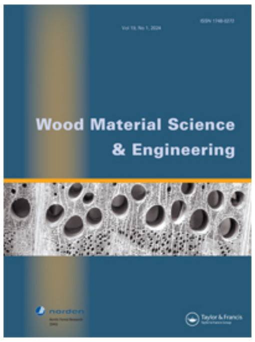

Wood Material Science & Engineering

ISSN: (Print) (Online) Journal homepage: www.tandfonline.com/journals/swoo20

Effect of pretreatment and compaction ratio on the properties of oriented strand board from sengon (*Paraserianthes falcataria* L. Nielsen) wood

Muhammad Iqbal Maulana, Fadilah Fitrianum, Derisna Noviyanti, Refany Audy, Denni Prasetia, Sena Maulana, Muhammad Adly Rahandi Lubis, Wahyu Hidayat, Rita Kartika Sari, Fauzi Febrianto & Nam Hun Kim

To cite this article: Muhammad Iqbal Maulana, Fadilah Fitrianum, Derisna Noviyanti, Refany Audy, Denni Prasetia, Sena Maulana, Muhammad Adly Rahandi Lubis, Wahyu Hidayat, Rita Kartika Sari, Fauzi Febrianto & Nam Hun Kim (2024) Effect of pretreatment and compaction ratio on the properties of oriented strand board from sengon (*Paraserianthes falcataria* L. Nielsen) wood, Wood Material Science & Engineering, 19:1, 206-219, DOI: 10.1080/17480272.2023.2233952

To link to this article: https://doi.org/10.1080/17480272.2023.2233952

Published online: 17 Jul 2023.

WOOD MATERIAL SCIENCE & ENGINEERING
2024, VOL. 19, NO. 1, 206–219
https://doi.org/10.1080/17480272.2023.2233952

ORIGINAL ARTICLE

Effect of pretreatment and compaction ratio on the properties of oriented strand board from sengon (*Paraserianthes falcataria* L. Nielsen) wood

Muhammad Iqbal Maulana [a], Fadilah Fitrianum[a,b], Derisna Noviyanti[b], Refany Audy[b], Denni Prasetia[c], Sena Maulana [d], Muhammad Adly Rahandi Lubis [a], Wahyu Hidayat [e], Rita Kartika Sari [b], Fauzi Febrianto[b] and Nam Hun Kim[c]

[a]Research Center for Biomass and Bioproducts, National Research and Innovation Agency (BRIN), Cibinong, Indonesia; [b]Department of Forest Products, Faculty of Forestry and Environment, IPB University, Bogor, Indonesia; [c]Department of Forest Biomaterials Engineering, College of Forest and Environmental Science, Kangwon National University, Chuncheon, Republic of Korea; [d]Forestry Engineering Studi Program, Institut Teknologi Sumatera (ITERA), South Lampung, Indonesia; [e]Department of Forestry, Faculty of Agriculture, Lampung University, Bandar Lampung, Indonesia

ABSTRACT

Low-density wood produces composites with low dimensional stability, requiring a high compaction ratio (CR) to produce an oriented strand board (OSB). This study evaluates the physical and mechanical properties of the OSB prepared from low-density wood, i.e. sengon (*Paraserianthes falcataria* L. Nielsen), under steam modification and various CRs. The wood strands were steamed at 126°C under 0.14 MPa pressure for an hour and then washed with 1% sodium hydroxide for 30 sec. Three-layered OSBs with a shelling ratio (face-to-core layers ratio) of 1:2:1 were manufactured using 10% resin content of phenol formaldehyde. Panels with three different strand pretreatments and five levels of CR were evaluated. The results show that there is an improvement in the bonding between the strand and the resin with steam and the steam followed by washing with 1% NaOH pretreatments. Both pretreatments of strands significantly improved the dimensional stability of obtained OSB but did not affect the mechanical properties. The physical and mechanical properties of OSB improved by the increased CR. The OSBs with a CR of 1.58 has the best physical and mechanical properties.

ARTICLE HISTORY
Received 13 March 2023
Revised 3 July 2023
Accepted 4 July 2023

KEYWORDS
Compaction ratio; low-density wood species; oriented strand board; steam treatment

Introduction

Recently, timber production in Indonesia has been supplied mainly by plantation forests. The timber is dominated by low-density hardwood species such as sengon (*Paraserianthes falcataria* (L.) Nielsen) wood. It is reported that sengon wood production has increased by 112% from 2015 to 2019 (BPS 2016, 2020). Sengon is a fast-growing species with the highest production in Java at 5.43 million m^3 or 61.21% of total wood production (BPS 2020). The use of sengon wood as a raw material for wood products supports the goal of the Indonesian government to become the world's largest supplier of low-density wood products, which has been planned since 2017 on "The Indonesian Lightwood Cooperation Forum" platform. Therefore, information regarding suitable wood products for using sengon wood is needed. To date, sengon wood is mainly used as barecore and plywood (Susilawati *et al*. 2019, Stewart *et al*. 2021, Susilawati and Kanowski 2021).

Sengon wood has recently been studied as a raw material for oriented strand boards (OSB) (Baskara *et al*. 2022). OSB is a panel made of rectangular wood strands glued together with a water-resistant adhesive and hot pressed (APA 2017). Similar to plywood, OSB is also a structural panel having layers that are cross-oriented to one another. Hence, OSB is often used as a substitute for plywood with advantages such as overcoming knot defects in raw materials, uniformity, and relatively high shear strength (Febrianto 2017). From the market side, world consumption of OSB shows promising opportunity with an increase from 31 million m^3 in 2017 to 37 million m^3 in 2021, while, OSB consumption in Indonesia fluctuates, only recording 236 m^3 in 2021 relying on imported products (FAO 2023). Therefore, promoting sengon wood as OSB raw material is considered a good prospect. For fast-growing species, sengon wood has a low microfibril angle (MFA) (Kojima *et al*. 2009). Ishiguri *et al*. (2012) reported that the lower the MFA, the compression properties of sengon wood tended to increase. Moreover, sengon wood has diffuse-porous arranged vessels (Alia-Syahirah *et al*. 2019), which means that changes in the growth rate will not remarkably affect the density of the wood. This is an advantage to produce OSB with a slight variation of final density. In addition, such vessels distribution usually has higher surface wettability than ring-porous vessels (Laskowska and Kozakiewicz 2017). Previous studies have shown that OSB from sengon wood has good mechanical properties, but some still require improvement (Baskara *et al*. 2022).

Several studies have reported various methods to improve the properties of OSB. Hornus *et al*. (2020) performed pretreatment through a pressure-assisted hydrothermal process at 120–160 °C to remove hemicellulose from pine wood strands. Hydrothermal pretreatment produces more dimensionally

CONTACT Muhammad Adly Rahandi marl@biomaterial.lipi.go.id Research Center for Biomass and Bioproducts, National Research and Innovation Agency (BRIN), Cibinong 16911, Indonesia; Muhammad Iqbal Maulana muha337@brin.go.id Research Center for Biomass and Bioproducts, National Research and Innovation Agency (BRIN), Cibinong 16911, Indonesia

stable OSB by removing hemicelluloses such as xylan and mannan (Carvalho *et al*. 2018). Rahimi *et al*. (2019) showed that the media in the hydrothermal treatment, whether it is steam or hot-compressed water, will affect the properties of the treated wood. They reported that the highest increase in mechanical properties of yellow-poplar was obtained by HCW treatment at 100 °C while the higher dimensional stability was shown by steam treatment at 140 °C. Steam pretreatment is an easy and inexpensive treatment. Steam treatment of logs results in fewer defects in its sawn timber by reducing longitudinal surface growth strains (Moya *et al*. 2021), which are present more frequently and stronger in fast-growing species such as sengon wood (Kojima *et al*. 2009). Steam pretreatment of wood and bamboo strands has been reported to increase the OSBs dimensional stability and mechanical properties (Maulana *et al*. 2017, 2021a, Aisyah *et al*. 2021). The physical and mechanical properties of bamboo OSB improved after being treated with steam followed by washing. According to Fatrawana *et al*. (2019), the steam process causes extractive substances to move to the strand surface and then be removed during the washing process. In addition, steam treatment followed by washing with 1% NaOH reduced the hemicellulose content, dissolved impurities on the strand surface, and increased the pH value of the strand (Maulana *et al*. 2021b). However, the effect of steam treatment on sengon wood strands on the resulting OSB has not been reported. Sengon has a water absorption of about 37.8% (Anwar Uyup *et al.* 2021) with a hemicellulose content of about 21% (Kaida *et al*. 2009), and a pH value of 4–5 (Kaida *et al*. 2009, Yusoh *et al*. 2021). Steam pre-treatment and alkaline washing are expected to reduce wood-water interactions to increase the dimensional stability of sengon OSB. Increasing the pH value is also expected so that the strand has a pH that is curing in alkaline conditions such as phenol-formaldehyde (PF).

