International Information and Engineering Technology Association
Advancing the World of Information and Engineering

International Journal of Heat and Technology
Vol. 41, No. 3, June, 2023, pp. 769-774
Journal homepage: http://iieta.org/journals/ijht

Environmentally-Friendly Wood Modification: Physical and Mechanical Properties of Jabon Wood (*Anthocephalus cadamba*) as Affected by Oil Heat Treatment

Wahyu Hidayat[1*], Intan Fajar Suri[1,2], Indra Gumay Febryano[1], Hade Afkar[1], Lusy Rahmawati[1], Duryat[1], Nam Hun Kim[2]

[1] Department of Forestry, Faculty of Agriculture, University of Lampung, Bandar Lampung 35145, Indonesia
[2] Department of Forest Biomaterials Engineering, Kangwon National University, Chuncheon 24341, Republic of Korea

Corresponding Author Email: wahyu.hidayat@fp.unila.ac.id

https://doi.org/10.18280/ijht.410334

Received: 9 March 2023
Accepted: 16 June 2023

Keywords:
Anthocephalus cadamba, mechanical properties, oil heat treatment, physical properties

ABSTRACT

Jabon (*Anthocephalus cadamba*) is a promising fast-growing wood species to overcome the decreasing wood supply from natural forests. However, fast-growing wood has inferior properties compared to wood from natural forests, so improving the wood quality through oil heat treatment is needed. This research aimed to determine the effects of treatment temperature during oil heat treatment on the physical and mechanical properties of jabon wood. Each wood specimen was oil heat-treated at 170°C, 190°C, and 210°C for 4 hours. Color change of wood after treatment was evaluated using the CIE-Lab color system. The weight changes, volume shrinkage, density, moisture content, compressive strength, and hardness before and after heat treatment were also observed. The results revealed that the lightness (L^*) of wood remarkably decreased after oil heat treatment, showing a darker color with increasing treatment temperature so that it resembled the color of exotic wood with high economic value. Oil heat treatment resulted in a weight gain and a volume reduction of jabon wood, followed by an increase in density. The wood moisture content decreased as the temperature increased, indicating that wood is more hydrophobic after oil heat treatment, thereby enhancing its dimensional stability. Moreover, the oil heat treatment also increased the compressive and hardness of wood samples. In conclusion, it was found that the characteristics of jabon wood could be enhanced with oil heat treatment.

1. INTRODUCTION

The decline in the quality and quantity of natural forests requires community and plantation forests as wood suppliers [1]. According to Marsoem [2], community forests have enormous potential in supplying wood as industrial raw materials because the wood produced from community forests is mostly fast-growing. Statistics Indonesia [3] reported that the potential of community forests in Indonesia is promising, with a total area of 2,000 ha and is dominated by fast-growing trees, such as jabon (*Anthocephalus cadamba*). Jabon trees are suitable as investment plants, reclamation of ex-mining land, and reforestation [4]. However, fast-growing wood has weaknesses such as low specific gravity and durability, which impact wood resistance and low dimensional stability [5].

To enhance certain qualities of wood, one of the most cutting-edge techniques is to subject it to a heat treatment [6-9]. Wood modification via heat treatment has been proven to enhance the hydrophobicity, dimensional stability, and biological resistance of wood [10, 11]. Hydrophobicity increased as shown by higher contact angle and lower wettability characteristics, and equilibrium moisture content was lower in heat-treated wood than the untreated wood [7, 12]. Heat treatment can also modify the wood's physiology by destroying the tracheid wall, stingray tissue, and desperation pits [13]. Wood species, heat treatment method, and process conditions all have a role in this [14].

Oil heat treatment (OHT) is one of the affordable, chemically sustainable, and environmentally friendly wood modification techniques [15]. Dimensional stability, hydrophobicity, mold, and darkening resistance and fire safety can be improved by oil absorption, as was shown in another study connected to the heat treatment of oils [16, 17]. Treatment with oil heat improved the dimensional stability of wood, as compared to treatment with hot air and nitrogen [18]. OHT is another option that may be utilized to further improve the quality of wood for use in outdoor applications as well as uniformly stain the surface [19].

There have been a number of studies in the past that have been widely reported on the effect of OHT on improving wood in the property. After being heated in an oil media, *Populus* spp. wood's compressive strength rose as a result of the oil's ability to thicken cell walls and fill lumens [20]. A separate study found that heating Chinese fir wood in oil made it denser and less likely to shrink [21]. After being changed by heat treatments in oil and air, *Paulownia tomentosa* and *Pinus koraiensis* woods changed in color and weight in different ways [22]. The structure of gmelina and Mindi wood is also changed by oil heat treatment. In both wood species, OHT thickens the cell walls of the fibers [23]. Recent research also explains that OHT causes an increase in wood density, volume shrinkage, compressive strength, and hardness [24].

