

THE SURFACE CHARACTERISTICS AND PHYSICAL PROPERTIES OF SENGON WOOD AT HIGH-TEMPERATURE HEATING TREATMENTS

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THE SURFACE CHARACTERISTICS AND PHYSICAL PROPERTIES OF SENGON WOOD AT HIGH-TEMPERATURE HEATING TREATMENTS. Sengon (*Falcataria moluccana* Miq.) is a fast-growing timber species widely distributed in Indonesia. However, its dimensional instability and low surface quality have limited its widespread use. Wood modification is essential for enhancing these properties, and one effective approach is heat treatment. This study investigated the effects of different heat treatment methods and durations on color change, surface roughness, weight loss (WL), decreased density, and dimensional stability of sengon wood. The heat modification process was conducted using two methods: oven-heating and hot press-heating, with temperatures set at 200°C for durations ranging from 1 to 5 hours. The results indicated that oven-heated samples exhibited higher surface roughness, weight loss, density reduction, and dimensional stability while showing less color change than hot press-heated samples. Additionally, the hot press-heated samples displayed more significant color changes (darkening) and smoother surface roughness. WL and decreased density were also more pronounced with longer heating durations, except for the 4- and 5-hour hot press-heating treatments. Notably, oven-heated samples demonstrated higher dimensional stability than hot press-heated samples as the duration of heating increased. Based on the results, the optimal treatment varies depending on the desired product characteristics. For improved surface qualities with consideration of WL, the optimum treatment is a 2-hour hot press-heating treatment. Higher dimensional stability can be achieved through a 3-hour oven-heating treatment.

Keywords: Surface characteristic, heat treatments, sengon, physical properties

KARAKTERISTIK PERMUKAAN DAN SIFAT FISIS KAYU SENGON PADA PERLAKUAN PANAS DENGAN SUHU TINGGI. Sengon (*Falcataria moluccana* Miq.) merupakan salah satu jenis tanaman cepat tumbuh yang tersebar luas di Indonesia. Namun, stabilitas dimensi dan kualitas permukaan yang rendah mengakibatkan kayu sengon tidak dapat diaplikasikan secara luas. Modifikasi kayu diperlukan untuk memperbaiki sifat-sifat tersebut, salah satunya dengan perlakuan panas. Penelitian ini menganalisa pengaruh metode dan durasi pada penerapan perlakuan panas yang berbeda terhadap perubahan warna, kekasaran permukaan, penurunan berat (WL), penurunan kerapatan, dan stabilitas dimensi kayu sengon. Proses modifikasi panas dilakukan menggunakan dua metode, yaitu oven dan hot-press. Pemanasan dilakukan pada suhu 200°C selama 1 hingga 5 jam. Hasil penelitian menunjukkan bahwa sampel yang dipanaskan dengan oven memiliki kekasaran permukaan, kehilangan berat, penurunan kerapatan, dan stabilitas dimensi yang lebih tinggi,

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namun menghasilkan perubahan warna yang lebih rendah dibandingkan dengan sampel yang dipanaskan dengan hot-press. Sementara itu, sampel yang dipanaskan dengan hot-press menunjukkan perubahan warna yang lebih signifikan (lebih gelap) dan permukaan yang lebih halus. WL dan penurunan densitas meningkat seiring bertambahnya durasi pemanasan, kecuali untuk perlakuan hot-press selama 4 dan 5 jam. Seiring bertambahnya durasi pemanasan, sampel kayu yang dipanaskan dengan oven menunjukkan stabilitas dimensi yang lebih tinggi dibandingkan dengan sampel yang dipanaskan dengan hot-press. Berdasarkan hasil penelitian, perlakuan yang optimal tergantung pada tujuan produk akhir. Untuk meningkatkan karakteristik permukaan dengan pertimbangan WL, perlakuan yang optimal adalah pemanasan dengan hot press selama 2 jam. Sementara itu, peningkatan stabilitas dimensi terbaik dapat dihasilkan dari perlakuan pemanasan oven selama 3 jam.

Kata kunci: karakteristik permukaan, perlakuan panas, sengon, sifat fisis

I. INTRODUCTION

Fast-growing species have emerged as viable plantation forest commodities, serving as alternative raw materials sources for the wood-based industry in Indonesia. These species are characterized by their rapid growth rates, short-cutting cycles, and high productivity, as well as their ability to act as pioneer species for open-land rehabilitation and reforestation (Alamsyah et al., 2007; Augustina et al., 2023; Nuraini et al., 2023). Sengon (*Falcataria moluccana* Miq.) is a fast-growing species recognized for its lightweight wood, with a specific gravity range of 0.24 to 0.49 and a strength class of IV-V (Martawijaya et al., 1989). However, the latter species is susceptible to wood-destroying agents due to its low durability (durability class IV-V). The wood contains more juvenile than mature wood, contributing to its dimensional instability (Rahayu et al., 2021). Currently, the utilization of sengon wood is limited to lightweight construction, pulpwood, furniture, and plywood. Therefore, a technological approach is necessary to enhance its properties and broaden its applications.

Heat treatment is the oldest wood modification technique. It offers several novel properties, including higher dimensional stability, increased resistance to wood-destroying agents (such as fungi and microorganisms), an aesthetically pleasing dark color, lower moisture content, improved water resistance, and improved thermal insulation properties (Yildiz et al., 2006; Sivrikaya et al., 2015). This process is typically carried out at temperatures ranging

from 150 to 240°C for 15 minutes to 24 hours (Chu et al., 2016; Hill et al., 2021). According to Hill et al. (2021), thermal conditions applied below 150°C are defined as thermal aging; those between 150 and 240°C are classified as thermal modification; and temperatures above 240°C are categorized as thermal degradation. In the early stages of heat treatment, the temperature of wood increases rapidly. Free water evaporates at a temperature around 100°C. Meanwhile, some water vapor will move deeper into the wood, distancing itself from the heating surface. This moisture transport generates three distinct zones: a dry zone near the surface closest to the heat source, a dehydrating zone, and a wet zone (Bartlett et al., 2019; Zhang et al., 2017). Generally, the wood surface (dry zone) has a slightly higher temperature increase than the inside (dehydrating zone and wet zone). The wood surface is unable to attain the ambient temperature because of thermal resistance during the heat convection process (Zhang et al., 2017). The heat treatment alters the wood's chemical composition, resulting in the degradation of hemicellulose, lignin, and certain extractives (Salca & Hiziroglu, 2014).