Another factor affecting OSB quality is the compaction ratio (CR), i.e. the ratio between the panel density and the raw material density. Van (2021) reported that the mechanical properties of OSB made from kiri wood (density of about 238 kg m^{-3}) increased with increasing panel density from 300 kg m^{-3} to 400 kg m^{-3}, or increasing CR from 1.26 to 1.68. Chen *et al*. (2010) reported that the improvement in OSB strength made from aspen (density of about 400 kg m^{-3}) was optimum at board densities of 660–690 kg m^{-3} (CR of about. 1.65–1.72), higher densities did not provide a significant increase in strength. Meanwhile, Zhou (1990) suggested that a density of 650 kg m^{-3} with a CR of about 1.63 would be ideal for OSB of poplar wood (density of about 400 kg m^{-3}). CR effect on OSB water-related properties is relatively complex. Several studies have reported that a more substantial spring-back effect from a higher OSB CR results in a higher thickness swelling (Van 2021, Zhuang *et al*. 2022). On the other hand, despite having a more significant swelling potential, panels with a higher CR may have high contact between strands, limiting the water penetration rate and panel swelling (Jin 2009, Chen *et al*. 2010). The results from previous reports were obtained from OSB with different raw materials, and therefore, the difference in the wood-water relationship for each species also affected the resulting responses. The effect of CR on OSB made from sengon wood has not been reported, and it will be interesting because the low density of sengon wood causes a high CR to be obtained at relatively low panel density.

As previously stated, sengon wood has the potential to be used as a raw material for OSB, and there are methods for improving OSB qualities, such as strand pretreatments and CR adjustment. Strand pretreatments through steam and steam followed by alkaline solution washing have been shown to improve OSBs physical and mechanical properties. However, the effect on OSB prepared from sengon wood has never been reported. Furthermore, determining the optimal CR is critical for panels made from low-density raw materials such as sengon wood in order to achieve the preferable density and characteristics. Meanwhile reports on the optimum CR for OSB from low-density hardwoods are still limited. Therefore, this study aims to investigate the effect of steam pretreatments and CR on OSB made from sengon wood to provide valuable information for the further development of OSB from this species and low-density hardwoods in general.

Materials and methods

Materials

A 10-year-old sengon log (*Paraserianthes falcataria* L. Nielsen) with a diameter at breast height of 28 cm was harvested from a local plantation forest in Bogor, West Java, Indonesia. Sengon logs with a specific gravity of 0.38 were converted into strands using a disk flaker with a $70 \times 25 \times 0.5$ mm target size. The air-dried moisture content and oven-dried density of sengon wood is 12.42% and 405 ± 42 kg m^{-3}, respectively. Strands were sorted according to size and then air-dried for 14 days. The sodium hydroxide used was the analytical grade. Commercial PF adhesive with a solids content of 46.13%, a specific gravity of 1.20, pH of 12.30, viscosity of 225 mPa·s (25 °C), and gel time of 12.33 min (35 °C) was purchased from PT Pamolite Adhesive Industry, Probolinggo, Indonesia, and used as received.

Pretreatment and characterization of strands

Strands were divided into three groups, i.e. untreated, steam treated, and steam treated followed by washing with 1% NaOH solution. The steam process was carried out using an autoclave at a temperature of 126 °C under 0.14 MPa pressure for 1 h. The strands were washed with 1% NaOH for 30 s after the steam process (Maulana *et al*. 2021b). All strands were then air-dried for 5 days and oven dried at 60 °C for 14 days until the moisture content (MC) was below 5%. The illustration of strand pretreatment is presented in Figure 1(a). Gradual drying is carried out to prevent the strands from curling. Strands geometry (length, width, thickness, slenderness ratio (SR), and aspect ratio (AR)) for each treatment was measured using 100 oven-dried strand samples according to Maloney (1993). Determination of solubility in cold, hot water, and 1% NaOH solution were referred to TAPPI T-207 cm-99 (TAPPI 1999) and TAPPI T-212 om-02 (TAPPI 2002). The pH value of the strand was determined referred to SNI 06-6989.11-2004 (BSN 2004).

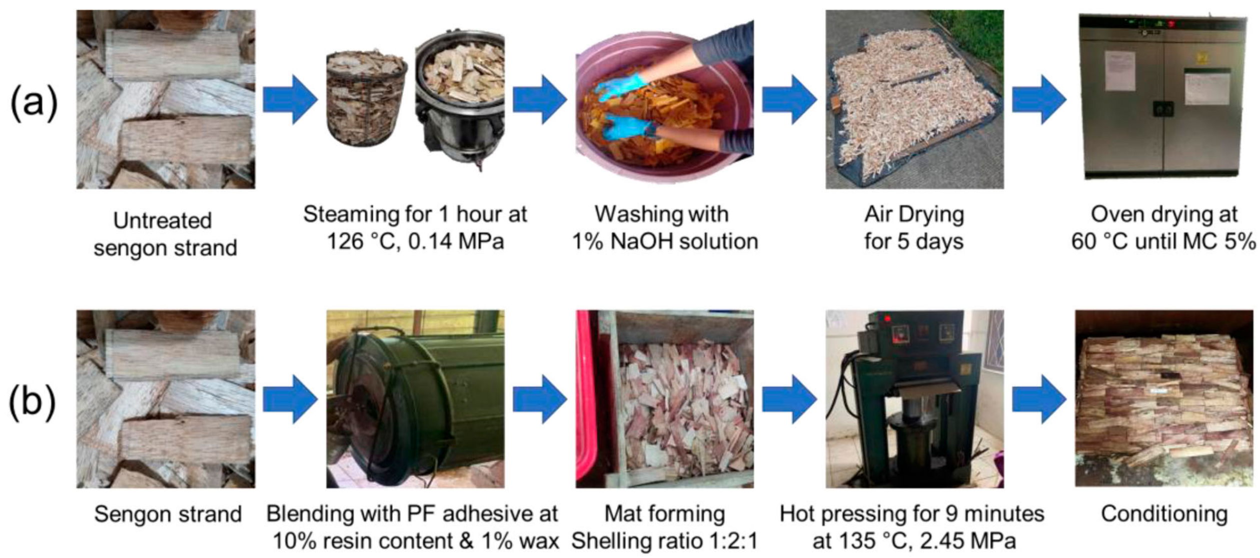

Figure 1. Graphical illustration of strand pretreatment (a) and OSB manufacturing (b).

FTIR Spectroscopy and FE-SEM EDX analyses

The functional groups of strands, OSBs, and cured PF resin were analyzed using FTIR spectroscopy (SpectrumTwo, PerkinElmer, Waltham, MA, USA) and the Universal Attenuated Total Reflectance (UATR) technique at 25 ± 2°C. The analysis was conducted at wavenumber 4000–400 cm^{-1} with a resolution of 4 cm^{-1}.

Morphology and chemical element of raw strand and strand from OSB was observed by scanning a strand surface using FE-SEM (Quattro S, Thermo Fisher Scientific, USA) coupled with an EDX (Ultim Max, Oxford UK) at 2500 times magnification using 3.0 kV power with a Kα1 X-ray source.

