

THE PHYSICAL PROPERTIES AND COLOR CHANGES OF TREATED FAST-GROWING WOODS WITH BORON COMPOUNDS, CHITOSAN, AND HEATING

Ninin Istriana¹, Trisna Priadi^{1*}, Lisman Suryanegara², Lilih Cipta Pangestu¹

¹Departement of Forest Products, IPB University, Jl. Ulin, Kampus IPB Dramaga Bogor 16680, Indonesia

²Badan Riset dan Inovasi Nasional, Jl. Raya Jakarta-Bogor No.KM.47, Nanggewer Mekar Cibinong Bogor 16911, Indonesia

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THE PHYSICAL PROPERTIES AND COLOR CHANGES OF TREATED FAST-GROWING WOODS WITH BORON COMPOUNDS, CHITOSAN, AND HEATING. Boric acid preservative is known to be easily leached when exposed to rain during exterior use. So, it needs to be combined with other treatments to improve its performance. This research aimed to evaluate the effects of boric acid preservative, chitosan, and heat treatments on physical properties, preservative leaching, and weathering resistance of two fast-growing woods. Manii (*Maesopsis eminii* Engl.) and mindi (*Melia azedarach* Linn.) woods were impregnated with 5% boric acid preservative at a pressure of 7 kg cm⁻² for 4 hours. The next step involved a second-stage impregnation with chitosan (at a 2% concentration) and a mixed combination of boric acid-chitosan, under the same pressure and duration. The final step was heat treatment at 70 °C and 140 °C under atmospheric conditions for 4 hours. The retention of boric acid in manii and mindi woods was 18,1 ± 0,8 kg m⁻³ and 12,7 ± 0,9 kg m⁻³, respectively. The interaction of boric acid, chitosan, and heat treatments significantly affected the density, water absorption, leaching, wood dimensional stability, shrinkage, and wood resistance to weathering. Impregnation with a boric acid-chitosan mixture and heating at 140 °C (M140) successfully increased the density, ASE, and reduced water absorption and leaching in manii and mindi woods.

Keywords: Boric acid, chitosan, impregnation, physical properties, weathering

IDENTIFIKASI DAN PEMETAAN SISTEM DUSUNG SEBAGAI AGROFORESTRI BERBASIS BUDAYA LOKAL DI KOTA AMBON, PROVINSI MALUKU, INDONESIA. SIFAT FISIS DAN PERUBAHAN WARNA KAYU CEPAT TUMBUH DENGAN PERLAKUAN SENYAWA BORON, KITOSAN, DAN PEMANASAN. Bahan pengawet asam borat dikenal mudah tercuci jika terkena hujan pada penggunaan eksterior. Oleh karena itu, perlu kombinasi dengan perlakuan lain untuk memperbaiki performanya. Penelitian ini bertujuan untuk mengevaluasi efek pengawetan asam borat, kitosan, dan pemanasan terhadap sifat fisis, ketercucian bahan pengawet, dan ketahanan terhadap paparan alami pada kedua jenis kayu cepat tumbuh. Kayu manii (*Maesopsis eminii* Engl.) dan mindi (*Melia azedarach* Linn.) diimpregnasi dengan pengawet asam borat 5% pada tekanan 7 kg cm⁻² selama 4 jam. Proses selanjutnya adalah melakukan impregnasi tahap kedua dengan kitosan (konsentrasi 2%) dan kombinasi antara asam borat-kitosan, pada tekanan dan durasi yang sama. Tahap terakhir yaitu perlakuan pemanasan pada suhu 70 °C dan 140 °C pada tekanan ruang selama 4 jam. Retensi asam borat pada kayu manii dan mindi masing-masing sebesar 18,1 ± 0,8 kg m⁻³ dan 12,7 ± 0,9 kg m⁻³. Interaksi antara asam borat, kitosan, dan perlakuan panas berpengaruh signifikan terhadap kerapatan, penyerapan air, ketercucian, stabilitas dimensi kayu, penyusutan, dan ketahanan kayu terhadap paparan alami. Impregnasi kombinasi campuran (asam borat-kitosan) dan pemanasan pada suhu 140 °C (M140) mampu meningkatkan kerapatan, ASE, mengurangi penyerapan air, dan ketercucian pada kayu manii dan mindi.

Kata kunci: Asam borat, impregnasi, kitosan, paparan alami, sifat fisis kayu

*Corresponding author: e-mail: trisnapr@apps.ipb.ac.id

I. INTRODUCTION

Manii (*Maesopsis eminii* Engl.) and mindi (*Melia azedarach* Linn.) are fast-growing wood species commonly found in community forests and widely used for construction purposes (Haryanto et al. 2021). Manii wood has an air-dry density of 0.39 g cm⁻³ (Sadiyo et al., 2017) and a specific gravity of 0.42, but it exhibits low natural durability (durability class V) (Muslich & Rullianty, 2016). Meanwhile, mindi wood belongs to strength class II–III and has a specific gravity of 0.53, however, its durability remains relatively low (durability class IV) (durability class IV) (Herawati et al., 2021). Although fast-growing species can be harvested within a relatively short rotation period, they generally exhibit lower wood quality, particularly in terms of density (Suri et al., 2021a) and durability (Fauziyyah et al., 2023). Therefore, effective wood modification strategies are needed to enhance the quality and durability of fast-growing wood species.

Improvements in the quality of fast-growing species can be achieved through preservation, thermal treatment, or a combination of both. One commonly used preservative is boric acid (H₃BO₃), which effectively increases wood resistance to fungi, insects, and termites (Percin et al., 2015). However, boric acid impregnation has a limitation, namely its susceptibility to water leaching under exterior exposure conditions (Verly et al., 2020). This reduces preservative retention and compromises long-term protection. This limitation necessitates the use of complementary materials or wood modification technologies to mitigate boric acid leaching.

Chitosan represents a promising complementary material to address this limitation. Chitosan is a bio-based and renewable derivative of chitin, primarily sourced from crustaceans and mollusks. It is widely recognized as a potential environmentally friendly wood preservative due to its natural abundance, sustainable availability, and inherent antibacterial and antifungal properties (Zivonic et al., 2015).

Chitosan, particularly when combined with other compounds (such as alginate, caffeine, and nitrilotris(methylenephosphonic acid)), has shown potential in enhancing the physical performance of wood, including thermal stability and structural integrity. Chitosan has been reported to improve caffeine fixation and reduce leaching, thereby increasing material stability. Modified chitosan systems can also improve fire-related properties by reducing heat release characteristics (Walsh-Korb et al., 2022; Woźniak et al., 2022; Cho et al., 2022). Chitosan, with its polysaccharide structure ((C₆H₁₁NO₄)_n), can be used as a natural adhesive (Winarto, 2014). Electrostatic interactions between chitosan and cellulose hydroxyl groups facilitate the bonding of chitosan to wood. Hydroxyl groups form hydrogen bonds with chitosan (Patel et al., 2013). Heat treatment can reduce the hygroscopic behavior of wood and lower its moisture content, thereby improving its dimensional stability. In addition, thermal modification can enhance resistance to preservative leaching and alter wood mass through chemical changes in cell wall components (Hill et al., 2021).

The combination of boron compounds, chitosan, and heat treatment has the potential to improve the performance of fast-growing wood species. The interaction among boron, chitosan, and heat treatment may contribute to wood performance through complementary mechanisms. Istriana and Priadi (2021) reported improved performance in boron–chitosan heat-treated (140 °C) wood compared with untreated and boron-only treated samples. Boric acid reduces fungal-induced weight loss, while chitosan suppresses microbial growth and reduces boron leaching. Heat treatment degrades hemicellulose and increases wood hydrophobicity, thereby reducing moisture availability and improving dimensional stability. Heating in combination with boron treatment can convert boric acid into metaboric acid (HBO₂) at around 138 °C, promoting crystallization and reducing preservative leachability (Kaur et al., 2021).

Although previous studies have examined boron compounds, chitosan, and heat treatment in wood modification, most investigations have focused on individual applications or partial combinations, such as boron–heat or chitosan–heat treatments. The fully integrated interaction among boric acid, chitosan, and heat treatment, particularly using sequential impregnation techniques, has not been widely explored, highlighting the need for a systematic evaluation of their combined application. A more comprehensive understanding of how these combined treatments perform is therefore required, particularly regarding their potential to enhance the quality of fast-growing wood species. The novelty of this study lies in the integration of boric acid, chitosan, and heat treatment through different impregnation strategies, including sequential and mixed treatments. In addition, this study provides a systematic comparison of these treatment approaches in manii and mindi woods, which have received limited attention in previous wood modification studies.

This research aimed to evaluate the effects of boric acid preservative, chitosan, and heat treatments on the physical properties, preservative leaching, and weathering resistance of two fast-growing woods.

II. MATERIALS AND METHODS

A. Location and Materials

This research was conducted in several laboratories within the Faculty of Forestry and Environment, IPB University. Wood sample preparation was carried out at the workshop. The impregnation process was conducted at the Laboratory of Drying and Preservation. The heat treatment tests were conducted at the Laboratory of Physical Properties, and the weathering test was carried out in an outdoor exposure area located near the Laboratory of Termites, Faculty of Forestry and Environment, IPB University.

Two fast-growing wood species, manii (*Maesopsis eminii* Engl.) and mindi (*Melia*

azedarach Linn.) were used in this study. Manii wood was obtained from a tree approximately 15 meters in height and 50 cm in diameter from the arboretum of the Faculty of Forestry and Environment, IPB University. Mindi wood was obtained from a sawmill at UD. Sumber Jaya, Bogor. Manii and mindi woods were processed into boards using a circular table saw with a thickness of 6 cm. The boards were dried in an experimental kiln at 50°C to a moisture content (MC) of 14%.

Specimens were prepared for density (2 cm × 2 cm × 2 cm), water absorption, leaching, and dimensional stability tests (2.5 cm × 2.5 cm × 10 cm), as well as weathering tests (2 cm × 7.5 cm × 15 cm). Five specimens were prepared for each treatment combination and used for subsequent analyses.