Over the last decade, numerous researchers have explored various heat treatment methods. These applications include complex processes such as the ThermoWood, Plato, Rectification, and Le Bois Perdure/Perdure processes, which generally utilize vacuum and/or steam under air (oxygen) or inert gas (nitrogen) conditions. Other methods include oil heat treatment, which employs oil as a heat transfer medium without

oxygen (Esteves & Pereira, 2009; Korkut & Budaksci, 2010; Sanberg et al., 2012; Rajković & Miklečić, 2019), microwave heat treatment (Mascarenhas et al., 2021), oven treatment (Yildiz et al., 2006; Kučerová et al., 2016), and hot pressing in an open system (Qiaofang et al., 2019; Ding et al., 2022). Although the more complex methods are preferable for producing commercially viable products, they require sophisticated equipment and intricate procedures. Consequently, simpler methods are more suitable to apply by small and medium enterprises (SMEs).

During heat treatment, several surface characteristics and physical properties of wood can be altered due to the severity of heat exposure, which varies with temperature and duration. Yildiz et al. (2006) studied heat-treated spruce (*Picea orientalis*) wood in an oven at temperatures of 130, 150, 180, and 200°C for 2, 6, and 10 hours, respectively. Their results indicated that the equilibrium moisture content (EMC) decreases with elevated temperature and prolonged heat exposure. Consequently, the treated wood exhibited reduced shrinkage and swelling behavior, enhancing dimensional stability. Kučerová et al. (2016) investigated oven heating European silver fir (*Abies alba* L.) wood for 1 hour at various temperatures (100, 150, 200, 220, 240, 260, and 280°C). Their findings showed that color changes in the wood became more noticeable at temperatures between 200 and 220°C. Moreover, significant mass loss was noted above 200°C attributable to hemicellulose degradation, removal of volatile compounds, and loss of certain extractives. Ding et al. (2022) examined heat-treated Douglas fir (*Pseudotsuga menziesii*) using a hot press at 200°C for 380 and 480 minutes and reported that the treated wood became darker and hydrophobic in the surface layer, ultimately improving its dimensional stability. Qiaofang et al. (2019) treated rubberwood (*Hevea brasiliensis*) using a hot press for 1.5 and 3 hours at several temperatures (170, 185, and 200°C), observing that the treated wood exhibited higher oven-

dried density, lower EMC, and more excellent dimensional stability.

It is interesting to observe the straight forward technologies, such as the oven and hot-press system, and comparing their effectiveness when applied to fast-growing wood species, particularly sengon wood (*Falcataria moluccana* Miq.). Therefore, this study aimed to evaluate two heating methods, utilizing an oven and a hot press system at 200°C, with heat exposure durations ranging from 1 to 5 hours. The investigation focused on assessing the impact of these treatments on various surface quality characteristics, including color changes and surface roughness, as well as physical properties such as weight loss, decreased density, and dimensional stability. This procedure may provide an alternate method to improving these properties, potentially increasing the value of sengon wood and allowing its use as a substitute material with quality comparable to other commercially available wood species.

II. MATERIAL AND METHOD

A. Materials

This study used sengon wood (*Falcataria moluccana* (Miq.) Barneby & Grimes) with a 30-35 cm diameter (5-6 years) sourced from Bogor, West Java, Indonesia. The lower section of the sengon wood was processed into boards comprising heartwood and sapwood sections, measuring 300 cm (length) x 12 cm (width) x 6 cm (thickness). The boards were acclimatized to ambient temperature (moisture content 12-15%). Subsequently, the boards were cut into the dimensions of 30 cm (length) x 5 cm (width) x 2 cm (thickness) and were then sanded with a 400-grit belt sander to standardize the surface roughness. The samples were analyzed for various properties, including color changes, surface roughness, weight loss (WL), and density reduction. After treatment, the samples were cut into the dimension of 2 cm (length) x 2 cm (width) x 2 cm (thickness) and subjected to dimensional stability testing. The sample preparation process is presented in Figure 1.

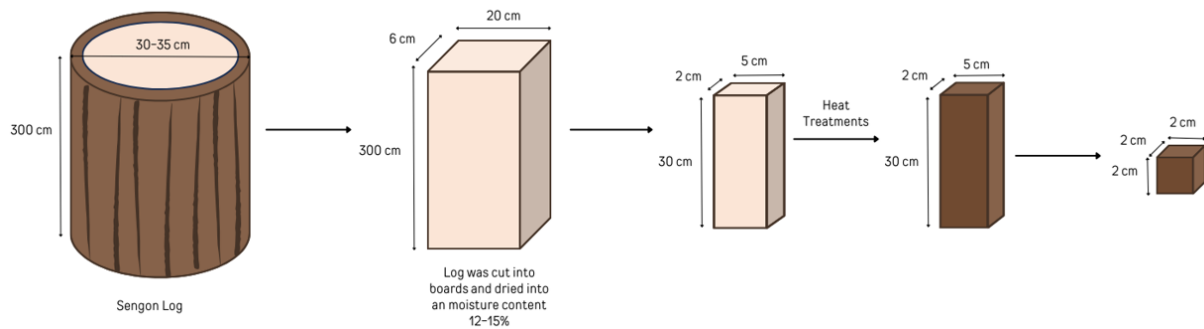


Figure 1. Samples preparation process

B. Methods

Each air-dried sample had its initial weight and dimensions measured. Subsequently, the samples were subjected to high-temperature treatment using two different heating techniques: oven and hot press (Denes & Lang, 2013; Kučerová et al., 2016; Qiaofang et al., 2019; Ding et al., 2022). The heating process was conducted at 200°C for 1, 2, 3, 4, and 5 hours. After treatment, the samples were air-dried until they achieved a constant weight. Each sample was re-weighed and re-measured. The treated samples were evaluated for color change, surface roughness, weight loss, decreased density, and dimensional stability, with three repetitions for each test parameter.

