U-30% LU values. Also, the BC of ED-U-15% ($5.26 \pm 1.56\%$) was significantly smaller compared to EJ-U-30% ($10.04 \pm 2.68\%$) and ED-U-30% ($10.75 \pm 7.10\%$). No significant difference was observed between EJ-U-30% and ED-U-30%. However, there was no significant difference between EJ-U-15% ($6.68 \pm 2.39\%$) BC and former. Increase in WPG values was accompanied by increase in LU and BC, especially in 30% extract concentration. Higher values of WPG, LU and BC show the fact that more amount of the impregnating solution had been absorbed into the structure of the rattan (Prihatini et al., 2023). High value of WPG found in ED-U-30% suggests that more quantity of the extract along with the

Table 5. Physical and mechanical properties of dyed rattan.

Treatments	Moisture Content (%)	Density (g/cm ³)	WPG (%)	LU (%)	BC (%)	Hardness (kgf/mm ²)
K	11.20 ± 0.40	0.49 ± 0.08	-	-	-	2.03 ± 0.40^b
EJ-U-15%	9.77 ± 4.41	0.75 ± 0.10	67.25 ± 6.14^b	89.63 ± 12.5^b	6.68 ± 2.39^{ab}	2.97 ± 0.78^{ab}
EJ-U-30%	12.25 ± 3.80	0.86 ± 0.11	78.53 ± 11.5^b	93.67 ± 8.13^b	10.04 ± 2.68^b	4.12 ± 0.34^a
ED-U-15%	9.90 ± 4.56	0.76 ± 0.18	51.10 ± 2.91^a	72.07 ± 13.06^a	5.26 ± 1.56^a	3.25 ± 1.33^{ab}
ED-U-30%	12.52 ± 4.82	0.81 ± 0.12	97.15 ± 19.61^c	97.93 ± 16.94^b	10.75 ± 7.10^b	3.81 ± 0.24^a

Notes: Values are reported as mean $\pm$ SD. Different lowercase superscript letters within the same column indicate significant differences according to Duncan's Multiple Range Test (DMRT) at $\alpha = 0.05$.

material formed due to reaction with citric acid has been deposited into the rattan matrix. At an applied pressure of 7 kgf/cm², the aqueous dye-mordant solution penetrated the porous vascular matrix and the lumen space. After the drying process in the oven, the deposited extract and the cross-linked citric acid have remained inside the lumen space and microfibrillar spaces.

The ANOVA results showed that impregnation significantly affects rattan hardness ($p < 0.05$). From the analysis using DMRT (Table 5), the high degree of hardness noted at high levels of the extract could be attributed to deposition of more extracts and mordant related materials. Impregnation allows penetration of the dye-mordant aqueous solution through the cell structure. In the course of drying the material in the oven, the deposits could stay in the cell walls and lumen, resulting in mass deposition. Such a process would be consistent with the WPG and BC increase and possibly increase the rattan resistance to localized deformation during indentation. This phenomenon was also observed in modified wood, where vacuum pressure impregnation facilitates modifier absorption

and deposition into both cell lumens and cell wall sections, thereby increasing mechanical resistance (Augustina et al., 2023; Augustina et al., 2024; Wahyuningtyas & Dirna, 2025). Such results could also be consistent with the extractive deposition and crosslinking effects resulting in cell wall densification and hardness improvement (Malik & Ozarska, 2019).

D. Color Change and Leaching of Dyed Rattan

Using EJ and ED extracted by UAE, the dyeing process changed untreated rattan from pale taupe to dark gold, saddle, coconut, and russet, depending on treatment. After the hot-water fastness test, the corresponding colors changed to camel, deer, light taupe, and taupe (Table 6). The Δa^* and Δb^* values differed significantly among treatments ($p < 0.05$), whereas the changes in lightness (ΔL^*) and overall color difference (ΔE) were not statistically significant. Before leaching, the overall color differences (ΔE) were 19.16 for EJ-U-15, 26.53 for EJ-U-30, 22.77 for ED-U-15, and 23.40 for ED-U-30. After leaching, ΔE decreased to 8.65, 12.96, 8.94,

Table 6.. Color change in dyed rattan before and after leaching.