Manufacturing of OSBs

Oriented strand boards with dimensions of 30 × 30 × 0.9 cm were manufactured with five target densities, i.e. 400, 450, 500, 550, and 600 kg m^{-3}. The CR of the OSBs is shown in Table 1. The average bulk density of the oven-dried strands used is 387 ± 73 kg m^{-3}. Sengon strands were blended with phenol formaldehyde at 10% resin content (Van *et al.* 2022). About 1% wax was added based on the weight of the strands. The strand mats were then formed with a shelling ratio (face to core layers ratio) of 1:2:1 (Maulana *et al.* 2019). The mats for all pretreatment and CR were hot-pressed at 135 °C under a specific pressure of 2.45 MPa for 9 min. The pressing temperature is set based on the manufacturer's technical specifications. The final thickness was adjusted to 9 mm using two stop-bars in the hot press. The panels were then conditioned at 25–30 °C and 60–65% relative humidity for ±14 days until they reached equilibrium moisture content (EMC). OSB manufacturing is illustrated in the Figure 1(b).

Table 1. Compaction ratios of prepared sengon OSB.

Specific gravity	Strand bulk density (kg m^{-3})	Target mat density (kg m^{-3})	Compaction ratio
3.8	387 ± 73	400	1.05
		450	1.18
		500	1.32
		550	1.45
		600	1.58

Evaluation of OSBs properties

The physical and mechanical properties of the OSB were evaluated according to JIS A 5908 standards (JSA 2003), including density, MC, water absorption (WA), thickness swelling (TS), modulus of elasticity (MOE), modulus of rupture (MOR), and internal bonding (IB). The obtained values were then compared to the CSA 0437.0 standard (Grade O-1) for commercial OSB panels (CSA 2011).

Statistical analysis

The experiment was carried out in two research designs, i.e. (1) the effect of pretreatment and (2) the effect of the CR (Table 2). The research on the effect of pretreatment was conducted in a completely randomized design with one factor of three levels of strand pretreatment at CR 1.45 (i.e. untreated, steam treated, and steam treated followed by washing with 1% NaOH solution). The effect of CR was statistically evaluated at five levels CR for steam treated OSB (i.e. 1.05, 1.18, 1.32, 1.45, and 1.58). Analysis of variance (ANOVA) was used, and Duncan's multiple range test was performed to determine significant differences among variables.

Table 2. Research design of the experiment.

Research design	Level	Pretreatment of strand	Compaction ratio of OSB
1. Effect of strand pretreatment	1	Untreated	1.58
	2	Steam	
	3	Steam + 1% NaOH	
2. Effect of compaction ratio	1	Steam	1.05
	2		1.18
	3		1.32
	4		1.45
	5		1.58

Table 3. Geometry of pretreated and untreated sengon strands.

Parameter	Untreated	Steam	Steam + 1% NaOH
Length (cm)	7.01 ± 0.12	7.03 ± 0.10	7.07 ± 0.08
Width (cm)	2.50 ± 0.18	2.46 ± 0.17	2.46 ± 0.17
Thickness (cm)	0.06 ± 0.01	0.06 ± 0.01	0.06 ± 0.01
Slenderness Ratio	124.63[a] ± 13.94	120.73[a] ± 11.27	120.89[a] ± 10.64
Aspect Ratio	2.82[a] ± 0.22	2.91[a] ± 0.20	2.89[a] ± 0.20

Number in the same row followed by same letter are not significantly different at 5% significant level.

Results and discussion

Strands geometry

Strand geometry is one of the factors that affect the properties of OSB. Table 3 shows the strand geometry of sengon strands at various pretreatments. Generally, the length, width, and thickness of strand for the three treatments have the same distribution range with averages of 7.01–7.08, 2.46–2.50, and 0.06, respectively. The average AR and SR values of strands were ranged from 2.82 to 2.91 and from 120.73 to 124.63, respectively. There are no significant differences on the strand size and geometry (AR and SR) values for each treatment. In this study, the strand geometry in each pretreatment was measured to confirm that the strands have the same geometric distribution so that the influence of differences in strand geometry which can cause bias can be avoided. The strand geometry in this study is sufficient to produce OSB with good properties (Beck 2009, Febrianto *et al*. 2012). According to Kuklewski *et al*. (1985), an aspect ratio of 2 is sufficient to produce good OSB properties. AR value with more than 1 facilitates orientation during the mat formation process (Maloney 1993). The SR value of the strand is the ratio of length and thickness, which related to the mechanical properties of OSB. Higher SR values increase the contact area between the strands and adhesive which eventually improve the mechanical properties of the board (Maloney 1993, Iswanto *et al*. 2010).

Effect of pretreatment on strand properties

Figure 2 shows the appearance of untreated, steam treated, and steam followed by washing with 1% NaOH treated sengon strands. After the steam pretreatment the strand color became slightly darker and after the steam pretreatment followed by washing with 1% NaOH the strand color became slightly yellowish. However, no visible difference in color was observed in the dry strands as there was no noticeable difference in odor in the final strands. Table 4 shows some properties of sengon strand with and without pretreatments. Steam followed by washing with 1% NaOH showed higher weight loss than steam pretreatment although it was not significant. This indicates that a few components of the strand dissolve in the alkaline washing process. Strand pH value decreased after steam treatment but significantly increased after steam treatment followed by alkaline washing. The lower pH value after steam treatment can be caused by the degradation process of hemicellulose which produces acidic compounds.The hydrolysis of hemicellulose begins with the deacetylation of the esterified hydroxyl groups (Timar 2016). While, sodium hydroxide residue after washing increases the pH value (Maulana *et al*. 2021b). Changes in solubility in hot water, cold water, and 1% NaOH solution after steam treatment were found to be insignificant, but the solubility of strands pretreated with steam followed by washing with alkaline solution was found to increase significantly. Higher extractive content indicates a change in chemical components, especially the degradation of low molecular weight compounds.

Figure 2. Appearance of sengon strands at various pretreatments.

FTIR and morphological analyses

Figure 3(a) shows the FTIR spectra of sengon strand at various pretreatments. After the steam pretreatment, there was a decrease in absorption at wavenumber 1634 cm^{-1} which was related to the HOH bending vibrations of the water in the sample (Cheng *et al*. 2006). Such changes may occur due to some degradation of hemicellulose followed by removal of water-soluble impurities. The degradation of hemicellulose resulted in a strand surface that was rich in lignin and less hydrophilic as indicated by a slight increase in 1593 cm^{-1}. The peaks 1593 cm^{-1} come from and the aromatic skeletal vibrations of syringyl lignin (Báder 2020). Similar results were also reported in the heat treatment process on lightly steamed beech (Timar 2016). In the strand treated with steam followed by washing with 1% NaOH, the decrease at 1634 cm^{-1} and the increase at 1593 cm^{-1} was more pronounced and a decrease for unconjugated C=O acetyl groups in hemicelluloses at 1736 cm^{-1} (Huang *et al*. 2020) was also found. This was due to the dissolution of some of the hemicellulose during the alkaline washing treatment (Saiful Islam *et al*. 2012). In addition, a decrease was also found at 1231 cm^{-1}, related to C–O stretch in lignin and xylan syringyl ring (Maulana *et al*. 2021b), and a peak at 1264 cm^{-1}, related to guaiacyl ring breathing with C–O stretching (Hidayat *et al*. 2017). This indicates a change in lignin after alkaline washing treatment. Due to syringyl lignin reactivity is higher than guaiacyl (Tsutsumi 1995), under alkaline conditions, syringyl units are more easily affected than guaiacyl units (Nawawi 2017).

FTIR spectra of cured PF resin and sengon OSB at various strand pretreatment are shown in Figure 3(b). The absorption peak associated with the hydroxyl group on OSB shifted to a lower wavenumber at 3271–3300 cm^{-1} compared to the strand spectra. This indicates a hydrogen bond type interaction between the strand and the PF resin (Riedl and He 2004). In both untreated and steam treated OSB, there was no peak at

Table 4. Properties of sengon strand at various pretreatments.