In addition, analytical-grade boric acid (H_3BO_3) was obtained from Supelco, Denmark, which was then dissolved in distilled water at 5% concentration. Chitosan powder derived from shrimp shells was supplied by PT. Biotech Surindo, Cirebon, acetic acid by Merck, and alcohol. Boric acid solutions were made at 5% concentration for impregnation I, while 2% chitosan was used for impregnation II. In addition, A mixture containing 5% boric acid and 2% chitosan was used for the single-impregnation treatment. The 2% chitosan solution was prepared by dissolving 20 g of chitosan powder (60 mesh) in 10 mL of acetic acid under continuous stirring. Subsequently, 700 ml of distilled water was added. The chitosan solution was then transferred to a 1000 ml measuring cylinder and homogenized at 23000 rpm for 5 minutes. Distilled water was then added, while constantly stirring, to bring the total volume up to 1000 ml. The solution was then allowed to stand for 24 hours (Istriana, 2024; Istriana & Priadi, 2021).

B. Methods

1. Impregnation and Heating

The test samples were dried in a heating oven at a temperature of 60 °C until 15% MC. The impregnation process was conducted in

two stages, followed by heat treatments at temperatures of 70 °C or 140 °C for 4 hours, as shown in Table 1. Boric acid impregnation was carried out in a pressurized tank at 7 kg cm⁻² for 4 hours (Lestari, 2020). The samples were weighed before (W_0) and after the impregnation (W_1) to determine the retention (R) of boric acid according to Equation 1. Subsequently, chitosan impregnation was performed under the same pressure conditions (7 kg cm⁻²) for 4 hours (Istriana, 2024).

$$R = (W_1 - W_0) : V \times C \dots\dots\dots(1)$$

Where:

R = retention (kg m⁻³)

W_0 = sample weight before impregnation (kg)

W_1 = sample weight after impregnation (kg)

V = sample volume (m³)

C = boric acid concentration (%)

After impregnation, the wood samples were heat-treated in a Memmert oven at either 70 °C or 140 °C for 4 h under atmospheric pressure. The samples were oven-dried at 103 ± 2 °C

before and after the second impregnation to determine the weight percent gain (WPG) using Equation 2.

$$WPG = (W_2 - W_1) : W_1 \times 100 \dots\dots\dots(2)$$

Where:

WPG = weight percent gain of the sample (%)

W_2 = dry weight after impregnation (g)

W_1 = dry weight before impregnation (g)

2. Physical Properties Test

Wood density was determined according to the British Standard (BS 1957). Water absorption and leaching tests were conducted in accordance with ASTM D 1413-76 (ASTM 1976). The leaching value was calculated using Equation 3, which represents the difference in oven-dry weight after impregnation and after immersion. Water absorption was calculated using Equation 4, based on the difference between the weight after each immersion and its oven-dry weight.

Table 1. Treatment combination on manii and mindi woods without impregnation (N), with boric acid (B), chitosan (C), boric acid-chitosan (BC), chitosan-boric acid (CB), mix boric acid+chitosan (M), and heating temperatures (70 °C and 140 °C)

Treatment code	Impregnation I	Impregnation II	Heat treatment (°C)
N70	-	-	70
N140	-	-	140
B70	Boric acid	-	70
B140	Boric acid	-	140
C70	-	Chitosan	70
C140	-	Chitosan	140
BC70	Boric acid	Chitosan	70
BC140	Boric acid	Chitosan	140
CB70	Chitosan	Boric acid	70
CB140	Chitosan	Boric acid	140
M70	Boric acid+Chitosan		70
M140	Boric acid+Chitosan		140

$$L = (W_{ob} - W_{oa}) : W_{ob} \times 100 \dots\dots\dots(3)$$

Where:

- L = leaching (%)
 W_{oa} = oven dry weight after soaking (g)
 W_{ob} = oven dry weight before soaking (g)

$$WA = ((W_{wa} - W_{ob}) : W_{ob} \times 100 \dots\dots\dots(4)$$

Where:

- WA = water absorption (%)
 W_{wa} = wet weight after soaking (g)
 W_{ob} = oven dry weight before soaking (g)

Test samples were immersed in distilled water gradually for 2 hours, 24 hours, and 48 hours. Each immersion period was interrupted by oven-drying at a temperature of 103 ± 2 °C until a constant weight was achieved. The samples were weighed before and after immersion under both wet and oven-dry conditions. The anti-swelling efficiency (ASE) was calculated using Equation 5. Tangential and radial shrinkage were determined from the dimensional changes between wet and oven-dry conditions using Equation 6. The tangential-radial shrinkage ratio was calculated using Equation 7

$$ASE = (S_u - S_t) : S_u \times 100 \dots\dots\dots(5)$$

Where:

- ASE = the anti-swelling efficiency (%)
 S_u = the swelling of the untreated sample (%)
 S_t = the swelling of the treated sample (%)

$$SD = (D_b - D_a) : D_b \times 100 \dots\dots\dots(6)$$

Where:

- SD = the shrinkage (%)
 D_b = dimension (tangential, radial) before oven drying (cm)
 D_a = dimension (tangential, radial) after oven drying (cm)

$$T/R = SD_t : SD_r \times 100 \dots\dots\dots(7)$$

Where:

- T/R = the shrinkage ratio
 SD_t = the tangential shrinkage (%)
 SD_r = the radial shrinkage (%)

3. Color Changes and Weathering Test

The color of the wood was evaluated before and after treatments using a CanoScan 4400F scanner. The scanned images were analyzed using the CIELab color system. L^* , a^* , and b^* values were determined at three points on each sample surface using Adobe Photoshop CS3. Parameter L^* indicated light (+) or dark (-), a^* indicated reddish (+) or greenish (-), and b^* indicated yellowish (+) or bluish (-) colors (Cao et al., 2021). The changes in L^* , a^* , and b^* , (ΔL , Δa , and Δb , respectively) were calculated using Equations 8-10. Total color change (ΔE) was calculated using Equation 11 (Hidayat et al., 2021). The color change (ΔE) was classified according to Table 2.

$$\Delta L = L_1 - L_0 \dots\dots\dots(8)$$

$$\Delta a = a_1 - a_0 \dots\dots\dots(9)$$

$$\Delta b = b_1 - b_0 \dots\dots\dots(10)$$

$$\Delta E = [(\Delta L)^2 + (\Delta a)^2 + (\Delta b)^2]^{1/2} \dots\dots\dots(11)$$

Where:

- L_1, a_1, b_1 = the values of L^* , a^* , and b^*
 L_0, a_0, b_0 = the values before the treatments

The weathering test was conducted following the procedure described by Kim et al. (2016). Test samples were placed on an exposure rack at a 45° angle, oriented towards the east. The weathering period lasted 90 days, from June to August 2022. The primary parameters measured were wood color changes before and after weathering, along with alterations in weight. Weight loss was evaluated to assess the effectiveness of the modification treatments in reducing wood degradation. Weight loss was measured on days 30, 60, and 90. Concurrently with weight loss, moisture content was

Table 2. Classification of color change (ΔE)

Color change	Description
$(0 < \Delta E \leq 0.5)$	Negligible
$(0.5 < \Delta E \leq 1.5)$	Slightly perceivable
$(1.5 < \Delta E \leq 3.0)$	Noticeable
$(3.0 < \Delta E \leq 6.0)$	Appreciable
$(6.0 < \Delta E \leq 12)$	Very appreciable

assessed using a moisture meter. Initial sample weights were recorded and compared with weights measured after 30, 60, and 90 days of weathering. Finally, weight loss was calculated using Equation 12.

$$WL = (W_m - W_n) : W_m \times 100 \dots\dots\dots(12)$$

Where:

WL = the weight loss (%)

W_m = the wood weight on day-m (g)

W_n = the wood weight on day-n (g)

C. Analysis

The obtained data on retention and weight percent gain were analysed descriptively using Microsoft Excel software. The data from various tests on the impregnation of manii and mindi wood with boric acid, chitosan, and heat treatment were analyzed using IBM SPSS 26 based on a factorial completely randomized design. Factor A (wood species) had 2 types (manii and mindi), Factor B (impregnation) had 6 levels (without impregnation, boric acid, chitosan, boric acid-chitosan, chitosan-boric acid, boric acid+chitosan), and Factor C was heat treatment, which had 2 levels (70 °C and 140 °C). When significant differences were detected by ANOVA, Duncan's multiple range test was performed at a 95% confidence level.

III. RESULT AND DISCUSSION

A. Evaluation of Impregnation Results

The success of impregnation can be assessed by retention values and weight percent

gain. Preservative retention is a key parameter for effective wood preservation. Our findings indicate that boric acid retention reached $18.1 \pm 0.8 \text{ kg m}^{-3}$ in manii wood and $12.7 \pm 0.9 \text{ kg m}^{-3}$ in mindi wood. The retention value required by the SNI 01-5010.1-1999 standard (Indonesian National Standard) was a minimum of 8.2 kg m^{-3} for interior use and 11.3 kg m^{-3} for exterior use. The higher retention observed in manii wood may be related to its lower specific gravity (0.42) compared with mindi wood (0.53) (Muslich & Rullianty, 2016; Krisdianto et al., 2013). Mindi wood, with its higher specific gravity, generally requires greater pressure or longer treatment duration for effective preservative penetration, due to its denser anatomical structure and reduced permeability. In addition, retention can also be influenced by moisture content, preservative characteristics, and wood density (Syahrial et al., 2022). The retention of preservatives in wood determines its effectiveness in protecting against wood-destroying organisms (Vachlepi et al., 2015).

Weight percent gain (WPG) represents the percentage increase in wood weight after impregnation compared to its initial weight. Figure 1 shows that the highest WPG values for both wood species were obtained with the boric acid–chitosan mixture treatment combined with heating at 70 °C (M70), reaching 68.08% in manii wood and 57.61% in mindi wood. Conversely, the lowest WPG values for both wood types were observed with the chitosan-only treatment combined with heating at 140 °C (C140), which were 30.79% for manii wood and 17.36% for mindi wood.