Sample	Color	CIE Lab				Rattan
		ΔL	Δa	Δb	ΔE	
K	Pale taupe	—	—	—	—	
EJ-U-15	Dark gold	-13.54 ± 5.81	6.77 ± 1.82^b	11.26 ± 0.41^b	19.16 ± 4.51	
EJ-U-30	Saddle	-12.87 ± 5.47	13.93 ± 3.23^a	17.84 ± 1.05^a	26.53 ± 1.51	
ED-U-15	Coconut	-13.99 ± 10.27	13.14 ± 1.46^a	11.03 ± 4.54^b	22.77 ± 9.27	
ED-U-30	Russet	-15.74 ± 4.61	14.25 ± 3.01^a	6.23 ± 3.73^b	23.40 ± 1.34	
EJ-U-15 (Leaching)	Camel	-5.87 ± 4.71	3.48 ± 1.35^a	4.46 ± 1.97^{ab}	8.65 ± 3.91	
EJ-U-30 (Leaching)	Deer	-7.63 ± 6.67	7.83 ± 0.96^a	5.38 ± 1.83^a	12.96 ± 4.41	
ED-U-15 (Leaching)	Light taupe	-5.20 ± 4.58	5.89 ± 1.54^{ab}	2.44 ± 0.92^{ab}	8.94 ± 2.44	
ED-U-30 (Leaching)	Taupe	-13.07 ± 3.10	8.07 ± 1.56^a	1.16 ± 2.01^b	15.48 ± 3.50	

Notes: Values are reported as mean $\pm$ SD. Different lowercase superscript letters within the same column indicate significant differences according to Duncan's Multiple Range Test (DMRT) at $\alpha = 0.05$.

and 15.48, respectively. ED-U-30 showed the smallest proportional decrease in ΔE (33.85%), indicating the greatest color retention among the tested formulations. Natural dyes such as flavonoids and anthocyanins can penetrate rattan pores and interact through hydrogen bonding between hydroxyl groups and dye functional groups (Vespignani et al., 2023). The color data, together with the FTIR results (Figure 6), support retention of the dye-rattan interaction after the hot-water leaching test.

From FTIR analysis (Figure 6), it was observed that there are changes in the absorption bands at various wavenumber values showing interaction between natural dyes and rattan material. For the FTIR spectrum of the control sample, some peaks were identified such as -OH group at 3333.96 cm^{-1} , which is involved in hydrogen bonding with dyes, an aromatic C=C stretch for lignin at 1593.61 cm^{-1} , alcohol and ether groups present in hemicellulose and cellulose at 1237.18 cm^{-1} and 1032.66 cm^{-1} , respectively; and a peak at 559.08 cm^{-1} in the fingerprint region of the spectrum. On coloring of the rattan by using a 15% concentration of teak leaf extract, changes have been observed in O-H and C=O absorption bands, such as the formation

of a hydrogen bond at 3330.36 cm^{-1} and an increased carbonyl absorption band at 1712.14 cm^{-1} . With increasing dye concentration up to 30%, more intense peaks of hydroxyl (3347.03 cm^{-1}) and carbonyl (1714.85 cm^{-1}) bands were observed. The similar pattern was identified for jernang extract with hydrogen bonds recorded at 3336.49 cm^{-1} (15%) and 3335.92 cm^{-1} (30%), as well as carbonyls at 1720.35 cm^{-1} and 1721.84 cm^{-1} . The use of citric acid as a mordant is confirmed by the presence of carbonyl peaks around 1710-1720 cm^{-1} in the samples processed with this acid. The increase in the intensity of C=O vibrations in this range is explained by esterification of carboxyl groups of citric acid with hydroxyl groups of the lignocellulosic material. As a result, citric acid can act as a polycarboxylic crosslinker and provide additional interactions between the lignocellulosic substrate and phenolic molecules of dyes. Indeed, recent research conducted on an international level and dealing with the problem of dyeing fabrics with natural dye describes citric acid as a crosslinking agent promoting esterification and contributing to improved retention and durability of natural dye (Darmawan et al., 2024; Dai et al., 2023).