As explained above, oil heat treatment could be promising as a way to improve and change some properties of wood. However, there is still limited study on oil heat treatment of fast-growing wood species. In particular, there has not been much research on the oil heat treatment of jabon wood. Hence, this study was carried out to contribute novel scientific information regarding the impact of oil heat treatment on the properties of jabon wood.

2. MATERIALS AND METHODS

2.1 Materials preparation

Jabon (*Anthocephalus cadamba*) wood of 6-year-old was collected from a community forest in Tanjung Bintang, Lampung Selatan Regency, Lampung Province, Indonesia. The logs were cut into boards with as size of (300 × 90 × 20) mm^3 in length, width, and thickness, respectively. Boards were chosen for their lack of knots and straight grain. The board samples were then dried before subjected to oil heat treatment. Considering that the wood is freshly cut (green wood), wood drying was carried out in two stages, namely air drying for approximately 2 weeks to minimize drying defects, followed by oven drying at 100°C for 24 hours. Oven-dried samples were used for oil heat treatment.

2.2 Oil heat treatment process

The oil heat treatment process was performed using a lab-scale oil heat treatment kiln (Figure 1). Commercial palm oil (FILMA, PT. SMART Tbk., Jakarta, Indonesia) was used. The palm oil used has a light-yellowish color, density of 0.85 g/cm³, and viscosity of 4.70. The wood samples were organized using a metal sticker, and the top pile was held in place with a metal brace to avoid floating during treatment. The kiln receives vegetable oil. At room temperature, samples were soaked in oil and heated to 170°C, 190°C, and 210°C at 2°C/min for 4 h. After heat treatment, wood samples were cooled and drained to dry any remaining oil on the wood surface. Wood samples were stored indoors at room temperature for 2 weeks until further testing.

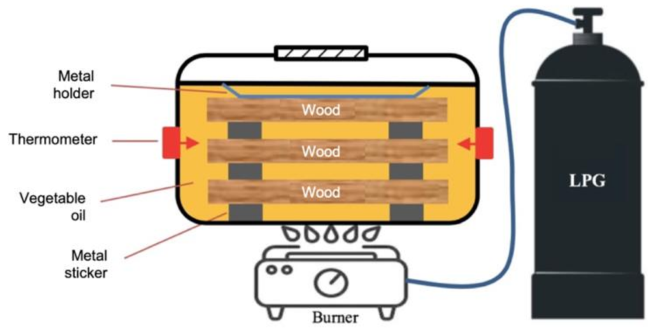

Figure 1. Oil heat treatment kiln

2.3 Wood properties evaluation before and after oil heat treatment

2.3.1 Color change

The CIE L*a*b* system was utilized to calculate the color change. This system is comprised of three factors, which are as follows: L^* (lightness), a^* (red/green chromaticity), and b^* (yellow/blue chromaticity). A chromameter (AMT507, Amtast, China) was used to collect three readings at different points on each specimen's radial surface before and after being subjected to heat treatment. The following equation was used to determine the overall color change:

$$\Delta E^* = (\Delta L^{*2} + \Delta a^{*2} + \Delta b^{*2})^{½} \quad (1)$$

The shift of lightness, red/green chromaticity, yellow/blue chromaticity, and overall color are shown by ΔL^*, Δa^*, Δb^*, and ΔE^*, respectively.

2.3.2 Physical properties evaluation

The following formula was used to determine the weight changes percentage before and after heat treatment:

$$WC(\%) = \frac{m_1 - m_0}{m_0} \times 100 \quad (2)$$

where, m_0 is the sample weight before heat treatment (g), and m_1 is the sample weight after heat treatment (g).

The volume shrinkage of samples before and after heat treatment was estimated using the following equation:

$$VS(\%) = \frac{V_0 - V_1}{V_0} \times 100 \quad (3)$$

where, V_0 is the volume of samples before oil-heat treatment (mm) and V_1 is the volume of samples after oil-heat treatment (mm).

Using the following formula, the density (D) of samples before and after heat treatment was estimated.

$$D(g/cm^3) = \frac{m}{v} \quad (4)$$

where, m is the weight (g), and v is the volume of samples (cm^3).