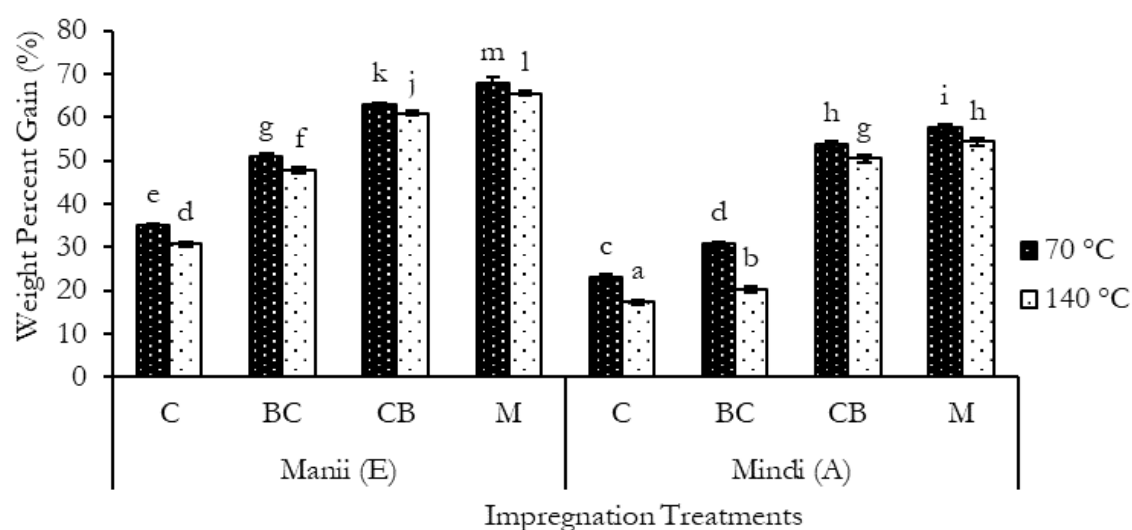


Figure 1. Weight percent gain of manii and mindi wood treated with chitosan (C), boric acid-chitosan (BC), chitosan-boric acid (CB), mixture combination boric acid +chitosan (M), and heating temperatures (70 °C and 140 °C). Values that are not substantially different in Duncan's test are shown by the same letters (a, b, c, etc.)

The analysis of variance result at a 95% confidence level shows that the interaction of wood type, impregnating agent, and heat treatment has a very significant effect on WPG ($F(5, 96) = 28.487, p < 0.001$). Duncan's test shows that the WPG for the boric acid-chitosan mixture with 70 °C heating (M70) was significantly higher than for that treated with chitosan with 70 °C heating (C70), boric acid-chitosan with 70 °C heating (BC70), and chitosan-boric acid with 70 °C heating (CB70) in both wood types. This indicates that the boric acid-chitosan mixed system (M) resulted in greater penetration into the wood lumen and void spaces compared to the sequential impregnation treatments (BC and CB). In the mixed system (boric acid-chitosan mixture), boron ions can diffuse into the chitosan matrix and interact with amino groups ($-NH_2$) through physicochemical interactions such as electrostatic attraction or complex formation, which may help stabilize boron within the chitosan matrix (Hammi et al., 2023) and facilitate the simultaneous diffusion of both compounds into the lumen and partially into the cell wall structure. In contrast, during sequential impregnation treatments (BC and

CB), a portion of boric acid may be leached out during the second impregnation step. Boric acid has high water solubility, making it prone to leaching from wood (Cahyono et al., 2020).

Test samples heated at 140 °C showed lower WPG compared to those heated at 70 °C for both wood types. This is likely due to the evaporation of some impregnants and the degradation of certain wood chemical components, particularly hemicellulose, at higher temperatures. Heating at elevated temperatures promotes the degradation of extractives and cell-wall components, particularly hemicellulose (Gokhan & Denis, 2019).

B. Physical Properties

Wood density increased in both manii and mindi woods following the applied treatments. Figure 2 shows that the highest density values were obtained in the boric acid-chitosan mixture treatment heated at 140 °C (M140). The densities reached 0.63 g cm^{-3} for manii wood and 0.64 g cm^{-3} for mindi wood. Untreated manii and mindi woods exhibited the same density value of 0.45 g cm^{-3} . The ANOVA test shows that heating significantly affects the

wood's density ($F(1,96) = 12,09$, $p = 0.001$). Mixture treatment with 140 °C heating (M140) significantly increased wood density by up to 39% for manii wood and 22% for mindi wood (Figure 2). The increase in density may result from the deposition of preservative compounds within the wood structure, filling cell voids, and adding mass to the wood matrix. Furthermore, the analysis of variance results show that wood density is influenced by the interaction between wood species and impregnation ($F(5, 96) = 11.99$, $p < 0.001$). Density tended to increase with increasing boric acid concentration in the

impregnation solution. A positive relationship between boric acid concentration and retention. Similarly, Fidan & Adanur (2019) reported a density value of 5% boric acid of 0.54 g cm^{-3} , slightly higher than the control (0.53 g cm^{-3}). This trend is consistent with the retention and WPG results observed in this study, where higher preservative uptake contributed to increased mass within the wood structure.

Heating at temperatures between 120 °C – 150 °C causes wood to lose its extractives (Todaro et al., 2015). High temperatures can also alter wood cell wall components, including

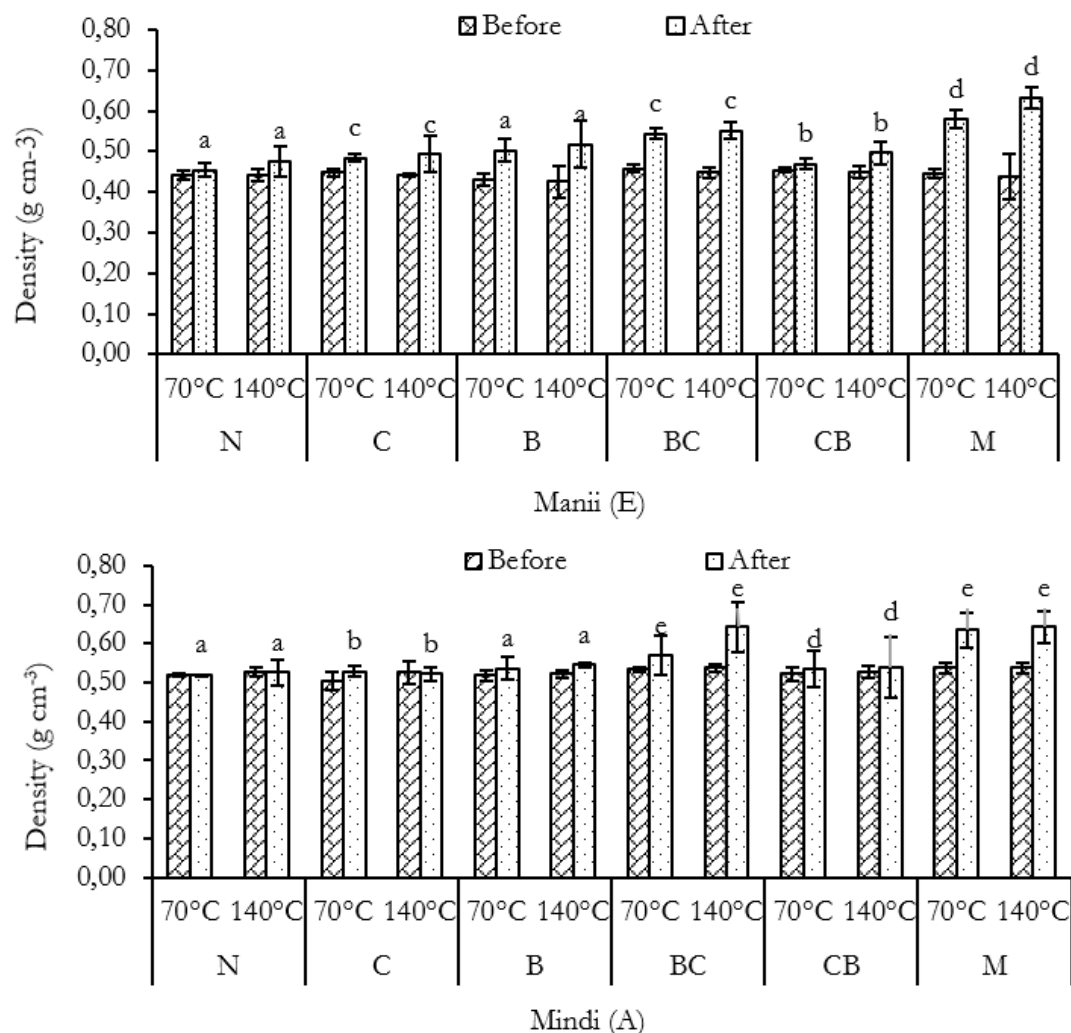


Figure 2. Density of manii and mindi wood treated without impregnation (N), with boric acid (B), chitosan (C), boric acid-chitosan (BC), chitosan-boric acid (CB), mixture combination boric acid +chitosan (M), and heating temperatures (70 °C and 140 °C). Values that are not substantially different in Duncan's test are shown by the same letters (a, b, c, etc.)

cellulose (Cahyono et al., 2021). The increase in density after heat treatment may be attributed to moisture loss, which reduces wood volume. As density is the ratio of mass to volume, this volume reduction can increase density. Differences in density between manii and mindi wood may also be related to variations in anatomical structure, which influence the penetration and distribution of preservative compounds.

Figure 3 shows that water absorption (WA) in the test samples decreased after the impregnation. The lowest WA values after

48 hours of immersion for both manii and mindi woods were observed in the boric acid-chitosan mixture with 140 °C heating (M140), which were 7.99% for manii wood and 7.37% for mindi wood. The lower WA in the M140 treatment may be attributed to the combined effect of boric acid, chitosan, and heat treatment, which limit water penetration and reduce wood hygroscopicity. Previous studies have reported that wood treated with boron can reduce hygroscopicity, water absorption, and shrinkage value (Demirel et al., 2018).