a. Color changes

The discoloration of the wood samples was measured using a Konica Minolta CR 10 colorimeter, equipped with a D65 light source, photodiode array sensor, and 10° observer standard. Measurements were performed before

and after heat treatment, with three repetitions for each sample. The analysis of color changes was carried out using the CIE Lab and CIE Lch methodologies, which included measurements of L^* (brightness), a^* (red-green), b^* (yellow-blue), c^* (chroma), and h^* (hue) values. In order to determine the differences in ΔL^* , Δa^* , Δb^* , Δc^* , and Δh^* , the measurements of the untreated wood sample (control) and the treated wood sample were compared using Equations (1)–(5). The total color differences (ΔE_{Lab^*} and ΔE_{Lch^*}) were computed using Equations (6) and (7), as described by Bessala et al. (2023). The classification of color change is presented in Table 1, as reported by ^bNguyen et al. (2018).

$$\Delta L^* = L^*_{\text{treated}} - L^*_{\text{untreated}} \dots\dots\dots(1)$$

$$\Delta a^* = a^*_{\text{treated}} - a^*_{\text{untreated}} \dots\dots\dots(2)$$

$$\Delta b^* = b^*_{\text{treated}} - b^*_{\text{untreated}} \dots\dots\dots(3)$$

$$\Delta c^* = c^*_{\text{treated}} - c^*_{\text{untreated}} \dots\dots\dots(4)$$

$$\Delta h^* = h^*_{\text{treated}} - h^*_{\text{untreated}} \dots\dots\dots(5)$$

$$\Delta E_{\text{Lab}^*} = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2} \dots\dots\dots(6)$$

$$\Delta E_{\text{Lch}^*} = \sqrt{(\Delta L^*)^2 + (\Delta c^*)^2 + (\Delta h^*)^2} \dots\dots\dots(7)$$

Table 1. Classification of color changes (ΔE^*)

The value of color changes	Classification of color changes
$\Delta E^* < 0.2$	No noticeable difference
$0.2 < \Delta E^* < 2$	Minor difference
$2 < \Delta E^* < 3$	Color differences were noticeable on a high-quality screen
$3 < \Delta E^* < 6$	Color differences were noticeable on a medium-quality screen
$6 < \Delta E^* < 12$	Significant difference
$\Delta E^* \geq 12$	Distinct colors

b. Surface roughness

The surface roughness was measured before and after treatment samples utilizing a surface roughness tester (Mitutoyo SJ-210). The measurements were executed according to the International Organization for Standardization (2021), with a cut-off length of 0.8 mm, a path length of 6 mm, and a speed of 0.5 mm/s. Measurements were taken at 10 points with three repetitions. The parameters for analysis of surface roughness included average roughness (R_a), mean peak-to-valley height (R_z), and root mean square deviation of the profile (R_q). Data points from each wood sample were collected and averaged to obtain the final measurements.

c. Weight loss

The wood samples were weighed before and after treatment, with three repetitions for each measurement. The calculation of weight loss (WL) involved determining the difference in weight between the untreated wood sample (W_0) and the treated wood sample (W_1), as shown in Equation (8) (Bessala et al., 2023). Each test for weight loss was performed with three repetitions.

$$WL (\%) = \frac{w_0 - w_1}{w_0} \times 100 \quad \text{.....(8)}$$

d. Density reduction

Density (ρ) was determined by dividing the weight of the sample (w) by its volume (V). The density measurements were taken before and after treatment, with three repetitions for each measurement. The objective was to quantify the decrease in density following the heating process. The initial density was calculated using Equation (9). In contrast, the decrease in density (ρ_L) was determined by subtracting the final density after heating (ρ_1) from the initial density (ρ_0), as indicated in Equation (10) (Bessala et al., 2023).

$$\rho (g/cm^3) = \frac{w}{V} \quad \text{.....(9)}$$

$$\rho_L (\%) = \frac{\rho_0 - \rho_1}{\rho_0} \times 100 \quad \text{.....(10)}$$

e. Dimensional stability

After the heat treatments, wood samples (treated and untreated) with dimensions of 2 cm x 2 cm x 2 cm analyzed for dimensional stability. They were placed in an oven at $103 \pm 2^\circ\text{C}$ for 24 hours. The samples were then weighed and measured to obtain its mass and volume. The samples were then completely immersed in water at room temperature for 24 hours. The weight and dimensions of the wood samples were reassessed after immersion and drying in an oven at $103 \pm 2^\circ\text{C}$ for another 24 hours (Rowell & Ellis, 1978; Sargent, 2019). The difference between the volumetric swelling coefficient of untreated wood samples (S_0) and treated wood samples (S_1), as shown in Equation (11), was used to calculate anti-swelling efficiency (ASE). Meanwhile, water absorption (WA) was calculated by comparing the weight of the wood samples before immersion (w_0) and after immersion (w_1), as shown in Equation (12).

$$ASE (\%) = \frac{S_0 - S_1}{S_0} \times 100 \quad \text{.....(11)}$$

$$WA (\%) = \frac{w_1 - w_0}{w_0} \times 100 \quad \text{.....(12)}$$

C. Analysis

The experimental design was entirely randomized. Data were presented as mean values with standard deviations. Analysis of variance (ANOVA) was used to assess the treatment-affected color changes, surface roughness, weight loss, density reduction, and dimensional stability in both untreated and treated wood. A subsequent Duncan's test (significance level $P < 0.05$) was conducted if the ANOVA results indicated a significant impact of the treatment on each response. The SPSS software was used to examine the data.