The moisture content of the wood before and after oil heat treatment was measured by weighing the air-dry weight and oven-dry weight of the samples using the following equation:

$$MC(\%) = \frac{M_1 - M_0}{M_0} \times 100 \quad (5)$$

where, M_0 is the initial weight (g), and M_1 is the final weight (g).

After measuring three samples for each physical attribute following each treatment, the mean values were calculated.

2.3.3 Mechanical properties evaluation

The compressive strength of untreated and heat-treated samples was calculated according to ASTM D 143-94 [25] with the formula:

$$P = \frac{F}{A} \quad (6)$$

where, F is the maximum load (N), A is the compressive surface area (mm^2), and P is the compressive strength of the wood (N/mm^2).

The hardness of OHT wood and control wood was compared using the maximum hardness value (ρ hard) referring to ASTM D 143-94 [25] on a sample size of 5 cm × 5 cm × 2 cm using half a steel ball. This test uses a steel ball compression section with a diameter of 11.7 mm.

2.4 Data analysis

Univariate analysis of variance and Duncan's multiple range tests were used to assess statistically significant differences between mean values of weight changes, density, volume shrinkage, compressive strength, and hardness across treatment temperatures (SPSS version 24; SPSS Inc., Chicago, IL, USA).

3. RESULTS AND DISCUSSION

3.1 Color change

Figure 2 depicts the appearance of jabon wood before and after oil heat treatment. As the temperature of the treatment increased, the wood color darkened. The wood after oil heat treatment has a darker color and looks more aesthetically similar to exotic woods from natural forests, so it can potentially increase economic value. The variations in lightness (L*) after heating oil are shown in Figure 3. The L* value drastically reduced as the temperature rose. Suri et al. [22] discovered that oil-heated *P. tomentosa* and *P. koraiensis* wood changed into darker color. Hidayat et al. [26] discovered that *L** decreased with increasing temperature in air-heated *P. tomentosa* and *P. koraiensis* woods. Kim et al. [27] discovered that *L** dropped as temperature increased in air-heated *P. tomentosa* wood.

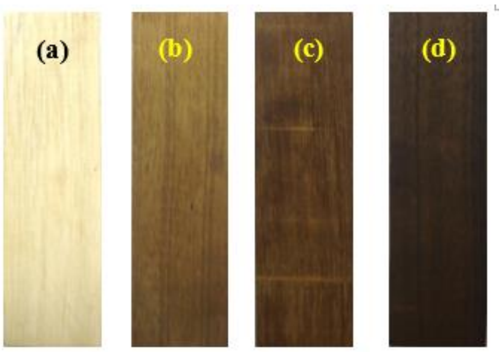

Figure 2. The look of jabon wood after being subjected to oil heat treatment at varying temperatures: (a) untreated sample, and heat-treated samples at (b) 170°C, (c) 190°C, and (d) 210°C

As seen in Figure 3, the *a** value increased as the treatment temperature increased. At 170°C and 190°C, the red/green chromaticity of both wood species increased, whereas it declined significantly at 210°C. The *a** value of heat-treated spruce wood, as observed by Bekhta and Niemz [28], increased during the first two hours of treatment and then stayed practically constant. *P. tomentosa* and *Populus tementiglandulosa* showed an increase in *a** value after heat treatment [27].

Figure 3 also illustrates the shift in yellow/blue chromaticity (*b**) of jabon wood after oil heat treatment. At 170°C and 190°C, the *b** value of the treated wood samples rose, however, it decreased rapidly at 210°C. According to Bekhta and Niemz [28], the *b** value of heat-treated Norway spruce wood peaked at 150°C and gradually fell to 200°C. Kim et al. [27] came to the same conclusion: after two hours of air treatment, the *b** value of *P. tomentosa* wood increased from 160°C to 200°C and then decreased to 220°C. The color shift of air heat-treated *P. koraiensis* wood also showed an increase of *b** at 160°C and then decreased at higher treatment temperatures [26].

Figure 4 displays the overall color changes (*ΔE**) of hot-oil-treated jabon wood. There was a correlation between the treatment temperature and the degree of color change in the wood. The high boiling point of oil means that it can be heated to very high temperatures during oil heat treatment, altering the chemical characteristics of wood components [22, 23, 29]. That could be one of the causes of oil discoloration while heating. The breakdown of hemicellulose shifts in chemical components and the generation of products of oxidation are the primary contributors to a dulling of coloration following heat treatment [17, 28].