	Pretreatments		
Properties	Untreated	Steam	Steam + NaOH 1%
Weight loss (%)	–	0.74 ± 0.27	1.67 ± 0.57
pH value	5.54^{b} ± 0.14	5.21^{a} ± 0.06	7.11^{c} ± 0.09
Solubility in			
Hot water (%)	1.98^{a} ± 0.08	1.97^{a} ± 0.02	5.41^{b} ± 0.03
Cold water (%)	0.85^{a} ± 0.09	0.92^{a} ± 0.36	4.12^{b} ± 0.06
1% NaOH (%)	7.93^{a} ± 0.47	8.91^{a} ± 0.49	10.79^{b} ± 0.47

1732–1736 cm^{-1} which was previously found in the strand spectra. The change is caused by the reaction between the phenolic groups of PF and the acetyl groups of hemicellulose. However, at the same wavenumber it can also indicate a reaction between the cellulose monomer units and formaldehyde of PF resin but is indicated by the peak intensity (Wang *et al.* 2016). This explains how the peak at 1737 cm^{-1} was found in OSB pretreated by steam followed by washing with 1% NaOH in which the hemicellulose in the strand had been reduced. Peaks at 1603 and 1470 cm^{-1} in resin spectra, caused by C=C stretching vibrations on the phenol aromatic ring (Wang *et al.* 2016), decreased after curing in OSB. This is due to the addition of wood which has fewer C=C bands. In steam pretreated OSB, relatively broader bands between 1150 and 1000 cm^{-1} associated with asymmetric stretching vibrations of C-O-C aliphatic ether were found and more intensive in steam followed by washing pretreated OSB. The appearance of these bands indicates the cross-linking reaction of the -OH group of the cell wall and phenol formaldehyde resin in the OSB (Huang *et al.* 2020). Removal of impurities during steam and washing processes increases cell wall exposure. The increase in pH by alkaline solutions could also be associated with bands between 1150 and 1000 cm^{-1} and the peak at 1736 cm^{-1}. This demonstrates how pretreatments improves the bonding reaction with the adhesive.

The surface morphology of the raw material strand and the prepared OSB at various pretreatments was analyzed using FE-SEM (Figure 4). Strand with pretreatment showed a smoother surface than without pretreatment. On the strand with steam pretreatment, small spherical-like droplets are found on the surface. Previous studies on thermally modified wood also reported a similar phenomenon(Donohoe *et al.* 2008, Sannigrahi, 2011). The droplet could be caused by migration of lignin to the wood surface during thermal treatment(Selig *et al.* 2007). This is also related to the increase in the peak of the FTIR spectra at 1593 cm-1 as previously mentioned. On the strand with steam treatment followed by washing with 1% NaOH, no impurities were found on the surface of the strand. During the alkaline washing process, some lignin, hemicellulose and other impurities may be dissolved (Maulana *et al.* 2021b). On the surface of the strand taken from the inside of the prepared OSB specimen, the fiber from the strand appeared to be covered by resin more evenly in the steam pretreatment than the others. Meanwhile, some damage was observed on OSB prepared from steam followed by alkaline washing pretreated strand. This may indicate that the strand is more brittle.

EDX analysis revealed that there was no significant change in chemical elements between the untreated and steam treated strands (Figure 5(a)). In the steam treatment followed by washing with 1% NaOH, there was a slight decrease in carbon in the presence of 0.7% sodium. The sodium present in the strand can be understood as a result of the alkaline washing treatment. Sodium was also found on EDX analysis in all OSB (Figure 5(b)). The PF resin production process which involves NaOH can contribute to the presence of this Sodium. Sodium content in OSB ranges from 4.3 to 6.9%. In addition, the presence of resin also increases the carbon content and decreases the oxygen content compared to the results of the analysis on the strands.

Effect of strands pretreatment on physical and mechanical properties of OSBs

Figure 6 shows the density (a) and MC (b) of sengon OSB on various pretreatments. The target mat density is 550 kg m^{-3}, while the average actual mat density is 558–578 kg m^{-3}. Analysis of variance showed that the pretreatment of the strands had

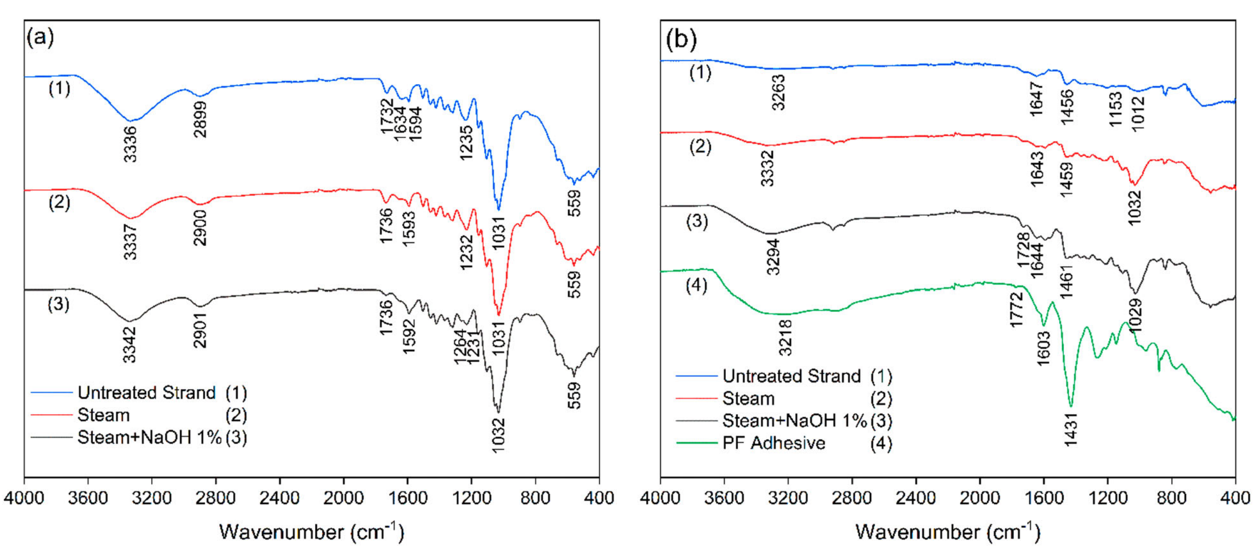

Figure 3. FTIR spectra of sengon (a) strand and (b) OSB at various pretreatments.

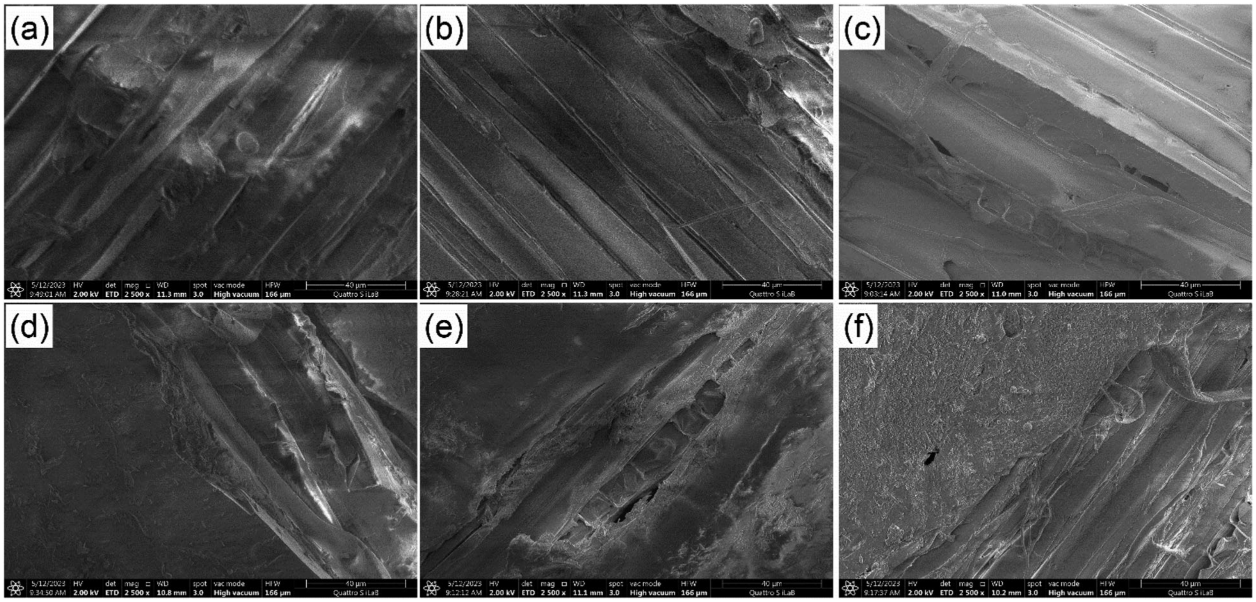

Figure 4. Micrograph of untreated strand (a), steam treated (b), steam followed by washing with 1% NaOH (c), OSB without pretreatment (d), OSB with steam pretreatment of strand (e), and OSB with steam followed by washing with 1% NaOH pretreatment of strand (f) at 2500× magnification.