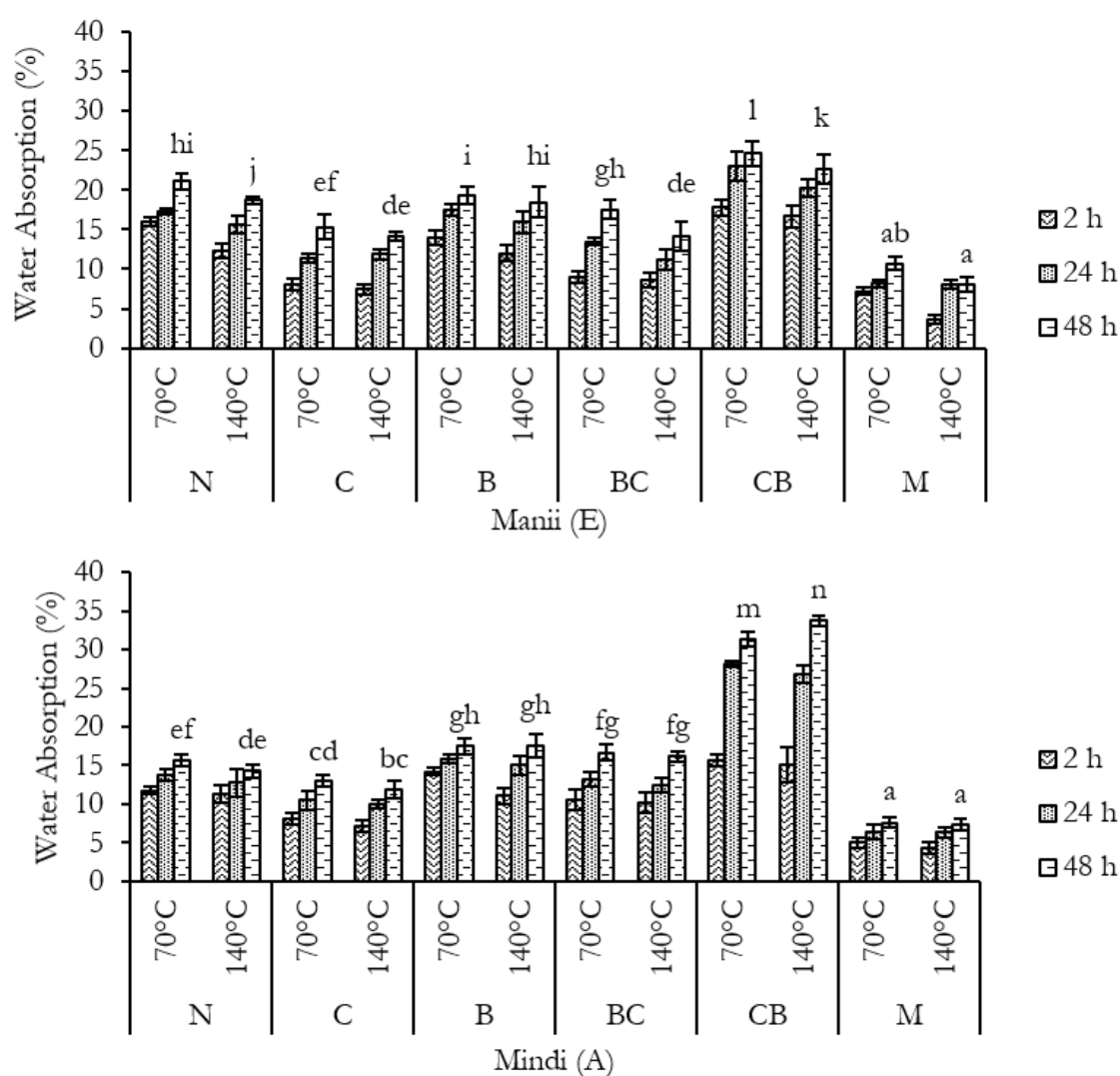


Figure 3. Water absorption of manii and mindi wood treated without impregnation (N), with boric acid (B), chitosan (C), boric acid-chitosan (BC), chitosan-boric acid (CB), mixture combination boric acid +chitosan (M), and heating temperatures (70 °C and 140 °C. Values that are not substantially different in Duncan's test are shown by the same letters (a, b, c, etc.)

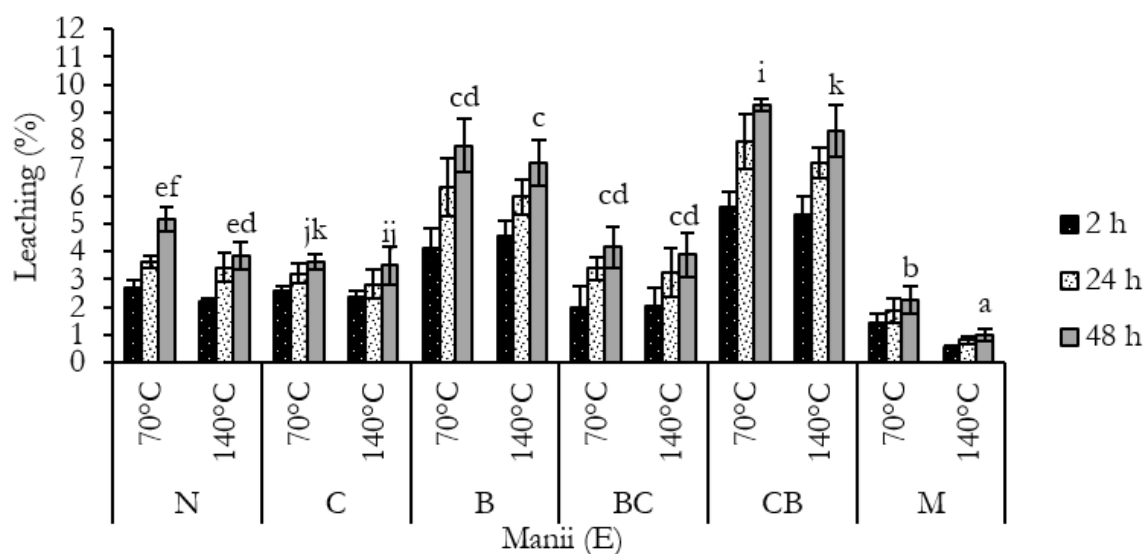
This is supported by the analysis of variance results, explaining that WA is influenced by the interaction between wood species, impregnation treatment, and heating ($F(5, 96) = 2.43$, $p = 0.041$). Both manii and mindi woods exhibited significantly lower WA values when subjected to the boric acid-chitosan mixture (M) and the chitosan impregnation treatment (C), compared to the untreated woods (control) (N70). Chitosan treatment reduced the hygroscopicity of wood, leading to a decrease in its equilibrium moisture content across all relative humidity levels (Papadopoulos et al., 2020). This is attributed to the chitin, which blocks the hydrophilic hydroxyl groups of the cellulose and reduces the hygroscopicity of the treated wood. Papadopoulos et al. (2020) demonstrated that the use of chitosan compounds resulted in a 23.8% reduction in total wood sorption. However, the higher WA observed in CB-treated (chitosan-boric acid) samples suggests that the response may depend on the treatment sequence and interactions between the impregnated compounds. The sequential chitosan-boron treatment may potentially affect water penetration and absorption.

Heat treatment at 140 °C (N140) also resulted in lower water absorption compared to heating at 70 °C (N70), suggesting that higher temperatures reduced the wood's water absorption (Lestari, 2020). The lower water

absorption is attributed to the reduction of free hydroxyl (-OH) groups during heat treatment, which decreases wood hygroscopicity, as reported for sengon and jabon woods (Priadi et al., 2019). Increased cellulose crystallinity after heat treatment limits the accessibility of water molecules to the cell wall, thereby reducing water absorption (Darmawan et al., 2017). Similar increases in cellulose crystallinity following heat treatment (160 °C, 180 °C, 200 °C, and 220 °C for 2 hours) have been reported in Royal Paulownia wood, supporting the reduction in water absorption (Kim et al., 2018).

Leaching is an important parameter in evaluating the fixation and long-term performance of wood preservatives. Figure 4 shows that chitosan can reduce preservative leaching by up to 30%, particularly in samples impregnated with the boric acid-chitosan mixture followed by heat treatment at 140 °C. The lowest leaching values after 48 hours of immersion were observed in the boric acid-chitosan mixture with 140 °C heating (M140), which were 0.99% for manii wood and 1.003% for mindi wood. The analysis of variance indicates that the leaching value after 48 hours is significantly influenced by the interaction between wood species and impregnation treatment ($F(5, 96) = 14.26$, $p < 0.001$).

The leaching values of the boric acid-chitosan mixture (M) and the boric acid-



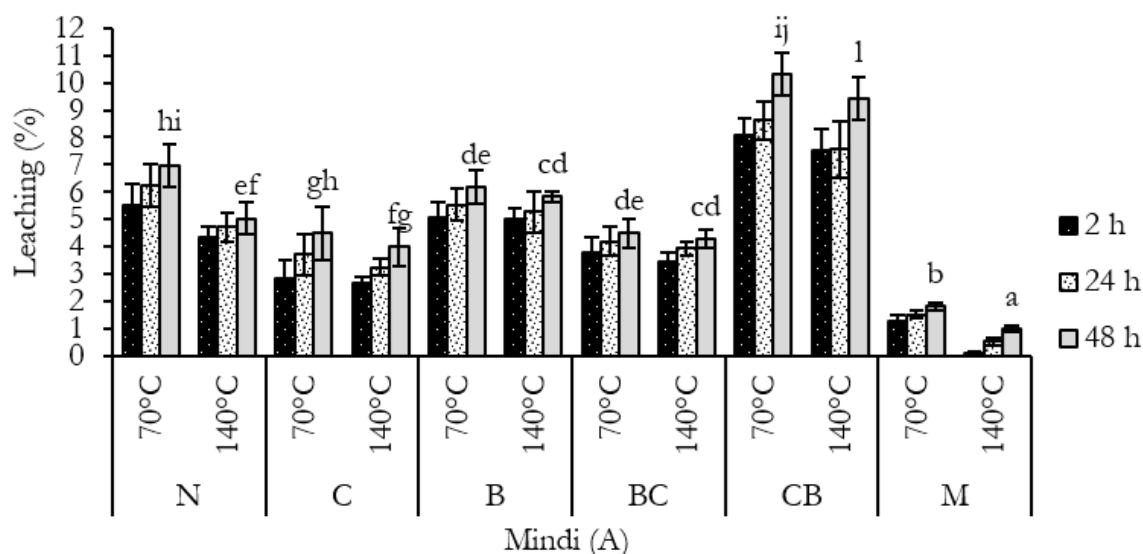


Figure 4. Leaching of manii and mindi wood treated without impregnation (N), with boric acid (B), chitosan (C), boric acid-chitosan (BC), chitosan-boric acid (CB), mixture combination boric acid +chitosan (M), and heating temperatures (70 °C and 140 °C). Values that are not substantially different in Duncan's test are shown by the same letters (a, b, c, etc.)

chitosan (BC) were significantly lower than those of the untreated samples (N70) after 48 h of immersion. Among the treatments, the M140 treatment showed the lowest leaching values. Chitosan can bond to cellulose polymers and occupy void spaces within the wood structure, which may hinder preservative migration and contribute to lower leaching. Treated wood with chitosan exhibits lower leaching compared to that of treated wood with PEG (Nowrouzi et al., 2015). Boron ions may interact with the amino groups ($-NH_2$) of chitosan through physicochemical interactions, promoting boron fixation within the wood structure and thereby reducing its susceptibility to leaching (Hammi et al., 2023). However, the higher leaching observed in CB (chitosan-boric acid) samples may be related to the relatively soluble nature of boron compounds. Boron that is not strongly retained within the wood structure may migrate during water exposure and subsequently leach out.