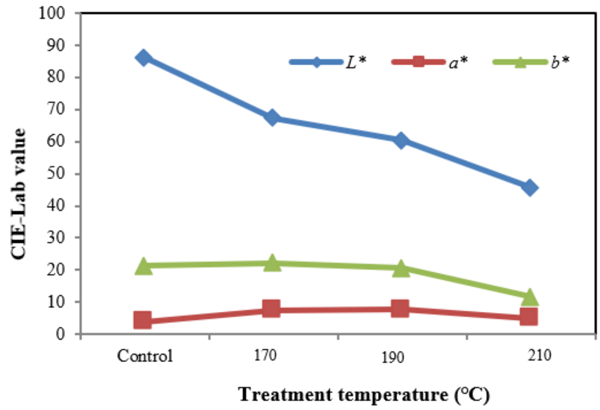

Figure 3. Change in *L**, *a**, and *b** of jabon wood after oil heat treatment

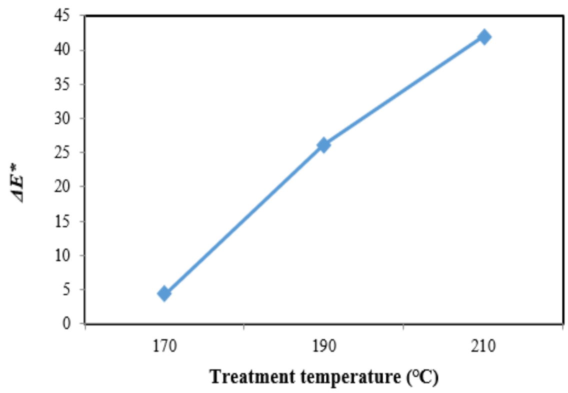

Figure 4. Change in *ΔE** of jabon wood after oil heat treatment

3.2 Physical properties

Table 1 displays the differences in jabon wood's weight before and after it was subjected to heat treatment. After being subjected to oil heat treatment, jabon wood indicated an increase in weight. One possible explanation for the increase in weight of the wood sample following oil heat treatment is oil uptake by the wood [17, 22, 30, 31].

Pinus radiata wood absorbs oil during heat treatment, leading to weight gain, followed by a decreasing trend in weight when heating times and temperatures are increased [17]. *P. tomentosa* and *P. koraiensis* woods treated with oil gained weight as the heat treatment temperature rose [22]. Upon subjecting aspen wood to heat treatment in oil at 190°C to 220°C for 4.5 and 6 h, the wood increased in weight by 83.2 to 86.2% [30]. Similarly, weight increased with oil heat treatment and decreased with air heat treatment in *Fagus orientalis* wood [31]. However, as the treatment temperature is raised, bound water and extractives are likely removed from the wood, resulting in weight loss. In addition, the heat treatment caused the hemicellulose in the wood to decompose, leading to a loss of weight [7].

Table 1. Physical properties of jabon wood during oil heat treatment

Temperature (°C)	Weight Changes (%)	Volume Shrinkage (%)	Density (g/cm³)	Moisture Content (%)
Control	-	-	0.45^{a} (0.08)	11.72^{d} (2.22)
170	44.49^{c} (2.72)	3.11^{c} (1.41)	0.87^{b} (0.21)	5.62^{c} (1.21)
190	41.19^{b} (5.93)	2.79^{b} (1.33)	0.74^{c} (0.16)	4.51^{b} (1.16)
210	40.41^{a} (3.07)	1.10^{a} (0.59)	0.75^{c} (0.16)	4.25^{a} (1.20)

*Standard deviations are shown by the numbers in brackets. Duncan's multiple range tests revealed statistically significant variations between treatment temperatures (shown by the various lowercase letters).

The oil heat treatment resulted in a volume reduction of jabon wood, as shown in Table 1. Wood that has been heated undergoes a reduction in volume. Treated wood with oil heat experienced a little volume reduction as the treatment temperature was raised. The shrinkage of heat-treated oak, teak, and chanul woods was shown to increase with increasing treatment temperature [32]. According to Uribe and Ayala [33], after heat treatment at 180°C, the volume shrinkage for species often demonstrates significant variation. It was also noted by Hidayat et al. [7] that the shrinking volume of *Cylicodiscus gabunensis* wood increased with rising temperature and that this was likely related to variations in the wood's density and volatile extractive content. When the number of cells in wood increased in thickness, the shrinkage and swelling values also did [34, 35].

As can be seen in Table 1, jabon wood's density altered after being heated. Density increased with increasing treatment temperature due primarily to oil absorption during treatment. The density peaked at 170°C and dropped at 190 and 210°C. Suri et al. [24] reported that the density of oil heat-treated *P. tomentosa* and *P. koraiensis* increased and decreased with increasing the treatment temperature and time. The density of oil-heated *P. radiata* wood was significantly raised, almost 80% greater than that of untreated samples [32]. The oil uptake caused an initial rise in density of 75% for oil-heat-treated Chinese fir wood, which then steadily reduced with increasing treatment temperature and time [21]. Degradation of hemicellulose and volatile components were cited as two potential causes of density loss after heat treatment.