no significant effect on the density of sengon OSB, indicating that the resulting sengon OSB has a homogeneous density at various pretreatments. The MC values of sengon OSB were 11.47–11.57%. This value meets the JIS A 5908 standard, which requires MC of OSB between 5 and 13% (JSA 2003). Analysis of variance also showed that the pretreatment on the strands had no significant effect on MC values. Homogeneous MC values can be achieved because the panels are conditioned at the same temperature and time. In addition, the small MC variation might be due to using a single tree to produce all strands in this experiment. The hygroscopic nature of wood which can absorb and release water causes the moisture content of the resulting board to change according to humidity and environmental conditions (Bowyer *et al*. 2007).

The WA and TS values of sengon OSB were 52.56–103.35% and 8.31–11.55% respectively (Figure 7). The highest WA and TS values were found in OSB without pretreatment, while the lowest values were found in OSB with steam followed by washing with 1% NaOH treatment. Analysis of variance showed that the pretreatment of sengon wood strands significantly affected the resulting WA and TS values. Duncan's multiple range test showed that the WA and TS OSB of sengon wood at each pretreatment were significantly different. Reduced WA and TS values suggested that steam treatment and steam followed by washing with 1% NaOH on the strands improved the dimensional stability of OSB. Similar results were reported from several studies regarding the effect of steam on OSB characteristics (Maulana *et al*. 2017, 2021a, Aisyah *et al*. 2021). This could be because the hemicellulose content in the treated strands has degraded as shown from the FTIR analysis. Steam and steam followed by washing with 1% NaOH treatments can reduce hemicellulose and extractives

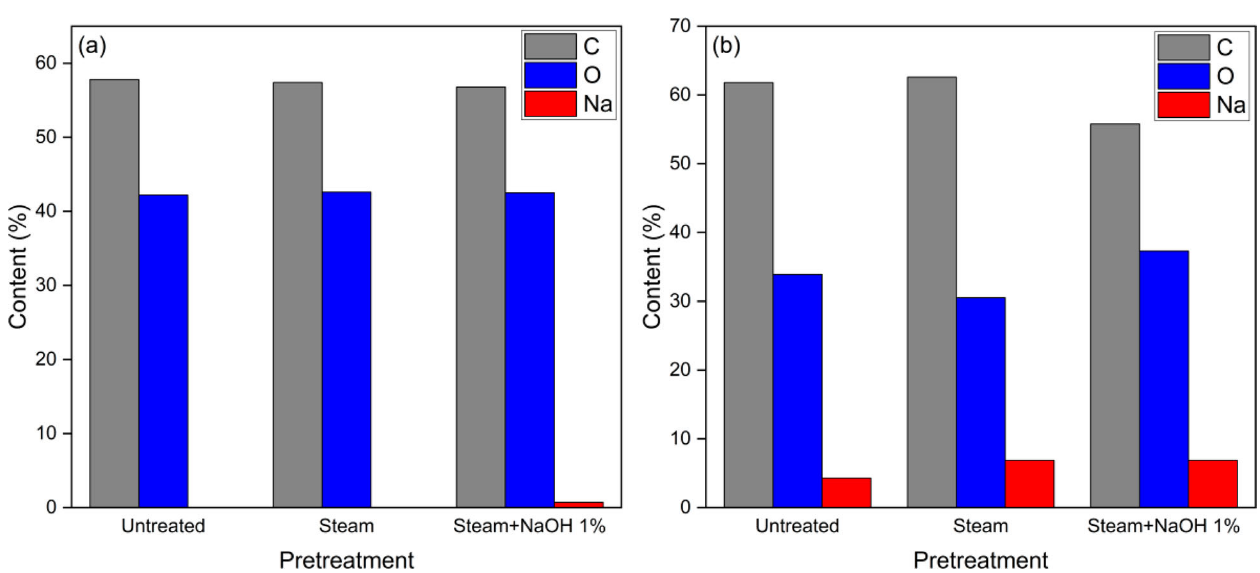

Figure 5. EDX of (a) strand and (b) OSB at various pretreatment.

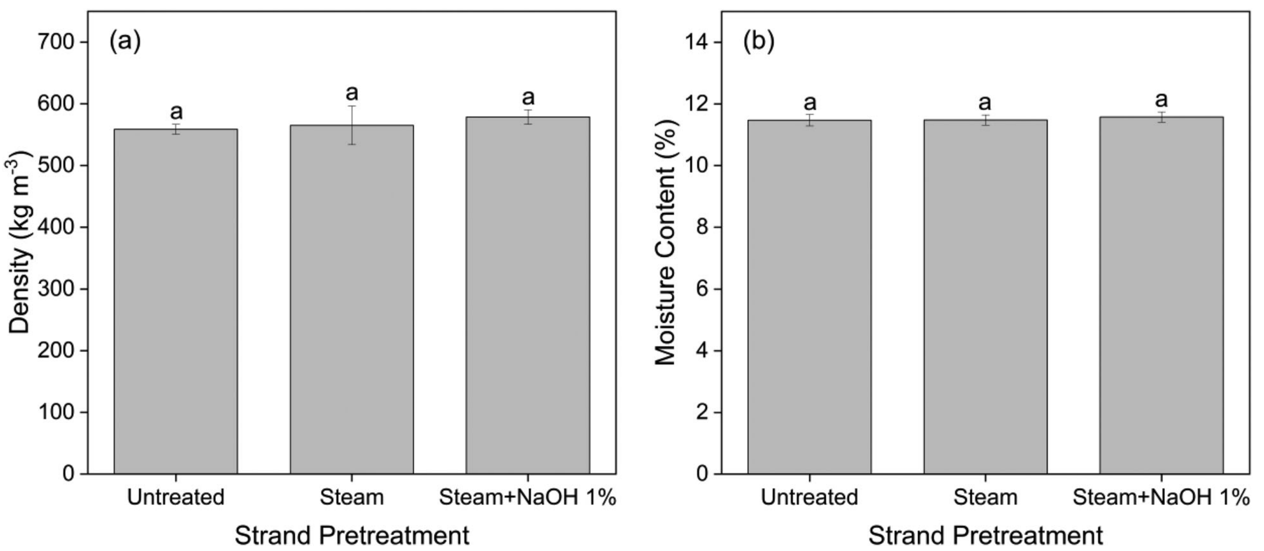

Figure 6. Sengon OSB with CR 1.45 at various pretreatments: (a) density and (b) moisture content. The same letters show no significant differences between treatments according to Duncan's multiple range test at a significant level of 5%. Error bars show standard deviations.

(Fatrawana *et al*. 2019). Reduced hemicellulose promotes strand crystallinity and reduces hydroxyl group bonding with water (Maulana *et al*. 2021b). In addition, Donohoe *et al*. (2008) reported that the steam process can loosen cell walls and soften lignin which causes strand porosity to increase due to heat and pressure during steam. High porosity can increase the penetration of the adhesive so that water cannot fill the cell walls and cause dimensional stabilization. The WA and TS values in this study were also lower than previous studies (Baskara *et al*. 2022) and met the CSA 0437.0 standard (Grade O-1) which required the maximum TS value of 15% (CSA 2011).