The impregnation of boric acid, chitosan, and heat modification has been proven to improve the dimensional stability of manii and mindi woods. The highest anti-swelling

efficiency (ASE) values after 48 hours of immersion were observed with the treatment of boric acid-chitosan mixture with 140 °C heating (M140), which was 44.64% for manii wood and 46.89% for mindi wood (Figure 5). The analysis of variance revealed that the ASE after 48 hours value is influenced by the interaction between wood species, impregnation, and heat treatment ($F(5,96) = 9.37, p < 0.001$).

Manii (E) wood showed positive anti-swelling efficiency (ASE) values with the impregnation treatment of boric acid-chitosan mixture (M) and boric acid-chitosan double impregnation treatment (BC). These results were significantly different from the untreated samples (N70). This improvement suggests that the combined treatment (boric acid, chitosan, and heat treatment) reduced the wood's susceptibility to moisture-induced swelling, thereby enhancing dimensional stability. Similar improvements in ASE have been reported in fir and beech wood treated with chitosan, supporting the role of chitosan in reducing moisture-induced swelling (Nowrouzi et al., 2015). This effect is attributed to chitosan treatment decreasing the hydrophilic nature of wood, as chitin forms a coating over

the wood's cellulose (Papadopoulos et al., 2020). Heat treatment also contributed to improved dimensional stability by reducing hygroscopicity and increasing cellulose crystallinity, which together limit moisture uptake and subsequent swelling. In addition, partial degradation of hemicellulose during heating further stabilizes the wood structure (Vybohova et al., 2018).

Boric acid, chitosan impregnation, and heat treatment reduced the dimensional shrinkage of manii and mindi woods (Figure 6). Manii wood (E) treated with the boric acid-chitosan mixture

at 140 °C (M140) exhibited lower shrinkage values compared to that without impregnation (N70), specifically 1.25% (tangential shrinkage) and 1.07% (radial shrinkage). Similarly, mindi wood (A) showed values of 3.42% (tangential shrinkage) and 2.92% (radial shrinkage) under the same treatment. The lower shrinkage observed in the radial direction compared to the tangential direction is influenced by the resistance of the wood rays (Susdiyanti et al., 2023).

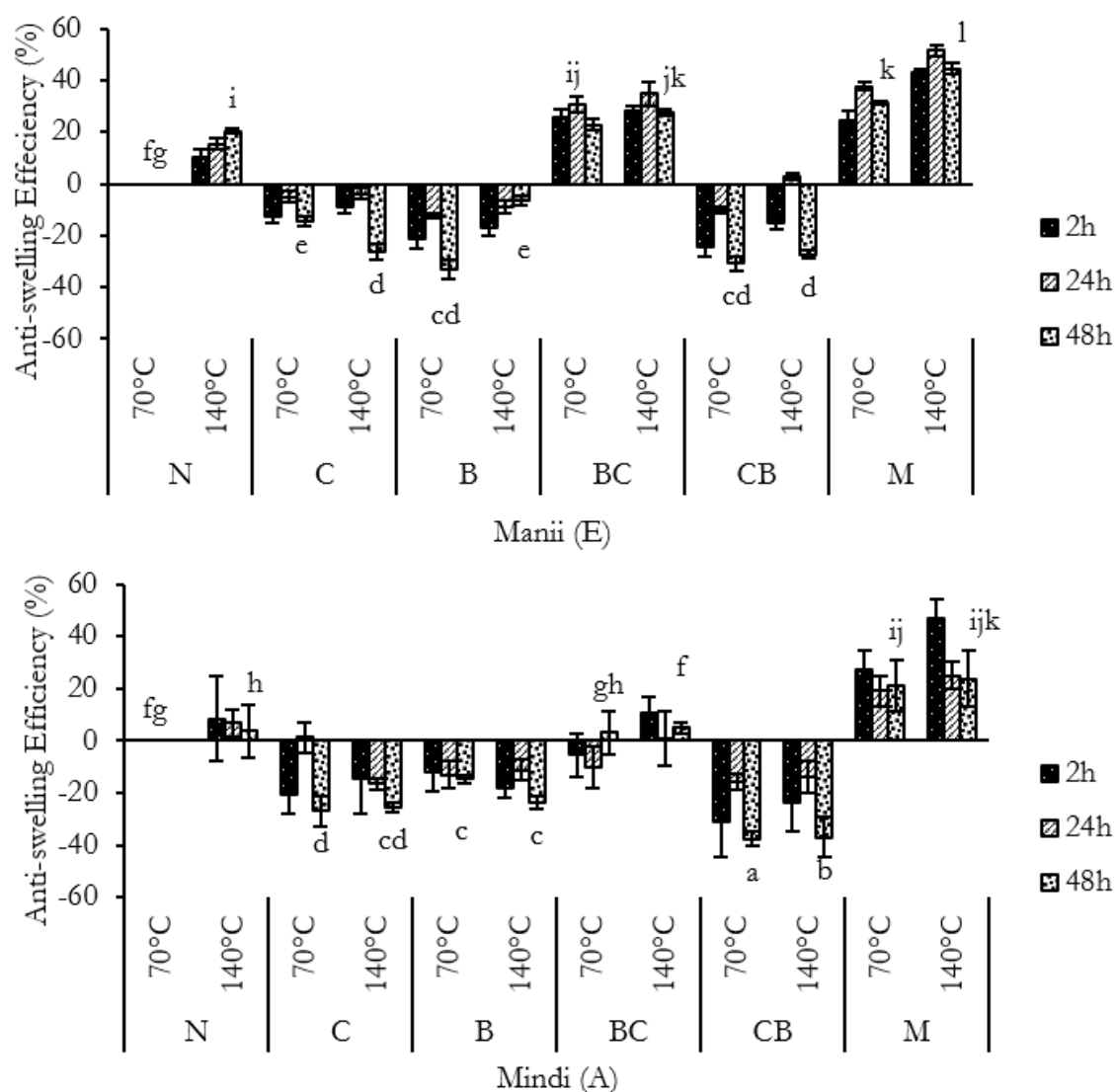


Figure 5. Anti-swelling efficiency of manii and mindi wood treated without impregnation (N), with boric acid (B), chitosan (C), boric acid-chitosan (BC), chitosan-boric acid (CB), mixture combination boric acid +chitosan (M), and heating temperatures (70 °C and 140 °C). Values that are not substantially different in Duncan's test are shown by the same letters (a, b, c, etc.)

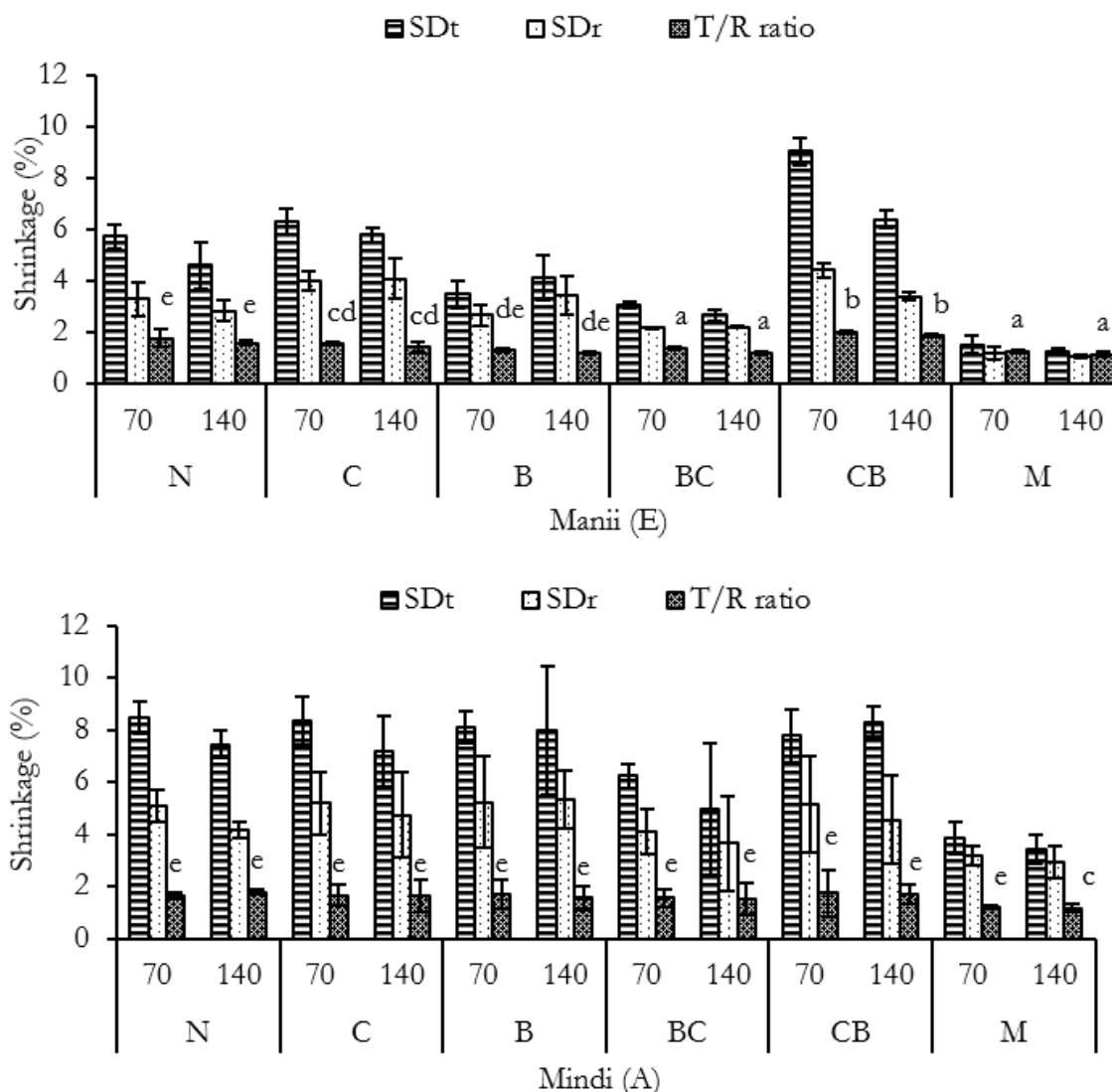


Figure 6. Shrinkage of manii and mindi wood treated without impregnation (N), with boric acid (B), chitosan (C), boric acid-chitosan (BC), chitosan-boric acid (CB), mixture combination boric acid +chitosan (M), and heating temperatures (70 °C and 140 °C). Values that are not substantially different in Duncan's test are shown by the same letters (a, b, c, etc.)