As shown in Table 1, the moisture content after oil heat treatment shows a decrease as increasing the treatment temperature. This tendency shows that wood is more hydrophobic so that it can increase wood's dimensional stability. The moisture content of *Picea glauca* wood treated with OHT was lower at 220°C compared to 200°C and control samples [16]. After oil heat treatment, the wood's moisture content drops because oil seeps into the wood and replaces the water lost through evaporation at temperatures above 100°C [18]. The moisture content of the wood reduced when oil heat treated wood is dried because the temperature utilized does not cause the oil to evaporate [30].

3.3 Mechanical properties

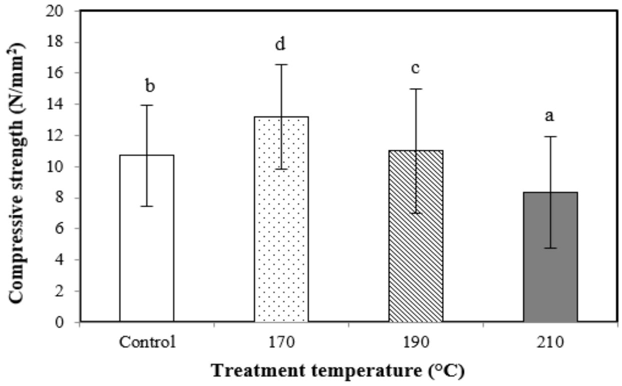

Figure 5. The temperature dependence of the increase in compressive strength of oil-heated jabon wood at various temperatures (different letters above the bar graph show significantly different at a 5% confidence level)

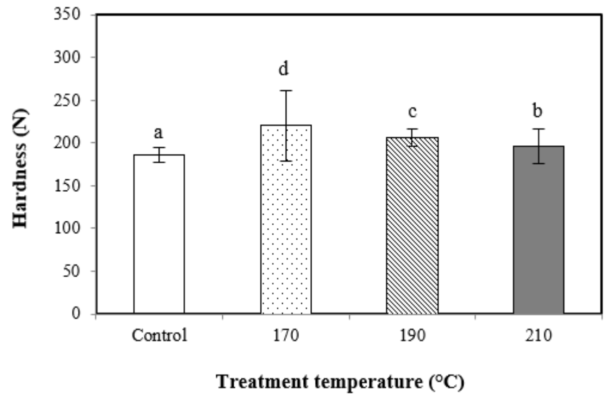

Figure 6. The temperature at which the oil is heated affects hardness of the jabon wood becomes (different letters above the bar graph show significantly different at a 5% confidence level)

Figure 5 displays the compressive strength of oil-heated jabon wood. When the treatment temperature was elevated over 180°C, all oil heat-treated samples reached their maximum compressive strength and then gradually lost strength as the temperature continued to rise.

The samples that had been subjected to heat treatment had a compressive strength that was much greater than that of the samples that had not been treated. Samples that were heat treated show their compressive strength peak at 170°C, then decline at 190 and 210°C. Increased axial compressive strength following oil heat treatment may be due to the oil ability to thicken, and lumen fills the cell walls of the treated samples [24]. This finding is consistent with those of other research that has examined oil heat treatment under varying temperatures. For example, following heat treatment in sunflower seed, linseed, and rapeseed oils at temperatures of 160 and 200°C for 2, 4, and 6 hours, respectively, the compressive strength of *Populus* wood rose by 15%-25% [36]. On the other hand, oil heat-treated Scots pine and beech woods showed minimal to no change in compression strength due to the wood's high density and strong oil absorption [37]. As a result of the increased density and crystallinity, heat-treating wood is thought to boost its compressive strength [17, 24, 27]. Nevertheless, hemicellulose degradation in wood polymers is primarily responsible for the loss in compressive strength of heated-treated *Picea orientalis* wood at temperatures between 150 and 200℃ [38].