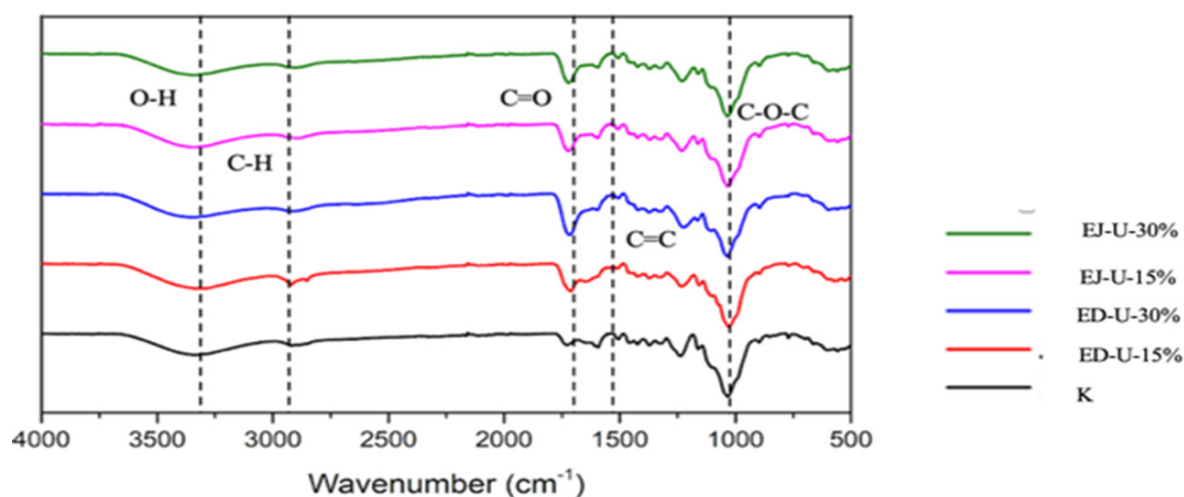


Figure 6. FTIR observation of rattan coloration using natural dyes in each treatment applied. Spectra are shown for untreated rattan (K) and rattan dyed with 15% and 30% jernang or teak leaf extracts.

E. Durability of Rattan Coloration and Rattan's Vinegar Coating

ANOVA using the one-factor CRD showed that treatment formulation significantly affected drywood-termite weight loss, drywood-termite mortality, and powderpost-beetle weight loss ($p < 0.05$). DMRT was then applied across the seven treatment formulations in Table 7. For drywood-termite weight loss, ED-U-30+RV50 had the lowest mean ($1.76 \pm 1.40\%$) and differed from the control, while several other treated formulations shared overlapping DMRT groups. For termite mortality, all RV-treated formulations were in the same statistical group (a), whereas the extract-only formulations were in group b and the control was in group c. For powderpost-beetle weight loss, RV-treated formulations had lower values than the control, and RV25 and RV50 formulations frequently shared overlapping statistical groups. Thus, the one-factor analysis compares the complete treatment formulations; rattan-vinegar concentration was not analyzed as an independent factor (Table 7). The relatively lower weight loss in the treated samples indicates that the natural dye extracts, as well as the vinegar, played a key role in making the

wood resistant to drywood termites. This is because the protective mechanism could have resulted from the deposition of extractives in the rattan, thereby making it less favorable to termites. The use of vinegar in the treatments may also have been important for this reason. However, the lack of a significant difference in some treatment combinations suggests that increasing the amount of vinegar did not necessarily increase the wood's resistance to termites. Similar results were obtained from powderpost beetle exposure, with all treated samples exhibiting less weight loss than the control sample. The lowest weight loss was recorded in ED-U-30+RV50 ($1.25 \pm 0.81\%$) and EJ-U-30+RV50 ($1.27 \pm 0.55\%$). All these treatments belonged to the same statistical group, indicating no significant difference in their protective effects against powderpost beetles. The fact that the weight loss in the treated rattan is much lower than in the control sample means that it exhibits better resistance to powderpost beetle infestation. The lower weight loss of treated rattan indicates greater resistance to drywood termite attack and greater preservative effectiveness (Sumariyanto et al., 2013).

Table 7. Durability of dyed rattan with rattan-vinegar coating against drywood termites and powderpost beetles.

Treatment Code	Drywood Termite Weight Loss (%)	Drywood Termite Mortality (%)	Powderpost Beetles Weight Loss (%)
K	6.82 ± 0.15^a	44 ± 3.46^c	6.93 ± 1.79^a
ED-U-30	3.35 ± 1.02^{bc}	54 ± 2.00^b	4.06 ± 1.54^b
EJ-U-30	3.94 ± 1.65^b	51.33 ± 2.30^b	3.50 ± 0.69^{bc}
ED-U-30+RV25	2.61 ± 0.82^{bc}	81.33 ± 1.15^a	1.49 ± 0.53^{cd}
EJ-U-30+RV25	2.93 ± 0.40^{bc}	81.33 ± 2.30^a	1.56 ± 1.13^{cd}
ED-U-30+RV50	1.76 ± 1.40^c	82.67 ± 4.16^a	1.25 ± 0.81^d
EJ-U-30+RV50	2.45 ± 0.52^{bc}	84.67 ± 3.05^a	1.27 ± 0.55^d

Notes: K = untreated rattan; RV = rattan vinegar; RV25 and RV50 denote 25% and 50% (w/v) rattan-vinegar post-treatments, respectively. Values are reported as mean $\pm$ SD. Different lowercase superscript letters within the same column indicate significant differences according to Duncan's Multiple Range Test (DMRT) at $\alpha = 0.05$.