Figure 8 shows the parallel (a) and perpendicular (b) MOE values of sengon OSB. MOE (||) and MOE (⊥) values of sengon OSB were 3035–3226 MPa and 1324–1629 MPa, respectively. Strand pretreatment tends to increase MOE, with the highest value being steam treatment for MOE (||) and steam followed by washing with 1% NaOH treatment for MOE (⊥). Nonetheless, the analysis of variance showed that there was no significant effect of pretreatment on the MOE values of sengon OSB. The MOR (||) values of sengon OSB ranged from 21.5 to 23.3 MPa (Figure 9(a)). The highest MOR (||) value was sengon OSB treated by steam and washing with 1% NaOH pretreatment, while the lowest value was in steam treated OSB. The MOR (⊥) of sengon OSB ranged from 14.9 to 16.2 MPa (Figure 9 (b)). The highest MOR (⊥) value was untreated OSB, while the lowest was OSB treated by steam and washing with 1% NaOH pretreatment. Analysis of variance showed that strand pretreatment had no significant effect on MOR values of sengon OSB. All sengon OSBs have MOE (||) and MOR (||) below the values required by CSA 0437.0 standard (Grade O-1), i.e. 4500 and 23.4 MPa, respectively, but have MOE (⊥) and MOR (⊥) above the required values, i.e. 1300 and 9.6 MPa respectively (CSA 2011).

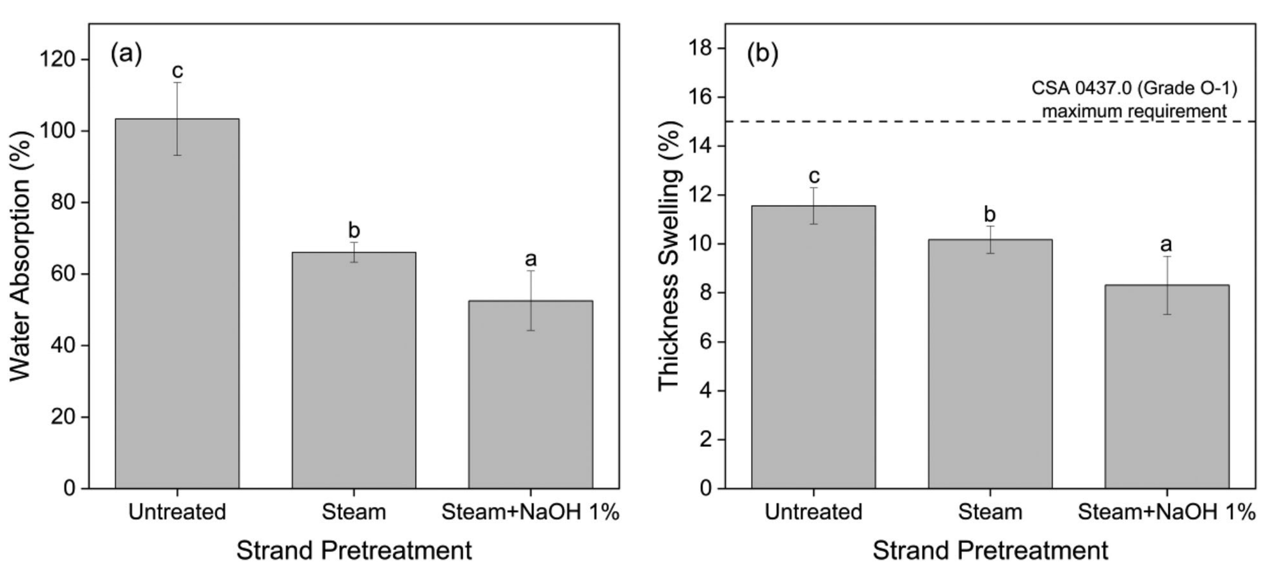

Figure 7. Sengon OSB with CR 1.45 at various pretreatments: (a) water absorption and (b) thickness swelling . The different letters show significant differences between treatments according to Duncan's multiple range test at a significant level of 5%. Error bars show standard deviations.

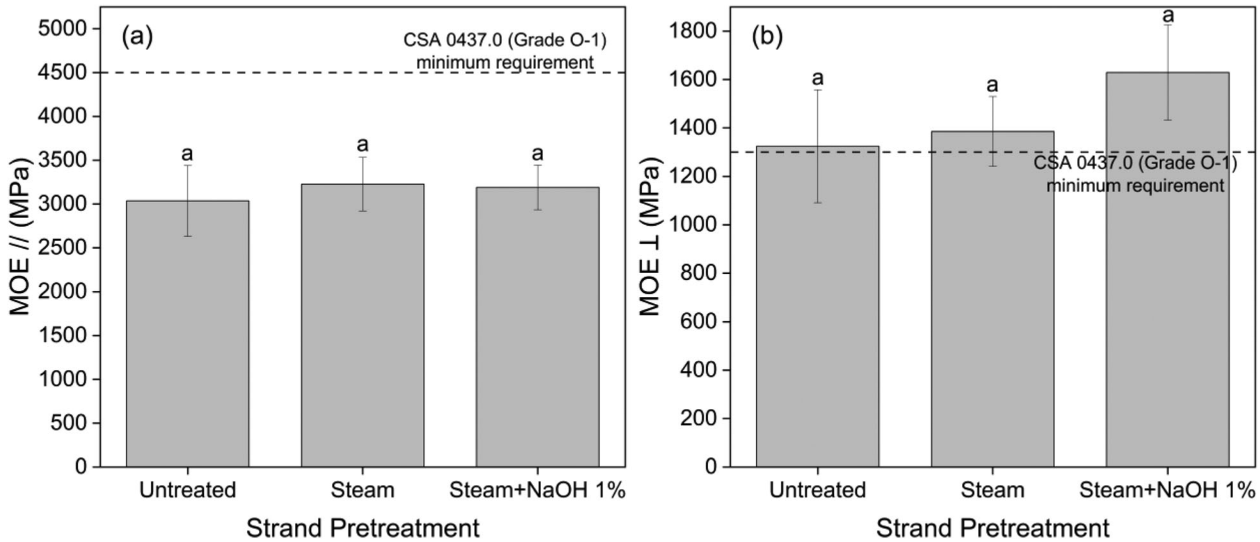

Figure 8. Sengon OSB with CR 1.45 at various pretreatments: (a) MOE // and (b) MOE ⊥ . The same letters show no significant differences between treatments according to Duncan's multiple range test at a significant level of 5%. Error bars show standard deviations.

Previous studies reported that the MOE of bamboo OSB increased by steam and washing with 1% NaOH treatments on the strands (Febrianto *et al*. 2015, Maulana *et al*. 2017, 2021a). In bamboo strands, the steam process can dissolve some extractive substances (Fatrawana *et al*. 2019). Washing with 1% NaOH solution was effective for washing the remaining impurities on the strand surface (Maulana *et al*. 2021b). With the loss of impurities, the gluing process will be more optimal to produce stronger inter-strand bonds and improve the mechanical properties of OSB. However, other studies have shown a trend similar to the results in this study. Iswanto *et al*. (2010) reported that there was no significant increase in dry MOE and MOR in sentang wood OSB with steam pretreatment. MOE (⊥) and MOR (||) of gmelina wood OSB bonded with PF adhesive also did not increase significantly with steam treatment (Aisyah *et al*. 2021). This indicates the possibility that different mechanisms may occur in the wood and bamboo strands during the steam process. From the properties of the strand and FE-SEM observations, it appears that the degradation of sengon wood strands occurs excessively. This results in an insignificant increase in mechanical properties.

Figure 10 shows internal bonding values (a) and failures on internal bonding specimen (b) of sengon OSB at various pretreatment. The internal bonding (IB) value of sengon OSB obtained was 0.23–0.28 MPa. The highest IB value was OSB with steam followed by washing with 1% NaOH treatment, while the lowest was untreated OSB. However, the analysis of variance showed that the pretreatment of the strands did not significantly affect the IB value. All IB values obtained do not meet the CSA 0437.0 standard (Grade O-1) which requires a minimum IB value of 0.345 MPa.