The analysis of variance revealed that the T/R ratio value is influenced by the interaction between wood species and impregnation ($F(5,96) = 9.00, p < 0.001$). The boric acid-chitosan mixture treatment with 140 °C heating (M140) resulted in significantly lower T/R shrinkage ratios compared to those without impregnation (N140), which were 1.17 for manii and 1.18 for mindi woods. The lower T/R ratio suggests a more uniform dimensional response during moisture fluctuations, reflecting improved dimensional stability. Similar reductions in T/R ratio following heat treatment (180 °C

for 4 hours) have been reported in *Pterocarpus macrocarpus*, supporting the stabilizing effect of thermal modification on wood dimension (Yang & Liu, 2020). Similar reductions in shrinkage after heat treatment (170 °C) were reported for *eastern beech wood* compared to controls (Kol et al., 2017). This improvement is associated with the partial degradation of hemicellulose and cellulose during heat treatment, which decreases the number of accessible hydroxyl groups and reduces wood hygroscopicity, thereby limiting shrinkage.

C. Color Changes and Weathering

Modification using boric acid, chitosan impregnation, and heating caused color changes in manii and mindi woods. Figure 7 shows that manii wood without boric acid or chitosan impregnation became slightly darker at 140 °C (EN140) than at 70 °C (EN70). Heat treatment has been reported to decrease the lightness (L^*) of oak, birch, and pine woods (Barcik et al., 2015). Boric acid treatment (B70 and B140) resulted in brighter wood than the untreated samples (N70 and N140), which is consistent with previous findings for manii wood by Priadi et al. (2022).

The a^* value slightly decreased, indicating a reduction in red coloration. Additionally, a slight increase in the b^* value resulted in a more yellow appearance. These color changes in wood are attributed to the formation of carbonyl groups from the oxidation of hydroxyl groups within phenolic components, or the formation of quinoid structures from adjacent hydroxyl groups (Wei et al., 2017). The color darkening observed after heat treatment is associated with hemicellulose degradation and intensified thermal reactions, including interactions between reducing sugars and amino compounds, as well as decarboxylation and dehydration, leading to the formation of chromophoric substances such as quinones.

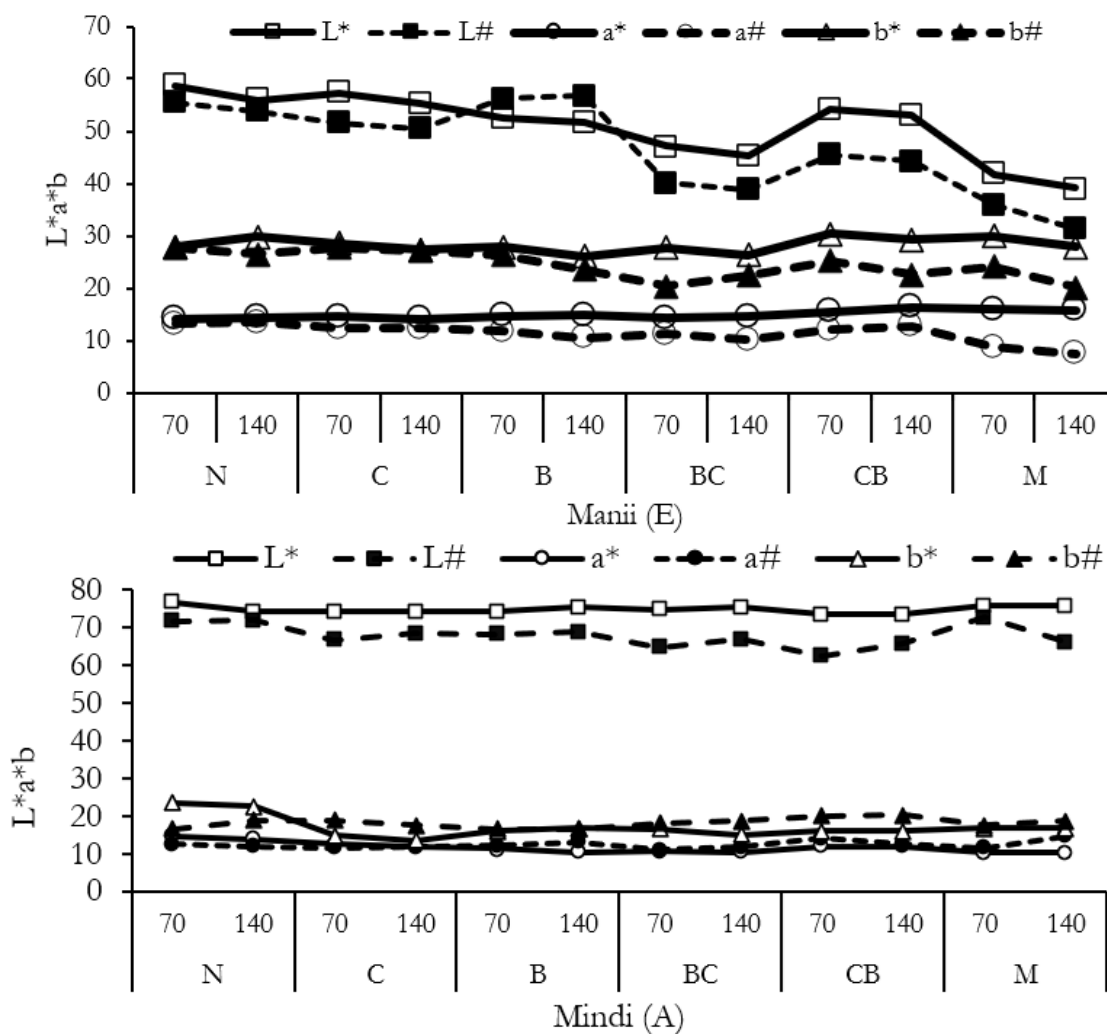


Figure 7. The L^*a^*b of manii and mindi wood treated without impregnation (N), with boric acid (B), chitosan (C), boric acid-chitosan (BC), chitosan-boric acid (CB), mixture combination boric acid +chitosan (M), and heating temperatures (70 °C and 140 °C).

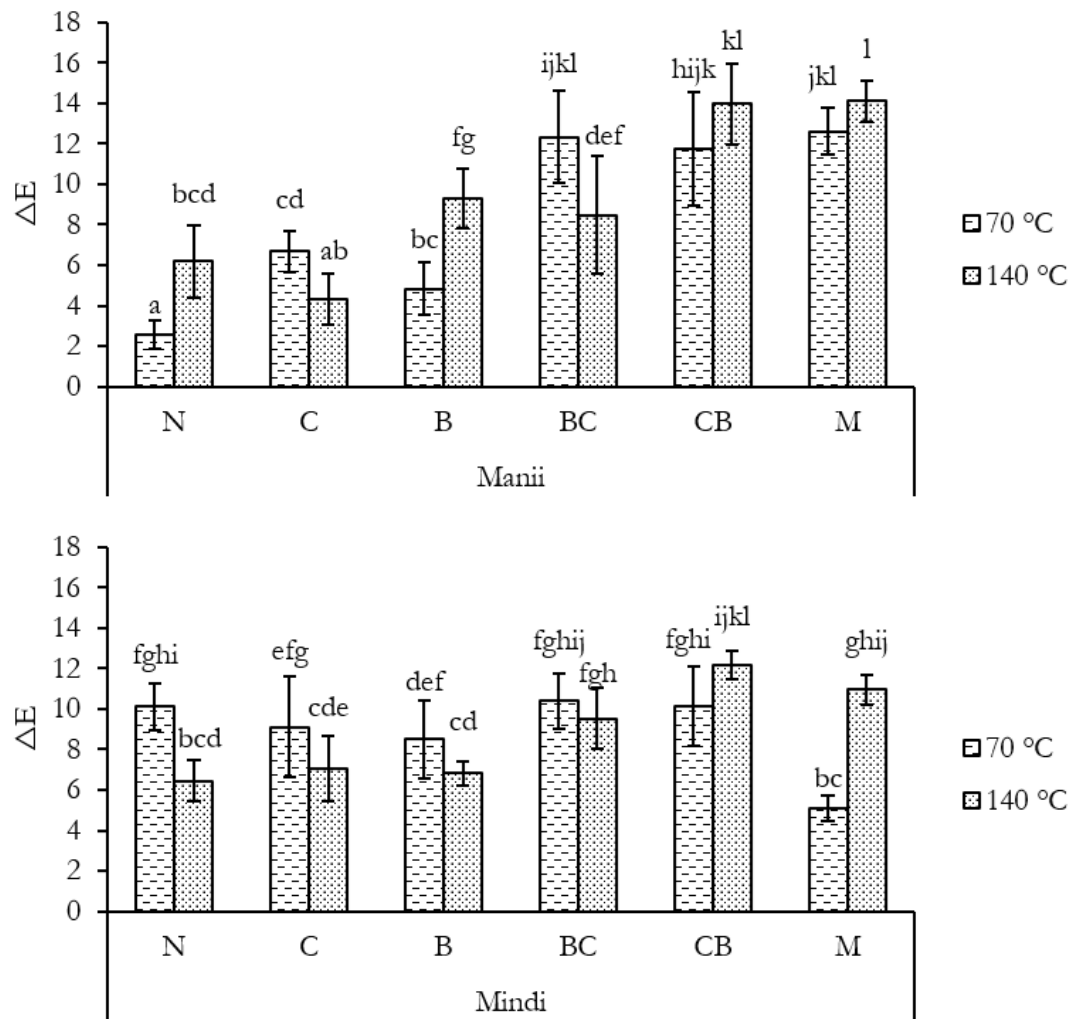


Figure 8. The ΔE of manii and mindi wood treated without impregnation (N), with boric acid (B), chitosan (C), boric acid-chitosan (BC), chitosan-boric acid (CB), mixture combination boric acid +chitosan (M), and heating temperatures (70 °C and 140 °C. Values that are not substantially different in Duncan's test are shown by the same letters (a, b, c, etc.)

Figure 8 shows that manii wood treated with the boric acid-chitosan mixture at 140 °C (M140) underwent the largest color change (ΔE) of 14.11. This value falls within the $\Delta E \geq 12$ range, indicating a very high color contrast. Meanwhile, mindi wood subjected to the same boric acid-chitosan mixture treatment at 140 °C (M140) exhibited its largest color change (ΔE) of 10.95. This value reflects a pronounced color modification, corresponding to a high color difference ($6 \leq \Delta E < 12$). Despite these color changes, all treatments retained the natural grain pattern of the wood, thereby preserving the aesthetic value of wood products.