III. RESULT AND DISCUSSION

A. Color changes

Generally, untreated wood samples have a light color (Nemoto, 2002). Unfortunately, this light color is less attractive to some consumers,

encouraging many modifications, such as heat treatment, to change the color (Ciritcioğlu et al., 2017; Hidayat et al., 2017). Throughout the heat treatment process, the wood samples eventually change to a darker color as the temperature and length of treatment increase. According to Hill (2006), the intensity of color change is influenced by various factors, including the heating technique, temperature, and duration of exposure. This phenomenon also varies between oven and hot press-heating treatments. The color change in heated wood samples after hot press-heating was only observed on the upper surface, whereas oven-heating resulted in homogeneous color changes throughout the entire wood sample, as shown in Figure 2 (a). This difference may be due to the distinct heat exposure mechanisms during these treatments. In hot-press-heating, the principal mechanism is conduction, which involves the transfer of heat energy from the hot-press iron plate to the wood surface. This process is limited to the top area of the wood samples. According to Cengel (2002), conduction occurs when heat energy is transferred, resulting in mutual interaction that facilitates higher thermal transfer and more pronounced heat-induced discoloration. In contrast, the mechanism during oven-heating is convection, which involves the transfer of heat between the circulating gas and the solid wood constituents (Cengel, 2002). As a result,

all parts of the wood samples are heated.

The values of color changes in the wood samples subjected to both heating treatments are presented in Table 2. It can be seen that the parameter values of L^* , a^* , b^* , c^* , and h^* of the oven-heated wood samples exhibited higher values than those of the hot press-heated wood samples. These values were inversely proportional to the $\Delta E^*(\text{Lab})$ and $\Delta E^*(\text{Lch})$ values, with the hot press-heating treatment yielding higher values than the oven-heating treatment. The lightness value (L^*) was observed to decrease due to discoloration at 200 °C, leading to an overall color change (ΔE^*) and resulting in a darker appearance (Denes & Lang, 2013). The color change ranges, as measured by $\Delta E^*(\text{Lab})$ and $\Delta E^*(\text{Lch})$, were 10.5–25.2 and 10.8–25.4 for the oven-heating treatment, and 27.3–38.7 and 27.7–39.2 for the hot press-heating treatment, respectively. According to the color classification provided in Table 1 (bNguyen et al., 2018), it can be observed that most samples exhibited a color difference classification of $\Delta E^* \geq 12$, except for the oven-heating treatment for 1 hour, which fell within the range of $6 < \Delta E^* < 12$. The findings suggest that applying heat treatment through hot press-heating resulted in a more pronounced color change than oven-heating, as visualized in Figure 2 (b). These results are contrary to the research by Denes and Lang

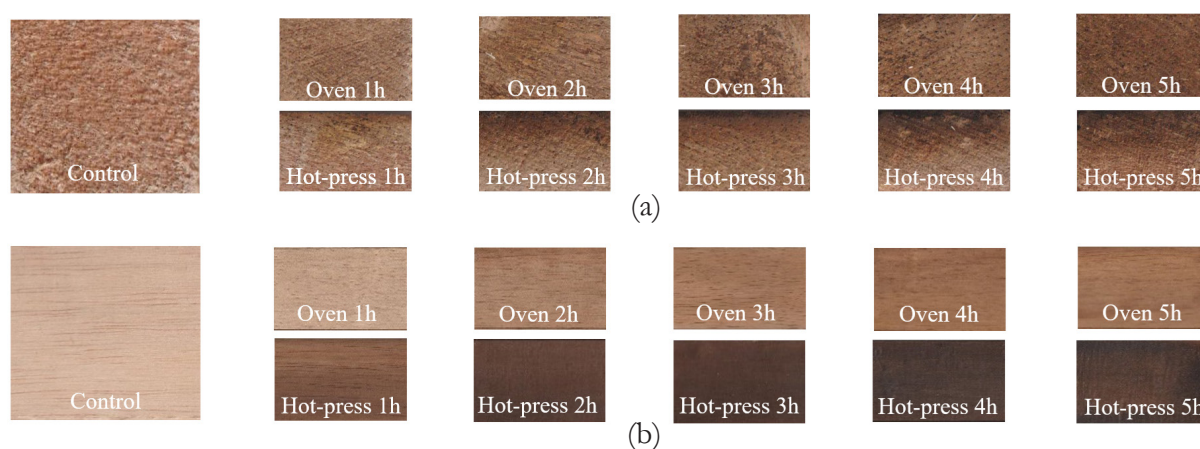


Figure 2. The changes in color on (a) cross-section and (b) surface of oven-heated and hot press-heated wood samples

(2013), which observed that the oven-heated yellow poplar (*Liriodendron tulipifera* L.) veneer was darker than the hot-pressed red oak (*Quercus rubra* L.) veneer treated for the same durations (10, 20, and 30 minutes). This difference in results is likely due to the significant variation in treatment duration. Direct exposure to heat (hot press) for a longer time allows for more color darkening due to hemicellulose degradation (Denes & Lang, 2013).

According to Table 2, the color changes (ΔE^*) were influenced by longer treatment durations. Extended treatment duration correlates with a more significant color change observed. Similar color changes due to heat treatment methods and durations have been reported for lime wood. Lime (*Tilia cordata* Mill.) wood was oven-heated treatment at 200°C for 1, 2, 3, and 4 hours, resulting in ΔE^* (Lab) values of 37.13, 45.14, 50.17, and 53.09, respectively (Olarescu

et al., 2014). A longer duration of treatment is associated with a corresponding darkening of the wood samples during the process (Piernik et al., 2002; ^aNguyen et al., 2018). The observed color change indicates the occurrence of chemical decomposition within the wood constituents, including hemicellulose, lignin, and extractives (Williams, 2005). According to previous studies, temperatures exceeding 190°C have a detrimental effect on hemicellulose content (Denes & Lang, 2013; Kac'ikova et al., 2013). Furthermore, volatile compounds evaporate when temperatures reach 200°C or higher, and chemical compounds decompose (Bekhta & Niemz, 2003; Sivrikaya et al., 2019). The decrease in hemicellulose, particularly pentosan, results in the reduction of measurable color coordinates. This phenomenon ultimately leads to discernible color changes (Bourgeois et al., 1991).