A comparison of the original and oil-heated jabon wood hardness is shown in Figure 6. After being treated with oil, jabon wood became much harder as the temperature increased. Heat treatment under varying atmospheric conditions has been demonstrated to increase wood hardness in numerous researches. For example, at temperatures of 165 and 210℃, it was observed that the air-heat treatment of silver birch wood resulted in an increase in the wood's hardness on both the radial and tangential surfaces [39]. This was most likely the result of an increased concentration of mannan in the hemicelluloses [39]. After one hour of treatment at 180 and 200℃, the hardness of *Betula pubescens* wood rose, but after two and a half and four hours of treatment at those temperatures, the hardness reduced dramatically [40]. More crystalline cellulose, less bound water, and crosslinked lignin polymers may all contribute to oil-heat-treated wood's increased hardness [24, 41, 42].

4. CONCLUSIONS

The wood's color became darker after being heated with oil. After undergoing oil heat treatment, jabon wood showed an increase in weight and a reduction in volume. Post-oil-heat-treatment weight gain slowed down as temperature increased. Moreover, oil heat treatment significantly enhanced the density of the wood samples. As the oil heat treatment temperature increased, wood became more hydrophobic, enhancing its dimensional stability. Moreover, the oil-heat treatment enhanced the compressive and hardness of wood samples. The study shows that species features could be improved by oil heat treatment.

ACKNOWLEDGMENTS

The authors acknowledge the financial support of the Institute for Research and Community Services (LPPM), Universitas Lampung, Indonesia.

REFERENCES

[1] Sarjono, A., Lahjie, A.M., Kristiningrum, R., Herdiyanto, H. (2017). Produksi kayu bulat dan nilai harapan lahan jabon (*Anthocephalus cadamba*) di PT Intraca Hutani Lestari. Jurnal Hutan Tropis, 5(1): 22-30. http://doi.org/10.20527/jht.v 5i1.4052

[2] Marsoem, S.N. (2013). Studi mutu kayu jati di hutan rakyat gunungkidul i. pengukuran laju pertumbuhan. Jurnal Ilmu Kehutanan, 7(2): 108-122. https://doi.org/10.22146/jik.7529

[3] Statistics Indonesia. (2020). Statistik Produksi Kehutanan 2020. Statistics Indonesia. Jakarta, Indonesia. https://www.bps.go.id/publication/2021/07/30/d45441e7214b3c12c9653c45/statistik-produksi-kehutanan-2020.html.

[4] Mansur, I.I., Tuheteru, F.D., Hut, S. (2010). Kayu jabon. Penebar Swadaya Grup. Jakarta, Indonesia.

[5] Arsad, E. (2015). Teknologi pengolahan dan manfaat bambu. Jurnal Riset Industri Hasil Hutan, 7(1): 45-52. http://doi.org/10.24111/jrihh.v7i1.856

[6] Biziks, V., Andersons, B., Beļkova, Ļ., Kapača, E., Militz, H. (2013). Changes in the microstructure of birch wood after hydrothermal treatment. Wood Science and Technology, 47: 717-735. https://doi.org/10.1007/s00226-013-0531-1

[7] Hidayat, W., Jang, J.H., Park, S.H., Qi, Y., Febrianto, F., Lee, S.H., Kim, N.H. (2015). Effect of temperature and clamping during heat treatment on physical and mechanical properties of okan (*Cylicodiscus gabunensis* [Taub.] Harms) wood. BioResources, 10(4): 6961-6974. https://doi.org/10.15376/biores.10.4.6961-6974

[8] Hidayat, W., Qi, Y., Jang, J.H., Febrianto, F., Lee, S.H., Kim, N.H. (2016). Effect of treatment duration and clamping on the properties of heat-treated okan wood. BioResources, 11(4): 10070-10086. https://doi.org/10.15376/biores.11.4.10070-10086

[9] Hidayat, W., Qi, Y., Jang, J.H., Febrianto, F., Kim, N.H. (2017). Effect of mechanical restraint on the properties of heat-treated *Pinus koraiensis* and *Paulownia tomentosa* woods. BioResources, 12(4): 7539-7551. https://doi.org/10.15376/biores.12.4.7539-7551

[10] Tjeerdsma, B.F., Militz, H. (2005). Chemical changes in hydrothermal treated wood: FTIR analysis of combined hydrothermal and dry heat-treated wood. European Journal of Wood and Wood Products, 63(2): 102-111. https://doi.org/10.1007/s00107-004-0532-8

[11] Welzbacher, C.R., Wehsener, J., Rapp, A.O., Haller, P. (2008). Thermo-mechanical densification combined with thermal modification of Norway spruce (*Picea abies* Karst.) in industrial scale-dimensional stability and durability aspects. Holz als Roh-und Werkstoff, 1(66): 39-49. https://doi.org/10.1007/s00107-007-0198-0

[12] Kocaefe, D., Shi, J.L., Yang, D.Q., Bouazara, M. (2008). Mechanical properties, dimensional stability, and mold resistance of heat-treated jack pine and aspen. Forest Products Journal, 58(6): 88-93.