In the weathering test (Figure 10), untreated (N), BC, and M treatments showed a decrease in L^* values, indicating darker wood, whereas B and CB treatments exhibited an increase in L^* , resulting in a brighter appearance in both manii and mindi woods. The increase in L^* values in the B and CB treatments may be attributed to the colorless nature of boron compounds and their susceptibility to leaching (Verly et al., 2020), which limits the formation of a protective surface layer against photodegradation, resulting in higher brightness during exposure. Additionally, all treatments exhibited lower a^* and b^* values, indicating a shift toward greener

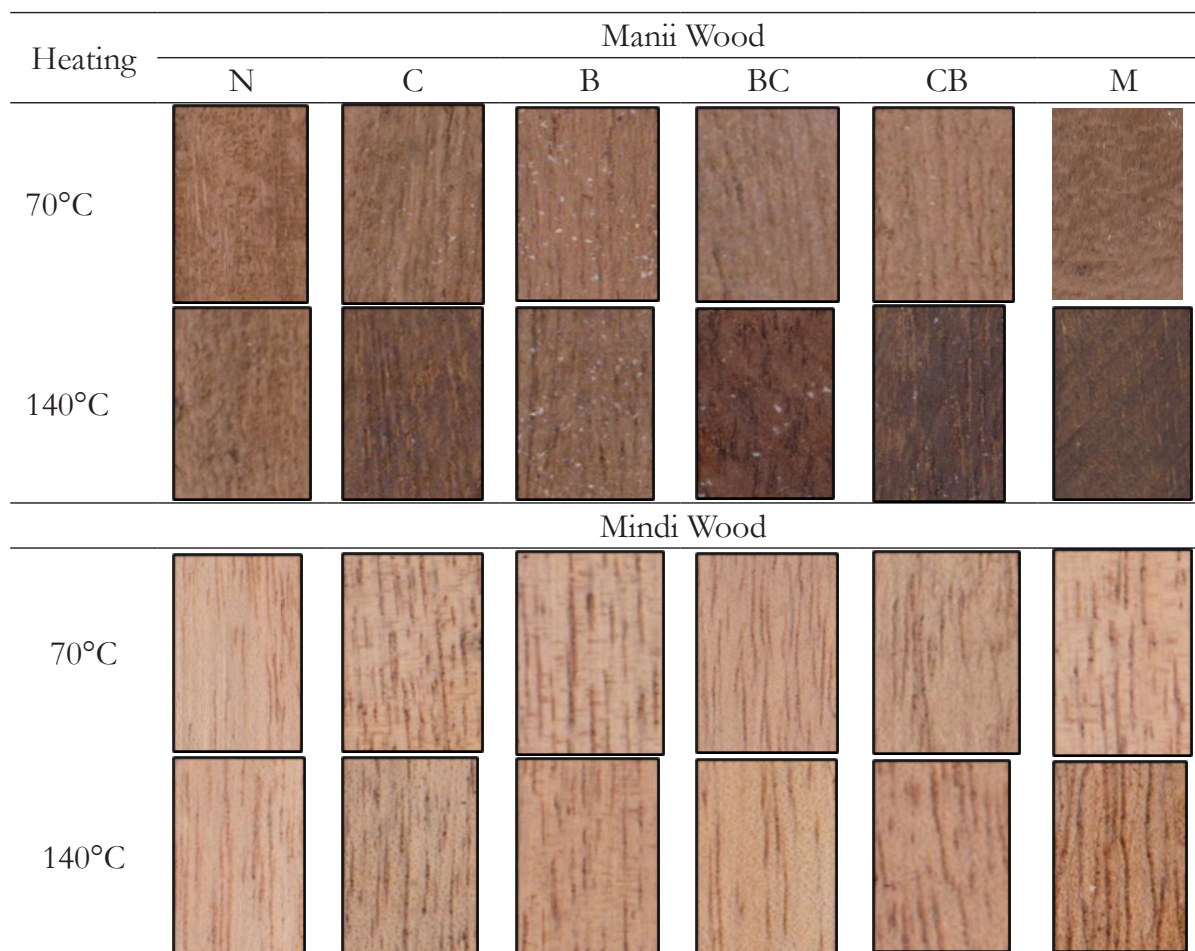


Figure 9. The color changes of manii and mindi wood treated without impregnation (N), with boric acid (B), chitosan (C), boric acid-chitosan (BC), chitosan-boric acid (CB), mixture combination boric acid +chitosan (M), and heating temperatures (70 °C and 140 °C). Values that are not substantially different in Duncan's test are shown by the same letters (a, b, c, etc.).

and bluer color tones during weathering. Turkoglu et al. (2015) suggest that changes in wood's redness (a^*) are due to alterations in extractive content, while changes in yellowness (b^*) are linked to lignin modifications. These observed color changes are influenced not only by weathering factors but also by fungal activity attacking the wood during weathering, particularly in the untreated samples.

Figure 11 shows that 90 days of weathering led to fading in wood color. Specifically, manii and mindi wood treated with the boric acid-chitosan mixture at 140 °C (M140) underwent color changes (ΔE) of 5.14 and 14.15, respectively. These results indicate moderate color ($3 \leq \Delta E < 6$) alteration in manii wood and substantial color modification ($\Delta E \geq 12$) in mindi wood after weathering.

The variations in weight loss (WL) in wood during weathering may result from the combined effects of fungal colonization, leaching of extractives, and degradation of cell wall components under fluctuating environmental conditions. Weight changes during weathering (Figure 13) showed that both manii and mindi woods gained weight between days 30 and 60, likely due to the absorption of rainwater (June–August 2022). Subsequently, a decrease in weight was observed by day 90 (September 2022). This observation is supported by data from BMKG (2022) concerning rainfall in Bogor Regency, which indicated substantial rainfall from June to August, reaching 77 mm/day to 132 mm/day, while rainfall decreased to 66.3 mm/day in March.

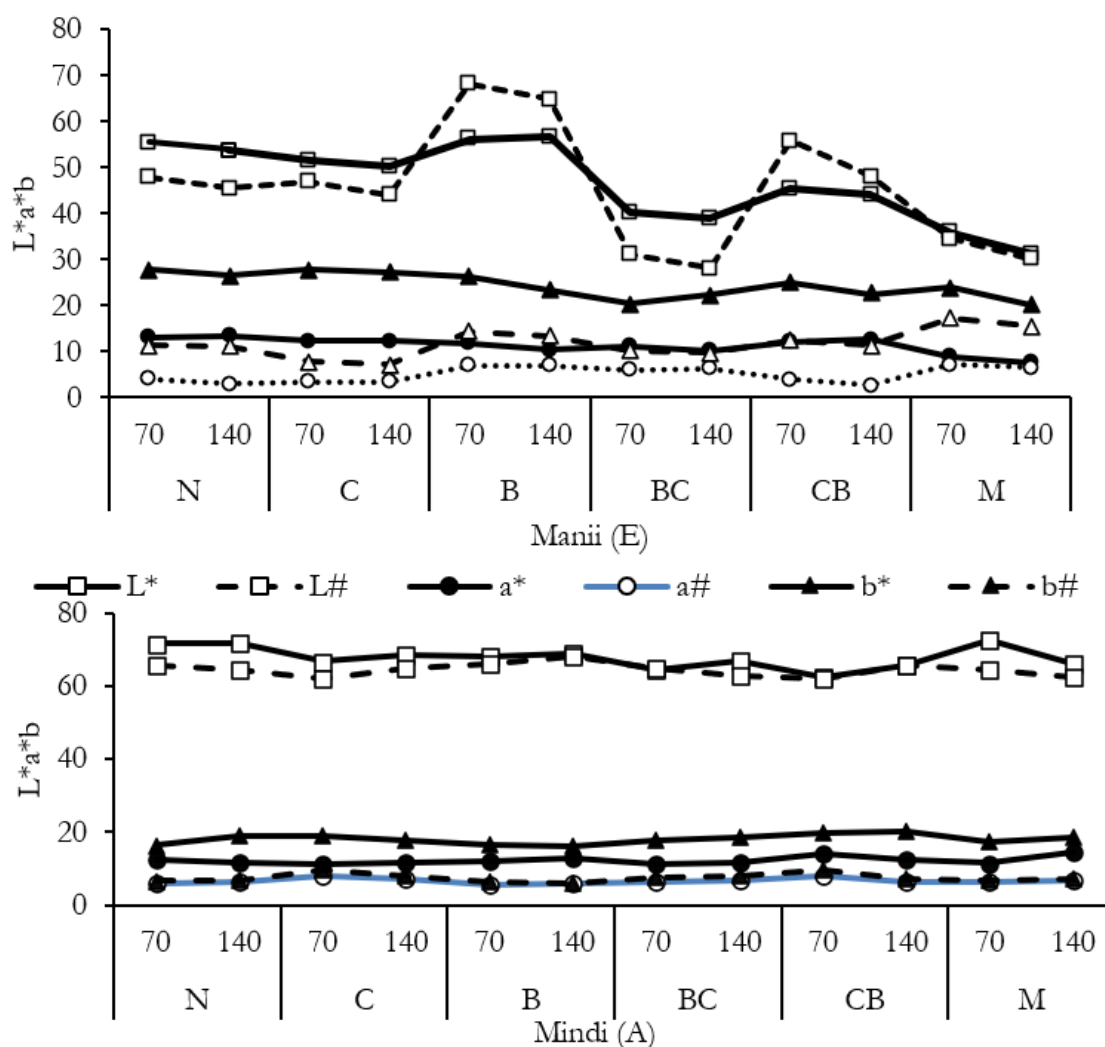
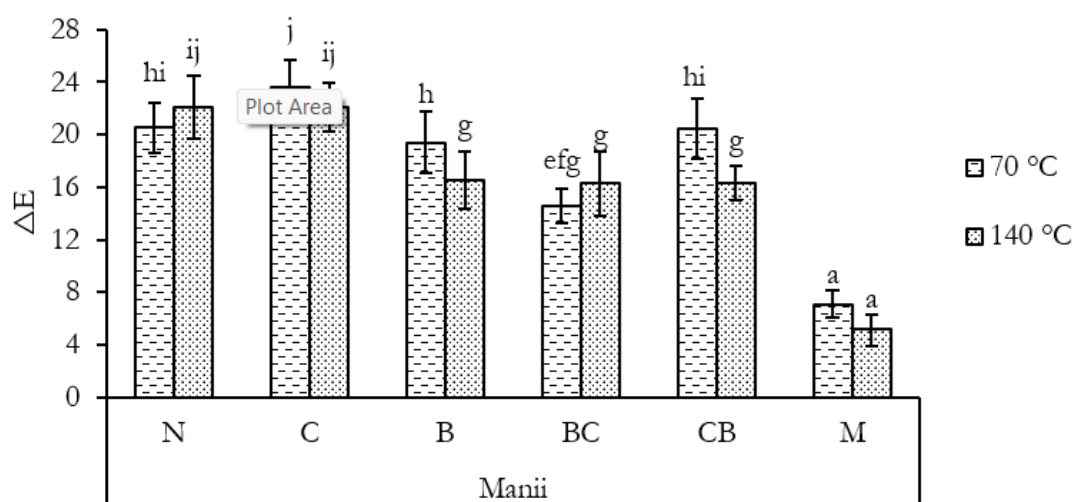


Figure 10. The L*a*b* after weathering of manii and mindi wood treated without impregnation (N), with boric acid (B), chitosan (C), boric acid-chitosan (BC), chitosan-boric acid (CB), mixture combination boric acid +chitosan (M), and heating temperatures (70 °C and 140 °C).