Table 2. Parameters of color changes in untreated and heated wood samples at different methods and duration of treatments

Heating Methods	Time (h)	Parameters of Colors Changes						
		L*	a*	b*	c*	h*	ΔE^* _(Lab)	ΔE^* _(Lch)
Untreated		72.3 ^a ± 1.52	7.7 ^c ± 1.13	17.4 ^c ± 1.51	19.0 ^c ± 1.82	66.2 ^b ± 1.42	-	-
Oven	1	62.8 ^b ± 2.8	8.2 ^c ± 0.4	20.6 ^b ± 0.7	22.2 ^{cd} ± 0.7	68.4 ^a ± 1.0	10.5 ^f ± 1.4	10.8 ^f ± 1.5
		57.9 ^c ± 2.8	9.2 ^b ± 0.3	21.0 ^{ab} ± 0.5	22.9 ^{bc} ± 0.5	66.4 ^b ± 0.9	15.7 ^e ± 1.2	15.7 ^e ± 1.2
	3	55.5 ^d ± 1.2	10.5 ^a ± 0.4	22.4 ^a ± 0.6	24.7 ^a ± 0.7	64.9 ^c ± 0.5	22.3 ^d ± 4.0	23.1 ^d ± 5.2
		50.6 ^e ± 1.1	10.9 ^a ± 0.2	21.6 ^{ab} ± 0.6	24.2 ^{ab} ± 0.6	63.1 ^d ± 0.4	23.8 ^d ± 0.8	24.0 ^d ± 0.9
	5	51.1 ^e ± 1.1	10.9 ^a ± 0.1	21.7 ^{ab} ± 0.4	24.3 ^{ab} ± 0.3	63.4 ^{de} ± 0.5	25.2 ^{cd} ± 0.6	25.4 ^{cd} ± 0.7
		46.8 ^f ± 3.7	9.7 ^b ± 0.5	18.4 ^c ± 1.8	20.8 ^d ± 1.7	62.3 ^{ef} ± 1.6	27.3 ^c ± 3.3	27.7 ^c ± 3.5
	2	39.8 ^g ± 1.9	7.6 ^{cd} ± 1.0	13.1 ^d ± 1.8	15.1 ^f ± 2.0	60.1 ^{hi} ± 0.2	37.8 ^b ± 4.2	39.1 ^b ± 4.6
		37.2 ^h ± 2.3	6.9 ^d ± 1.0	11.6 ^e ± 2.0	13.5 ^g ± 2.2	59.3 ⁱ ± 0.6	38.1 ^b ± 2.9	39.0 ^b ± 3.0
	4	33.1 ⁱ ± 0.9	3.6 ^f ± 0.6	6.4 ^g ± 0.9	7.3 ⁱ ± 1.1	61.0 ^{gh} ± 1.2	43.1 ^a ± 2.7	43.9 ^a ± 3.3
		35.9 ^h ± 1.1	4.8 ^e ± 0.6	8.9 ^f ± 1.1	10.1 ^h ± 1.2	61.3 ^{fg} ± 0.5	38.7 ^b ± 1.4	39.2 ^b ± 1.4
Hot-press	1	46.8 ^f ± 3.7	9.7 ^b ± 0.5	18.4 ^c ± 1.8	20.8 ^d ± 1.7	62.3 ^{ef} ± 1.6	27.3 ^c ± 3.3	27.7 ^c ± 3.5
		39.8 ^g ± 1.9	7.6 ^{cd} ± 1.0	13.1 ^d ± 1.8	15.1 ^f ± 2.0	60.1 ^{hi} ± 0.2	37.8 ^b ± 4.2	39.1 ^b ± 4.6
	3	37.2 ^h ± 2.3	6.9 ^d ± 1.0	11.6 ^e ± 2.0	13.5 ^g ± 2.2	59.3 ⁱ ± 0.6	38.1 ^b ± 2.9	39.0 ^b ± 3.0
		33.1 ⁱ ± 0.9	3.6 ^f ± 0.6	6.4 ^g ± 0.9	7.3 ⁱ ± 1.1	61.0 ^{gh} ± 1.2	43.1 ^a ± 2.7	43.9 ^a ± 3.3
	5	35.9 ^h ± 1.1	4.8 ^e ± 0.6	8.9 ^f ± 1.1	10.1 ^h ± 1.2	61.3 ^{fg} ± 0.5	38.7 ^b ± 1.4	39.2 ^b ± 1.4
		46.8 ^f ± 3.7	9.7 ^b ± 0.5	18.4 ^c ± 1.8	20.8 ^d ± 1.7	62.3 ^{ef} ± 1.6	27.3 ^c ± 3.3	27.7 ^c ± 3.5
	2	39.8 ^g ± 1.9	7.6 ^{cd} ± 1.0	13.1 ^d ± 1.8	15.1 ^f ± 2.0	60.1 ^{hi} ± 0.2	37.8 ^b ± 4.2	39.1 ^b ± 4.6
		37.2 ^h ± 2.3	6.9 ^d ± 1.0	11.6 ^e ± 2.0	13.5 ^g ± 2.2	59.3 ⁱ ± 0.6	38.1 ^b ± 2.9	39.0 ^b ± 3.0
	4	33.1 ⁱ ± 0.9	3.6 ^f ± 0.6	6.4 ^g ± 0.9	7.3 ⁱ ± 1.1	61.0 ^{gh} ± 1.2	43.1 ^a ± 2.7	43.9 ^a ± 3.3
		35.9 ^h ± 1.1	4.8 ^e ± 0.6	8.9 ^f ± 1.1	10.1 ^h ± 1.2	61.3 ^{fg} ± 0.5	38.7 ^b ± 1.4	39.2 ^b ± 1.4

Notes: The superscript letters signify the degree of statistical significance ($P < 0.05$). The various superscript letters denote significant differences in means between treatments and vice versa.