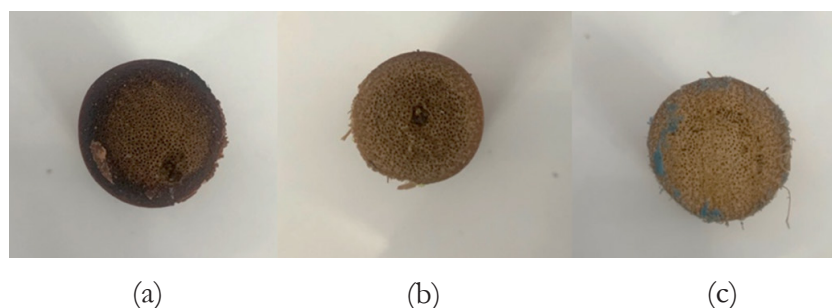


Figure 7. The effect of rattan's vinegar on drywood termites (a) control of rattan, (b) rattan with extract, (c) rattan with extract and rattan's vinegar.

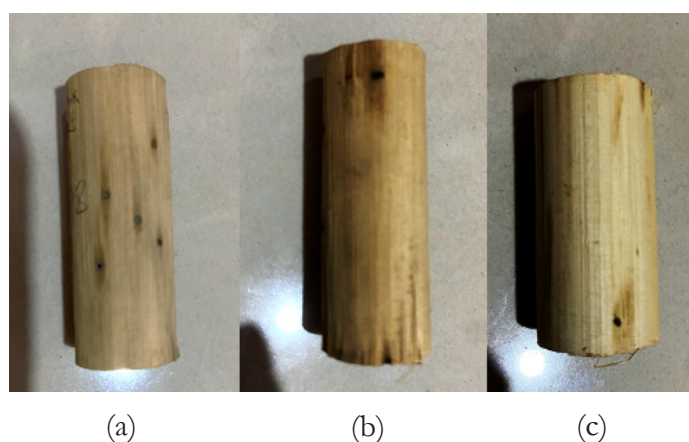


Figure 8. Effect of rattan vinegar on powderpost-beetle resistance: (a) untreated rattan; (b) rattan treated with natural dye extract; (c) rattan treated with natural dye extract and rattan vinegar.

Mortality increased in samples treated with the extract and in samples treated with the extract combined with rattan vinegar compared with the control. Mortality was higher in the combined treatments than in extract-only treatments. Analysis of variance (ANOVA) confirmed that treatment formulation significantly affected termite mortality ($p < 0.05$). Duncan's multiple range test showed that adding rattan vinegar significantly increased mortality, although the concentration level did not. Samples treated with rattan vinegar consistently showed higher termite mortality than those without. Such improved resistance against *Cryptotermes cynocephalus* (termite mortality rate $> 81\%$) and *Heterobostrychus* sp. (weight loss rate $< 1.6\%$) is supported by the biological activity

of pyroligneous acids, which consist mostly of organic acids and phenolic substances. It has been demonstrated that wood vinegar could increase the rate of termite mortality in a concentration-dependent manner (Oramahi et al., 2022) and could be a slow-acting toxic preservative after vacuum-pressure impregnation (Lee et al., 2022). At the physiological level, pyroligneous acid can decrease digestive and detoxifying enzyme activity and deplete energy reserves in stored-product insects, which may explain the observed reductions in feeding and survival (Homayoonzadeh et al., 2022). According to Iacomino et al. (2024), acetic acid and phenolic derivatives are key components of wood vinegar, and their biological activity depends significantly on concentration and application conditions.

Overall, this information corroborates the current effects of reduced weight loss and increased mortality of termites and suggests that the use of rattan vinegar can be efficient as a biopreservative provided its concentration is optimal. Thus, this study proves that extracts of jernang or teak leaves along with rattan vinegar can enhance the biological resistance of rattan to the insects studied

IV. CONCLUSION

The UAE method had higher efficiency compared to the maceration technique by improving the yield of teak leaf extracts from 12.04% to 15.90% and the yield of jernang processing-waste extracts from 8.81% to 10.64%. UAE extracts were more stable under UV and oxidizing conditions. pH had no significant effect on extract absorbance. Before the hot-water fastness test, ΔE values were 19.16 (EJ-U-15), 26.53 (EJ-U-30), 22.77 (ED-U-15), and 23.40 (ED-U-30); after leaching, they decreased to 8.65, 12.96, 8.94, and 15.48. ED-U-30 exhibited the lowest percentage decrease in ΔE (33.85%) and thus the best color retention after leaching. The dyeing process increased density, dye content, and hardness, while FTIR analysis confirmed interaction between the dye, citric acid mordant, and rattan components. Rattan vinegar treatment after dyeing enhanced the anti-termite activity towards drywood termites and powderpost beetles compared with untreated rattan.

The combination of these two processes could serve as an alternative, biological technique for rattan processing. Further research is needed to investigate long-term exposure to outdoor climate, extended UV radiation, biodeterioration resistance, and economic feasibility in industry conditions

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