The IB value of sengon OSB tended to increase slightly after being treated with steam and steam followed by washing with

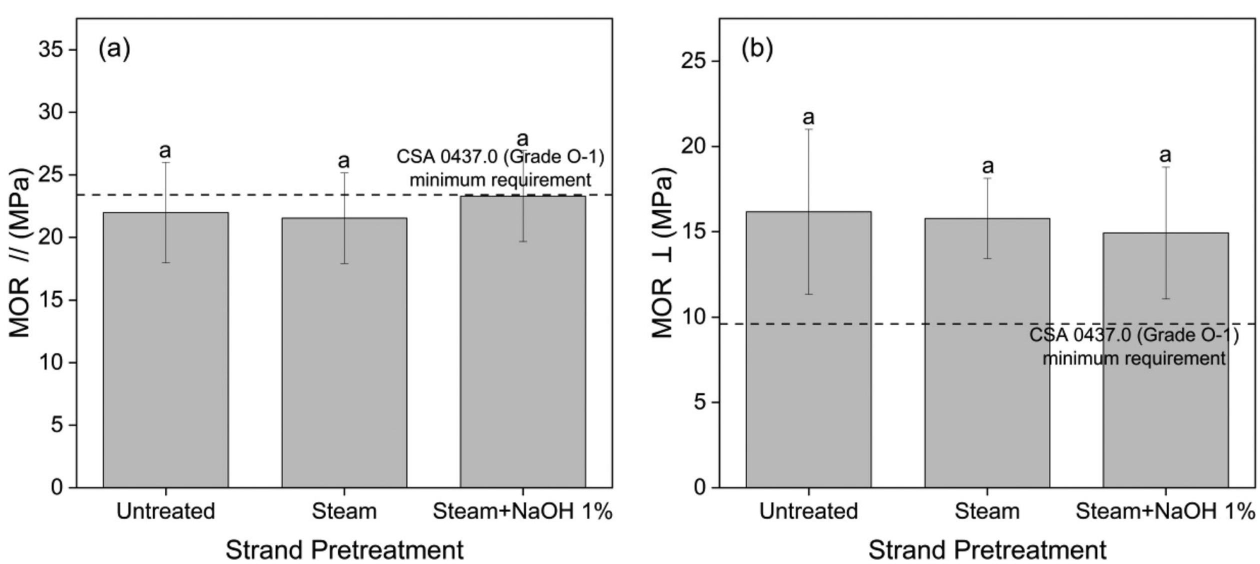

Figure 9. Sengon OSB with CR 1.45 at various pretreatments: (a) MOR // and (b) MOR ⊥ . The same letters show no significant differences between treatments according to Duncan's multiple range test at a significant level of 5%. Error bars show standard deviations.

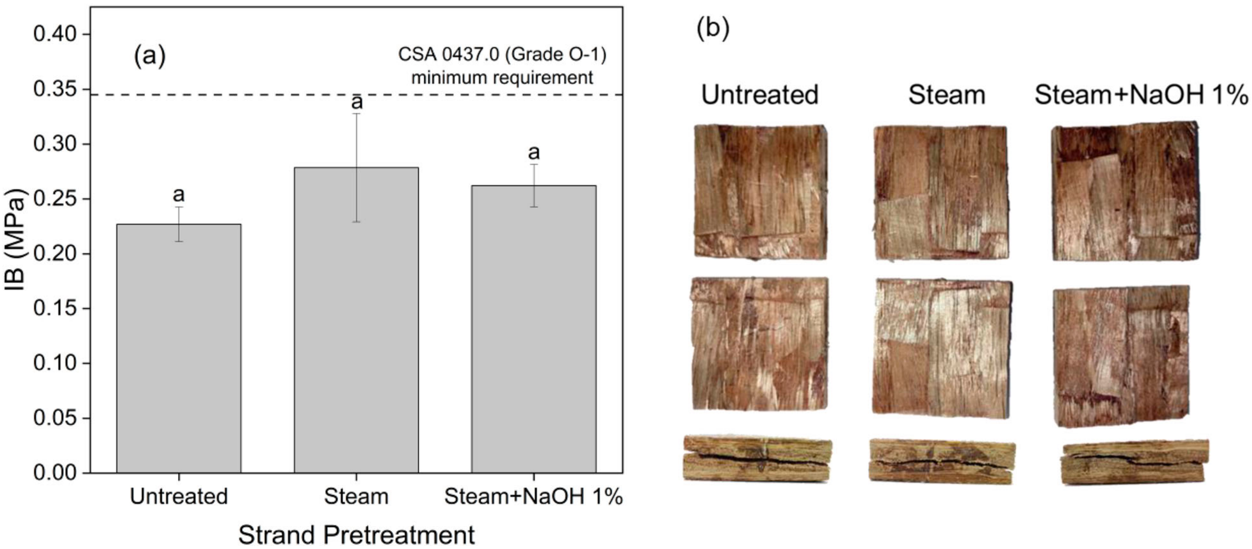

Figure 10. Sengon OSB with CR 1.45 at various pretreatments: (a) Internal bonding values and (b) failures on internal bonding specimen. The same letters show no significant differences between treatments according to Duncan's multiple range test at a significant level of 5%. Error bars show standard deviations.

1% NaOH. The increase in the IB value is due to the better bond quality between the strands and the resin. As shown by previous FTIR analysis, OSB prepared from strands pretreated with steam and steam followed by washing with 1% NaOH showed cross-linking between the cell wall and the resin (Figure 3(b)). Better strand surface as shown by FE-SEM analysis also contributes to the increase in IB (Figure 4). However, despite having a higher pH value, a slight decrease in the pretreatment followed by alkaline washing could be due to excess degradation of the chemical components.

Effect of compaction ratio on physical and mechanical properties of OSBs

In the previous section, steam and steam followed by washing with 1% NaOH pretreatments showed the same rating against standard criteria. Therefore, considering the simpler process and the cost implications, steam pretreatment was selected for this section. Sengon OSB with five different CRs, i.e.1.05; 1.18; 1.32; 1.45; and 1.58 was produced in this experiment using steam treated strands (Table 2). Figure 11 shows the density and MC values of sengon OSB. The MC value of sengon OSB at various CRs ranged from 11.48% to 11.87%. Analysis of variance shows that the CR has no significant effect on MC of OSB. The actual density value of each panel has met the desired density target. Analysis of variance shows that the CR has a very significant effect on OSB density. Based on Duncan's multiple range test, each CR has a significant difference in density. Thus, the resulting OSB properties can reflect the effect of differences in CRs.

The WA and TS values of sengon OSB decreased with increasing the panel CR (Figure 12). All TS values meet the CSA 0437.0 standard (Grade O-1) (CSA 2011). Analysis of variance showed that the CR significantly affected the WA and