B. Surface roughness

Table 3 shows the observed surface roughness parameters, which were Rq, Rz, and Ra. The oven-heated wood samples generally exhibited higher Rq, Rz, and Ra values than the hot press-heated wood samples. In contrast, the decrease in Ra, Rz, and Rq values for the oven-heated samples (5.67–17.09%) was lower than that for the hot press-heated samples (4.86–50.84%). This phenomenon was also observed in the heat treatment process of rubber (*Hevea brasiliensis*) wood, where the surface roughness of samples heated in the oven decreased less than that of the hot press samples. The Ra value for a rubber wood oven-heated at 180°C for 2 hours decreased by 38.4% (Ratnasingam & Ioras, 2012). This decrease in Ra was lower than that of hot-pressed rubber wood, which decreased by 42.59% and 48.74% at 185°C for 1.5 and 3 hours, respectively (Zhu et al., 2021). These results could be attributed to difference mechanism in heat treatment method applied. The oven method utilizes convection to transfer heat, exposing the sample's wood surface to the hot air within the oven. In the hot press method, heat is transferred through conduction, with the hot plate in direct contact with the sample's surface, allowing a direct heat reaction and

decreasing the wood surface's roughness. Heat treatment softens the wood fibers in the surface layer, causing the cell walls to plasticize. This leads to an enhancement in surface smoothness (Ayrilmis et al., 2019; Zhu et al., 2021).

Furthermore, surface roughness decreased with the extension of the heat treatment duration, as presented in Table 3. Wood samples that underwent heat treatment for 1 hour exhibited an average decrease in the Rq, Rz, and Ra values of 6.14–7.32%, 8.77–9.37%, and 4.86–5.67%, respectively. The reduction in surface roughness continued with the treatment duration, reaching a maximum after 5 hours. Heat treatment for 5 hours resulted in average decreases in Rq, Rz, and Ra values of 17.66–52.96%, 19.28–59.18%, and 17.66–50.84%, respectively. A similar decrease in surface roughness due to duration was seen in oriental beech wood treated to heat treatment at 200°C for 2, 4, and 8 hours, with reductions of Rq (10.13%, 16.85%, and 37.40%), Rz (8.29%, 17.15%, and 42.01%), and Ra (12.60%, 17.56%, and 35.53%) (Basyal et al., 2014). A decrease in Ra of around 10% was also noted in short rotation teak heated at 200°C for 2 hours (Martha et al., 2021). This reduction is attributed to alterations in the

Table 3. Parameters of surface roughness in untreated and heated wood samples at different methods and duration of treatments

Heating Methods	Time t (h)	Parameters of Surface Roughness		
		Ra (μm)	Rq (μm)	Rz (μm)
Untreated		10.40 ^a ± 0.21	13.48 ^a ± 0.48	74.61 ^a ± 4.05
Oven	1	9.81 ^b ± 0.23	12.49 ^b ± 0.21	67.62 ^b ± 2.97
	2	9.73 ^b ± 0.65	12.42 ^{bc} ± 0.72	66.11 ^b ± 3.40
	3	9.57 ^{bc} ± 0.41	12.50 ^b ± 0.65	68.79 ^b ± 2.52
	4	9.04 ^{cd} ± 0.09	11.67 ^{cd} ± 0.14	64.28 ^{bc} ± 1.04
	5	8.62 ^d ± 0.20	11.10 ^{de} ± 0.14	60.23 ^{cd} ± 1.44
Hot-press	1	9.90 ^b ± 0.12	12.65 ^b ± 0.24	68.07 ^b ± 2.66
	2	7.73 ^e ± 0.07	10.36 ^{ef} ± 0.16	57.65 ^d ± 1.14
	3	7.52 ^e ± 0.11	9.70 ^f ± 0.12	53.01 ^e ± 0.09
	4	6.34 ^f ± 0.53	8.14 ^g ± 0.46	44.74 ^f ± 3.01
	5	5.11 ^g ± 0.24	6.34 ^h ± 0.30	30.45 ^g ± 0.73

Notes: The superscript letters signify the degree of statistical significance ($P < 0.05$). The various superscript letters denote significant differences in means between treatments and vice versa.

biochemical constituents of the cell wall, which become more pronounced with increasing heating duration (Bakar et al., 2013; Basyal et al., 2014). Additionally, surface roughness can be influenced by multiple factors, such as wood species, cutting direction (radial, longitudinal, or tangential), annual ring width, juvenile and mature wood, cellular composition, machining conditions, and cutting characteristics (Sogutlu, 2005; Karagoz et al., 2011; Dundar et al., 2008).

The significant decrease in the Ra value indicates a progressive increase in the smoothness of the wood surface. This phenomenon arises from heat treatment, which induces plasticization of the wood surface by modifying the glass transition (T_g) temperature of the lignin (Korkut et al., 2009) and facilitating the migration of waxy and fatty substances from axial parenchyma cells to the outer surface (Nuopponen et al., 2003). A smoother wood surface can enhance adhesion between surfaces and improve the contact angle for wettability (Krystofiak et al., 2022). Additionally, it can improve the quality of wood surfaces and reduce the cost losses associated with sanding and planing operations (Dundar et al., 2008; Korkut et al., 2009).