[13] Awoyemi, L., Jones, I.P. (2011). Anatomical explanations for the changes in properties of western red cedar (*Thuja plicata*) wood during heat treatment. Wood Science and Technology, 45: 261-267. https://doi.org/10.1007/s00226-010-0315-9

[14] Boonstra, M.J., Rijsdijk, J.F., Sander, C., Kegel, E., Tjeerdsma, B., Militz, H., Acker, J.V., Stevens, M. (2006). Microstructural and physical aspects of heat treated wood. Part 1. Softwoods. Maderas. Ciencia y Tecnología, 8(3): 193-208. http://doi.org/10.4067/S0718-221X2006000300006

[15] Tang, T., Chen, X.F., Zhang, B., Liu, X.M., Fei, B.H. (2019). Research on the physico-mechanical properties of moso bamboo with thermal treatment in tung oil and its influencing factors. Materials, 12(4): 599. https://doi.org/10.3390/ma12040599

[16] Wang, J.Y., Cooper, P.A. (2005). Effect of oil type, temperature and time on moisture properties of hot oil-treated wood. European Journal of Wood and Wood Products, 63(6): 417-422. https://doi.org/10.1007/s00107-005-0033-4

[17] Dubey, M.K., Pang, S.S., Walker, J. (2012). Changes in chemistry, color, dimensional stability and fungal resistance of *Pinus radiata* D. Don wood with oil heat-treatment. Holzforschung, 66(1): 49-57. https://doi.org/10.1515/HF.2011.117

[18] Lee, S.H., Ashaari, Z., Lum, W.C., Halip, J.A., Ang, A.F.,

Tan, L.P., Chin, K.L., Tahir, P.M. (2018). Thermal treatment of wood using vegetable oils: a review. Construction and Building Materials, 181: 408-419. https://doi.org/10.1016/j.conbuildmat.2018.06.058

[19] Sailer, M., Rapp, A.O., Leithoiff, H., Peek, R.D. (2000). Upgrading of wood by application of an oil-heat treatment. Holz als Roh-und Werkstoff, 58(1-2): 15-22. https://doi.org/10.1007/s001070050379

[20] Cheng, D.L., Chen, L.J., Jiang, S.X., Zhang, Q.S. (2014). Oil uptake percentage in oil-heat-treated wood, its determination by soxhlet extraction, and its effects on wood compression strength parallel to the grain. BioResources, 9(1): 120-131. https://doi.org/10.15376/biores.9.1.120-131

[21] Okon, K.E., Lin, F.C., Lin, X., Chen, C.X., Chen, Y.D., Huang, B. (2018). Modification of Chinese fir (*Cunninghamia lanceolata* L.) wood by silicone oil heat treatment with micro-wave pretreatment. European Journal of Wood and Wood Products, 76: 221-228. https://doi.org/10.1007/s00107-017-1165-z

[22] Suri, I.F., Kim, J.H., Purusatama, B.D., Yang, G.U., Prasetia, D., Lee, S.H., Hidayat, W., Febrianto, F., Park, B.H., Kim, N.H. (2021). Comparison of the color and weight change in *Paulownia tomentosa* and *Pinus koraiensis* wood heat-treated in hot oil and hot air. BioResources, 16(3): 5574-5585. https://doi.org/10.15376/biores.16.3.5574-5585

[23] Suri, I.F., Purusatama, B.D., Lee, S., Kim, N., Hidayat, W., Ma'ruf, S.D., Febrianto, F. (2021). Characteristic features of the oil-heat treated woods from tropical fast growing wood species. Wood Research, 66(3): 365-378. https://doi.org/10.37763/wr.1336-4561/66.3.365378

[24] Suri, I.F., Purusatama, B.D., Kim, J.H., Yang, G.U., Prasetia, D., Kwon, G.J., Hidayat, W., Lee, S.H., Febrianto, F., Kim, N.H. (2022). Comparison of physical and mechanical properties of *Paulownia tomentosa* and *Pinus koraiensis* wood heat-treated in oil and air. European Journal of Wood and Wood Products, 80(6): 1389-1399. https://doi.org/10.1007/s00107-022-01840-4

[25] ASTM D143-94. (2007). Standard Test Methods for Small Clear Specimens of Timber. ASTM, American Society for Testing and Materials, West Conshohocken, Pennsylvania, USA. https://www.astm.org/d0143-22.html.