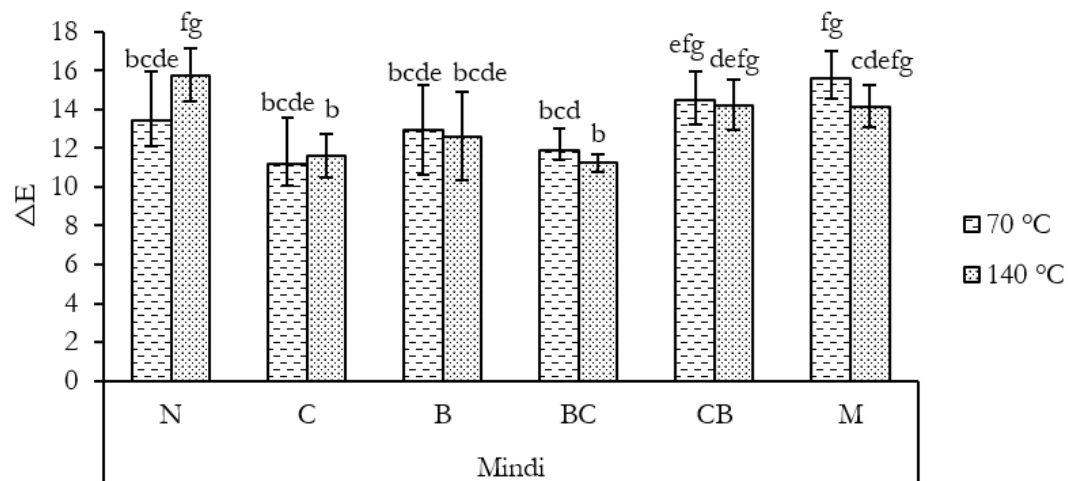


Figure 11. The ΔE after weathering of manii and mindi wood treated without impregnation (N), with boric acid (B), chitosan (C), boric acid-chitosan (BC), chitosan-boric acid (CB), mixture combination boric acid +chitosan (M), and heating temperatures (70 °C and 140 °C). Values that are not substantially different in Duncan's test are shown by the same letters (a, b, c, etc.).



Figure 12. The color changes after weathering of manii and mindi wood treated without impregnation (N), with boric acid (B), chitosan (C), boric acid-chitosan (BC), chitosan-boric acid (CB), mixture combination boric acid +chitosan (M), and heating temperatures (70 °C and 140 °C).

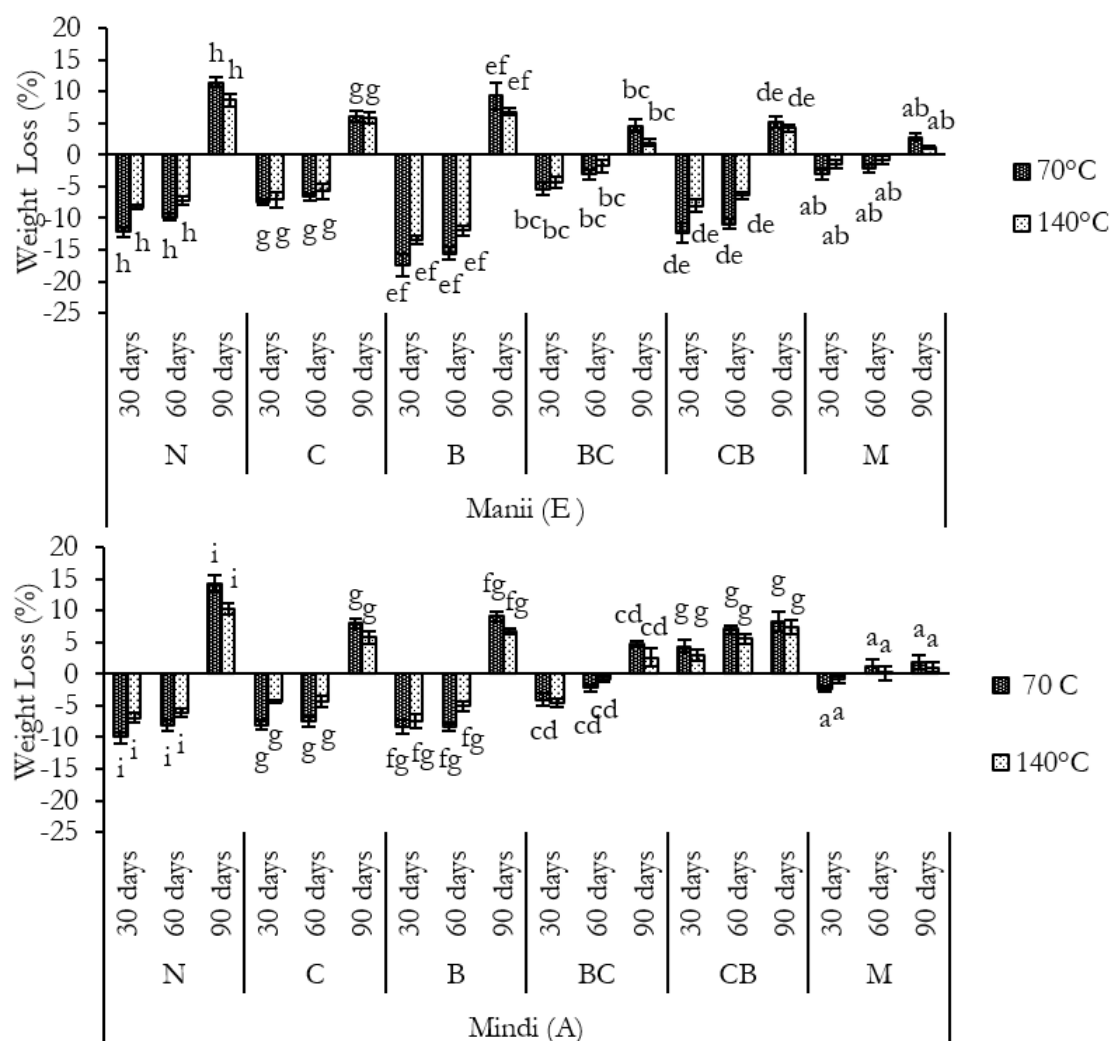


Figure 13. The weight loss after weathering of manii and mindi wood treated without impregnation (N), with boric acid (B), chitosan (C), boric acid-chitosan (BC), chitosan-boric acid (CB), mixture combination boric acid +chitosan (M), and heating temperatures (70 °C and 140 °C). Values that are not substantially different in Duncan's test are shown by the same letters (a, b, c, etc.).

The increase in wood weight during high rainfall periods is attributed to moisture uptake, while the subsequent decrease results from drying under lower rainfall conditions, reflecting dynamic moisture exchange during weathering. These environmental fluctuations may also contribute to color changes during weathering through repeated wetting–drying cycles and sunlight exposure (Krisdianto et al., 2018).

The analysis of variance revealed that weight loss was influenced by the interaction between wood species and impregnation treatment after 90 days of weathering ($F(5,96) = 10.01$, $p < 0.001$).

The weight loss values of M140 and BC140 were significantly lower than those of the untreated samples (N70). This reduction suggests that boric acid and chitosan acted synergistically to improve the resistance of wood to weathering and moisture-related deterioration. After 6 months of weathering, pine wood impregnated with 4% boric acid showed a weight loss of 17.67%, which was lower than that of the untreated samples (Can & Sivrikaya, 2019). In that study, the weight loss reduction was attributed to excess boron crystals remaining on the surface of the treated pine wood. Chitosan

exhibits antifungal activity due to its ability to interact with fungal cell membranes and its positively charged amino groups ($-NH_2$), which can disrupt microbial growth (Oldertroen et al., 2016). Heat treatment modifies the wood structure into a more hydrophobic form, thereby limiting water absorption and reducing biological susceptibility.

The improved performance observed in boron–chitosan heat-treated ($140\text{ }^{\circ}\text{C}$) samples compared to the control and boron-only treatments indicates enhanced protective effectiveness. Boric acid provides antifungal activity by reducing fungal-induced weight loss, while chitosan further strengthens protection through its antimicrobial properties. Heat treatment further enhances protection by increasing hydrophobicity and reducing moisture availability.

IV. CONCLUSION

Boric acid, chitosan, and heat treatments generally improved the physical properties and weathering resistance of manii (*Maesopsis eminii* Engl.) and mindi (*Melia azedarach* Linn.) woods. Chitosan treatment significantly reduced leaching, water absorption, and weight loss due to weathering compared with boric acid treatment in manii and mindi woods. Chitosan and heat treatments effectively reduced the leaching of the boron preservative, especially with the combined boric acid–chitosan mixture and $140\text{ }^{\circ}\text{C}$ heating (M140). The combination of boric acid and chitosan treatments successfully enhanced the wood's resistance to weathering more effectively than boric acid treatment. A higher concentration of boric acid was also observed in manii and mindi wood using the boric acid–chitosan mixture.

Therefore, the recommended modification treatment for manii and mindi wood is impregnation with a boric acid–chitosan mixture followed by heating at $140\text{ }^{\circ}\text{C}$ (M140). This treatment was generally better than other treatments in reducing leaching, increasing density, and significantly improving weathering resistance compared to untreated samples

of manii and mindi wood. These findings highlight the potential of boric acid–chitosan impregnation combined with heat treatment as a promising wood modification approach for fast-growing wood species and provide a basis for sustainable wood modification.

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