C. Weight loss and density reduction

The analysis of weight loss and density reduction is important because it indicates the quality of the treatment (Candelier et al., 2016). The weight loss showed a positive correlation with the treatment time, as illustrated by the data in Figure 3(a). During the 1–5 hours heat treatment period, weight loss ranged from 12.16% to 15.76% for the oven-heated wood samples and 8.82% to 12.61% for the hot press-heated wood samples. Olarescu et al. (2014) indicated that weight loss in lime wood escalated with heat treatment duration at 200°C for 1 to 4 hours, approximately 4.3% to 9.3%. Notably, air-dried sengon wood exhibited significantly higher weight loss than oven-dried lime wood, as the air-dried sengon wood samples had a higher initial water content, resulting in greater evaporation during heating. The initial weight

loss during the heating process can be ascribed to the evaporation of water molecules and the breakdown of heat-sensitive substances, particularly hemicellulose (Aydin & Colakoglu, 2005; Esteves et al., 2008). Furthermore, it was found that the oven-heating treatment resulted in greater weight loss than the hot press-heating treatment. This is reasonable, as the oven treatment affected the entire wood surface, while the hot-press treatment primarily influenced only the top-most surface layer.

Moreover, heat treatment has been observed to decrease wood density. The untreated wood sample's air-dry density is 0.29 g/cm³. Following a heating period of 1 to 5 hours, the density decreased. After oven-heating, the wood density varied from 0.19 to 0.22 g/cm³. The density positively correlates with the reduction of density, which varied from 9.42% to 12.89%. When the wood hot press-heated, its density decreased by around 3.46% to 8.81%, varying from 0.21 to 0.28 g/cm³. Similar decreases in density were observed in heat-treated wood at 200°C for 2 hours; for example, scots pine (*Pinus sylvestris* L.) experienced a density decreased by 18.41% (Kamperidou et al., 2014), while poplar (*Populus beijingensis* W. Y. Hsu) had a density decreased by 11.17% (Chu et al., 2016). Additionally, heat-treated beech wood (*Fagus orientalis* Lipsky) at 200°C for a duration of 1, 2, and 3 hours exhibited density losses of 11.17%, 13.68%, and 15.04%, respectively (Percin, 2016). Extending heat treatment duration enhances the degradation of various wood chemical components of wood, including hemicellulose, lignin, and particularly in the amorphous regions of cellulose, leads to the formation of micro-cracks that eventually reduce wood density (Nabil et al., 2018). Other factors contributing to density reduction include the evaporation of extractive substances, overall weight loss, and a decrease in equilibrium moisture content (EMC) (Korkut & Kocaefe, 2009; Pelit et al., 2018).

The decrease in density of oven-heated samples was more significant than that of the hot press-heated samples, as illustrated by the

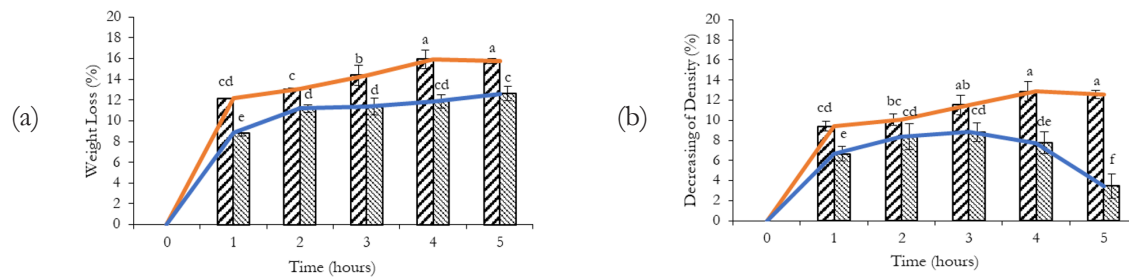


Figure 3. Weight loss (a) and density reduction (b) of the oven-heated (▨; —) and hot press-heated (■; —) wood samples. Columns lacking identical superscript letters exhibit significant differences ($p < 0.05$).

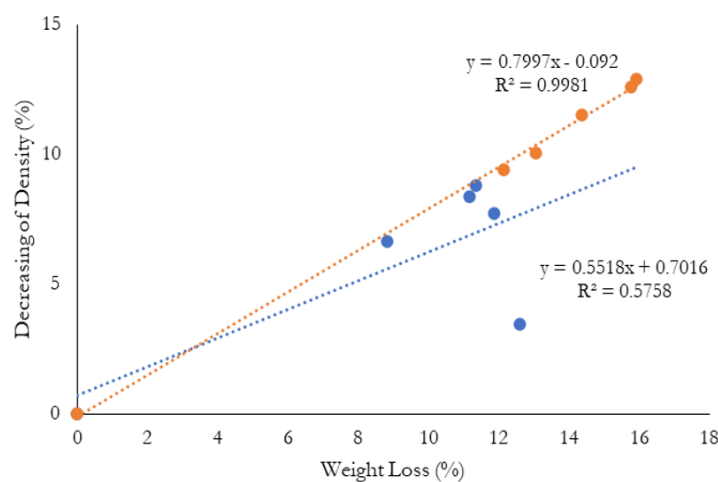


Figure 4. Relationship between density reduction and weight loss of oven-heated (●) and hot press-heated (●) wood samples

data in Figure 3 (b). A notable reduction in density occurred during the heating process for 1 to 2 hours in both treatments. Following this period, the density values for the oven-heated samples showed a slight increase during the 3 to 5-hour treatment. In contrast, a continued decrease in the density occurred of the hot press-heated wood samples during the 4 and 5-hour treatments. This phenomenon can be attributed to the reduction in wood dimensions, particularly on the surfaces of the samples subjected to hot press-heating. The surfaces of these samples were charred and degraded, as shown in Figure 3 (b), leading to a decrease in the overall volume and consequently affecting its density.

This finding is supported by a positive correlation between the decrease in density and

weight loss, as shown in Figure 4. A positive connection is shown between the percentage decrease in density and weight loss for the oven-heating treatment ($y = 0.7997x - 0.092$; $R^2 = 0.9981$) and the hot press-heating treatment ($y = 0.5518x + 0.7016$; $R^2 = 0.5758$). Notably, the oven-heating treatment demonstrates a higher correlation (R^2 value) compared to the hot press-heating treatment. This difference may be attributed to the effect of oven-heating on the entire wood surface, which enhances the evaporation of water molecules and the breakdown of heat-sensitive components. In contrast, the hot press-heating treatment primarily affects only the top-most layer of the wood's surface.