[26] Hidayat, W., Qi, Y., Jang, J., Park, B., Banuwa, I.S., Febrianto, F., Kim, N. (2017). Color change and consumer preferences towards color of heat-treated Korean white pine and royal paulownia woods. Journal of the Korean Wood Science and Technology, 45(2): 213-222. https://doi.org/10.5658/wood.2017.45.2.213

[27] Kim, Y.K., Kwon, G.J., Kim, A.R., Lee, H.S., Purusatama, B., Lee, S.H., Kang, C.W., Kim, N.H. (2018). Effects of heat treatment on the characteristics of royal paulownia (*Paulownia tomentosa* (Thunb.) Steud.) wood grown in Korea. Journal of the Korean Wood Science and Technology, 46(5): 511-526. https://doi.org/10.5658/wood.2018.46.5.511

[28] Bekhta, P., Niemz, P. (2003). Effect of high temperature on the change in color, dimensional stability and mechanical properties of spruce wood. Holzforschung, 57(5): 539-546. https://doi.org/10.1515/hf.2003.080

[29] Umar, I., Zaidon, A., Lee, S.H., Halis, R. (2016). Oil-heat treatment of rubberwood for optimum changes in chemical constituents and decay resistance. Journal of Topical Forest Science, 28(1): 88-96.

[30] Bazyar, B. (2012). Decay resistance and physical properties of oil heat treated aspen wood. BioResources, 7(1): 696-705.

[31] Bal, B.C. (2015). Physical properties of beech wood thermally modified in hot oil and in hot air at various temperatures. Maderas. Ciencia y tecnología, 17(4): 789-798. http://doi.org/10.4067/S0718-221X2015005000068

[32] Dubey, M.K., Pang, S.S., Chauhan, S., Walker, J. (2016). Dimensional stability, fungal resistance and mechanical properties of radiata pine after combined thermo-mechanical compression and oil heat-treatment. Holzforschung, 70(8): 793-800. https://doi.org/10.1515/hf-2015-0174

[33] Uribe, B.E.B., Ayala, O.A. (2015). Characterization of three wood species (Oak, Teak and Chanul) before and after heat treatment. Journal of the Indian Academy of Wood Science, 12(1): 54-62. https://doi.org/10.1007/s13196-015-0144-4

[34] Mazzanti, P., Togni, M., Uzielli, L. (2012). Drying shrinkage and mechanical properties of poplar wood (*Populus alba* L.) across the grain. Journal of Cultural Heritage, 13(3): S85-S89. https://doi.org/10.1016/j.culher.2012.03.015

[35] Tsoumis, G. (1991). Science and technology of wood: structure, properties, and utilization. Van Nostrand Reinhold, New York, 115.

[36] Bak, M., Nemeth, R. (2012). Modification of wood by oil heat treatment. In International Scientific Conference on Sustainable Development & Ecological Footprint, Sopron, Hungary.

[37] Tomak, E.D., Viitanen, H., Yildiz, U.C., Hughes, M. (2011). The combined effects of boron and oil heat treatment on the properties of beech and Scots pine wood. Part 2: Water absorption, compression strength, color changes, and decay resistance. Journal of Materials Science, 46: 608-615. https://doi.org/10.1007/s10853-10-4860-2

[38] Yildiz, S., Gezer, E.D., Yildiz, U.C. (2006). Mechanical and chemical behavior of spruce wood modified by heat. Building and Environment, 41(12): 1762-1766. https://doi.org/10.1016/j.buildenv.2005.07.017

[39] Borůvka, V., Zeidler, A., Holeček, T., Dudík, R. (2018). Elastic and strength properties of heat-treated beech and birch wood. Forests, 9(4): 197. https://doi.org/10.3390/f9040197

[40] Sundqvist, B., Karlsson, O., Westermark, U. (2006). Determination of formic-acid and acetic acid concentrations formed during hydrothermal treatment of birch wood and its relation to colour, strength and hardness. Wood Science and Technology, 40: 549-561. https://doi.org/10.1007/s00226-006-0071-z

[41] Boonstra, M.J., Van Acker, J., Tjeerdsma, B.F., Kegel, E.V. (2007). Strength properties of thermally modified softwoods and its relation to polymeric structural wood constituents. Annals of Forest Science, 64(7): 679-690. https://doi.org/10.1051/forest:2007048

[42] Mohebby, B., Kevily, H., Kazemi-Najafi, S. (2014). Oleothermal modification of fir wood with a combination of soybean oil and maleic anhydride and its effects on physico-mechanical properties of treated wood. Wood Science and Technology, 48: 797-809. https://doi.org/10.1007/s00226-014-0640-5