D. Dimensional stability

Dimensional stability is a crucial factor to consider when addressing the shrinkage caused by the hygroscopic nature of wood. The dimensional stability was assessed by measuring the water absorption (WA) and anti-swelling efficiency (ASE) values. Heat treatment application reduced WA values and increased ASE values for the wood samples, as shown in Figure 5. Compared to hot press-heated wood samples, oven-heated wood samples had lower WA values, ranging from 76.93% to 83.34%. The ASE values for wood samples subjected to hot press-heating ranged from 24.92% to 32.63%, while those from oven-heating ranged from 32.71% to 51.46%. This indicates that oven-heated samples exhibit lower WA values and higher ASE than hot-pressed samples. This difference occurs because all wood samples's surfaces are exposed to heat during oven-heat treatment, whereas hot press-heating typically only affects one side/surface of wood samples.

The findings indicated that the WA value negatively correlates with heating duration, while the ASE value shows a positive correlation, as illustrated in Figure 5. As the length of heat treatment extended, the WA value diminished. After 1 hour of heat treatment, the WA values ranged from 79.36% to 80.65%, decreasing further to 56.63% and 77.30% after 5 hours. A similar negative correlation between WA and heating duration was observed in ash wood

(*Fraxinus angustifolia* Vahl.), where the WA values decreased with longer treatment times. Specifically, wood heated at 190°C for 3, 6, and 9 hours exhibited WA values of 42.33%, 41.21%, and 39.54%, respectively (Sahin & Guler, 2018). Prolonged heating duration causes hemicellulose degradation and hydroxyl groups in cellulose amorphous areas to break down, which reduces hygroscopicity (Weiland & Guyonnet, 2003).

The decrease in water absorption (WA) values positively correlates with dimensional stability, as measured by anti-swelling efficiency (ASE). The ASE value also shows a positive correlation with heat treatment duration. Wood samples heated for 1 hour exhibited ASE values ranging from 24.92% to 32.71%, which increased to 32.63% to 51.46% after 5 hours of heating. The highest ASE value, recorded at 51.46%, was observed in wood samples heated in an oven for 5 hours. Similar results were reported in the research by Sahin and Guler (2018), where the ASE value of ash wood heated at 190°C for 9 hours was 49.44%. These findings can be explained by the decreased hygroscopicity of wood and the modification of its chemical components during the heating process (Martha et al., 2021), particularly in hemicellulose. Hemicellulose degradation releases organic acids, which reduce hydroxyl (OH) cross-links within the wood structure. This reduction in hydroxyl cross-links increases

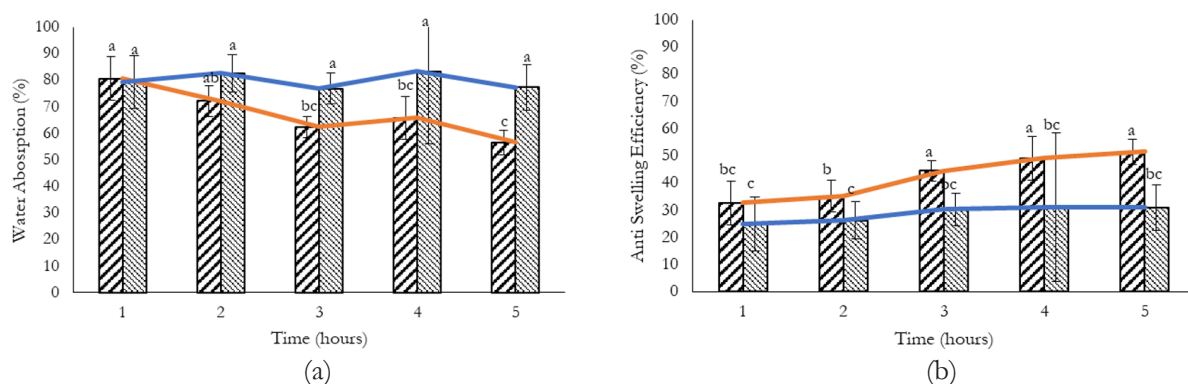


Figure 5. Water absorption (a) and anti-swelling efficiency (b) of oven-heated (▨; —) and hot press-heated (▤; —) wood samples. Columns lacking identical superscript letters exhibit significant differences ($p < 0.05$)

the hydrophobicity of the wood, thereby enhancing its dimensional stability (Bekhta & Niemz, 2003; Bakar et al., 2013). Furthermore, the migration of extractive substances to the wood surface has been shown to impede water penetration (Hill, 2006).

IV. CONCLUSION

Heat treatment of sengon wood resulted in a darker color, improved surface roughness, increased weight loss, decreased density, and enhanced dimensional stability. However, the differences in heat treatment techniques—oven versus hot press—led to varying changes in the characteristics of sengon wood. Oven-heating treatment relies on convection, allowing heating across the entire wood surface. In contrast, hot press-heating treatment utilizes conduction, influencing solely the sample area in direct contact with the heated iron plate. Consequently, hot press-heated wood samples exhibited a darker color, smoother surface roughness, lower weight loss, reduced density, and decreased dimensional stability compared to oven-heated wood. Additionally, longer heat treatment durations generally result in more distinct color darkening, lower surface roughness, greater weight loss, decreased density, and enhanced dimensional stability. Based on these findings, treatment selection depends on the desired outcome. If the goal is to enhance surface characteristics while considering weight loss, the optimal treatment is hot press-heating for 2 hours. Conversely, if the aim is to improve dimensional stability, oven-heating for 3 hours is recommended. Overall, the resistance of heat-treated samples to organism attack presents an area for potential future research.

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