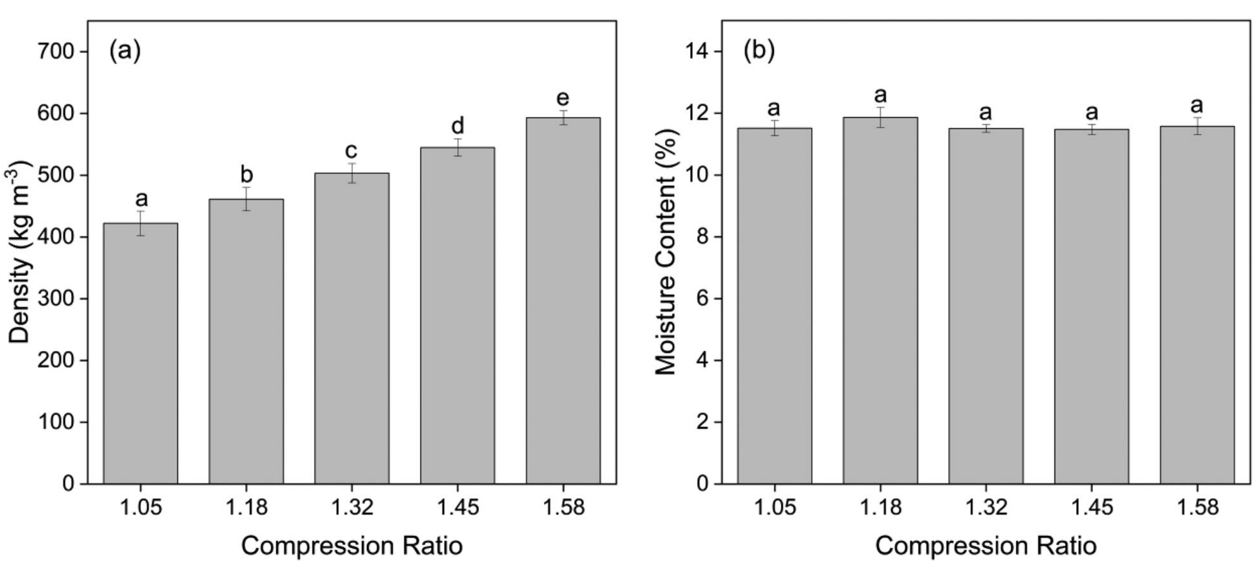

Figure 11. Steam pretreated sengon OSB at various compaction ratios (a) density and (b) moisture content . The different letters show significant differences between treatments according to Duncan's multiple range test at a significant level of 5%. Error bars show standard deviations.

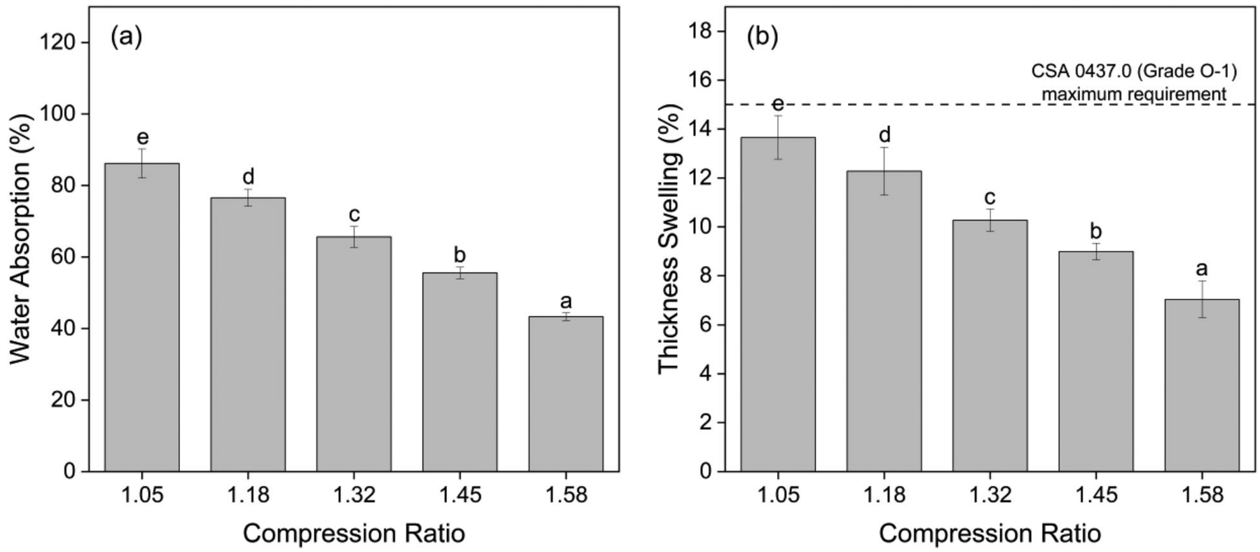

Figure 12. Steam pretreated sengon OSB at various compaction ratios (a) water absorptionand (b) thickness swelling. The different letters show significant differences between treatments according to Duncan's multiple range test at a significant level of 5%. Error bars show standard deviations.

TS of sengon OSB. Duncan's multiple range test shows that each CR has a significantly different WA and TS. These results are similar to previous studies (Vital *et al*. 1974, Jin 2009, Chen *et al*. 2010). Vital *et al*. (1974) reported that WA and TS of particleboard with a CR of 1.2 were higher than that of 1.6. Chen *et al*. (2010) also reported that the WA and TS OSB of aspen wood decreased with an increased CR. The low-density board has many voids in its structure, making it very porous (Dai *et al*. 2005). The porous structure facilitates the penetration and absorption of water and thereby swells. In addition, the lower contact between strand surfaces in low CR panels results in poor OSB bonding and facilitates water penetration during immersion (Jin 2009). However, several studies report different results. Maulana *et al*. (2021c) reported that the WA and TS of dual-species of bamboo OSB decreased with increasing CR. Meanwhile, Van *et al*. (2021, 2022) reported that kiri wood OSB with a higher CR had a lower WA but a higher TS. They stated that a higher TS could involve strand swelling, a spring-back effect, and the breaking of adhesive bonds by internal pressure developing voids between the strands. In this study, a slight spring-back effect may occur as indicated by a little increase in panel thickness after conditioning. However, there is no significant difference in panel thickness for each CRs.

Figure 13 shows the MOE (||) and (⊥) of sengon OSB at various CRs. MOE (||) and (⊥) increase with increasing CR. MOE (||) values range from 1527 MPa to 3976 MPa, so neither meets CSA 0437.0 standards (Grade O-1). Meanwhile, MOE (⊥) values range from 655 MPa to 1453 MPa, and only sengon OSB with CRs 1.32, 1.45, and 1.48 has values above the requirements of the CSA 0437.0 standard (Grade O-1). Analysis of variance shows that the CR significantly affects the MOE (||) and (⊥)values. Duncan's multiple range test shows that MOE (||) differs significantly at every CR except between 1.32 and 1.45

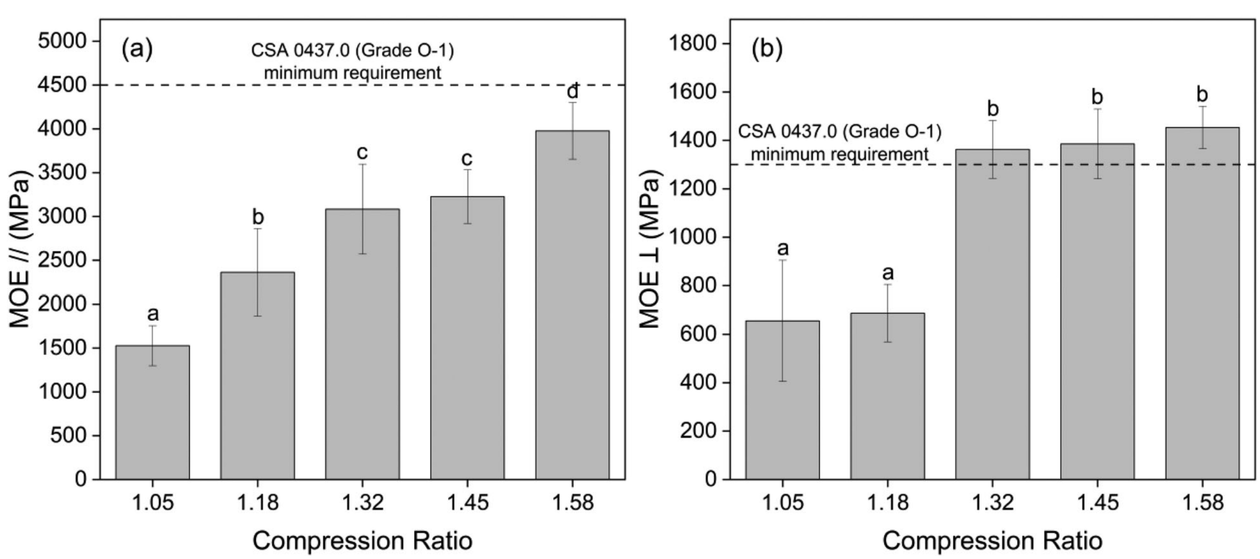

Figure 13. Steam pretreated sengon OSB at various compaction ratios (a) MOE // and (b) MOE ⊥. The different letters show significant differences between treatments according to Duncan's multiple range test at a significant level of 5%. Error bars show standard deviations.

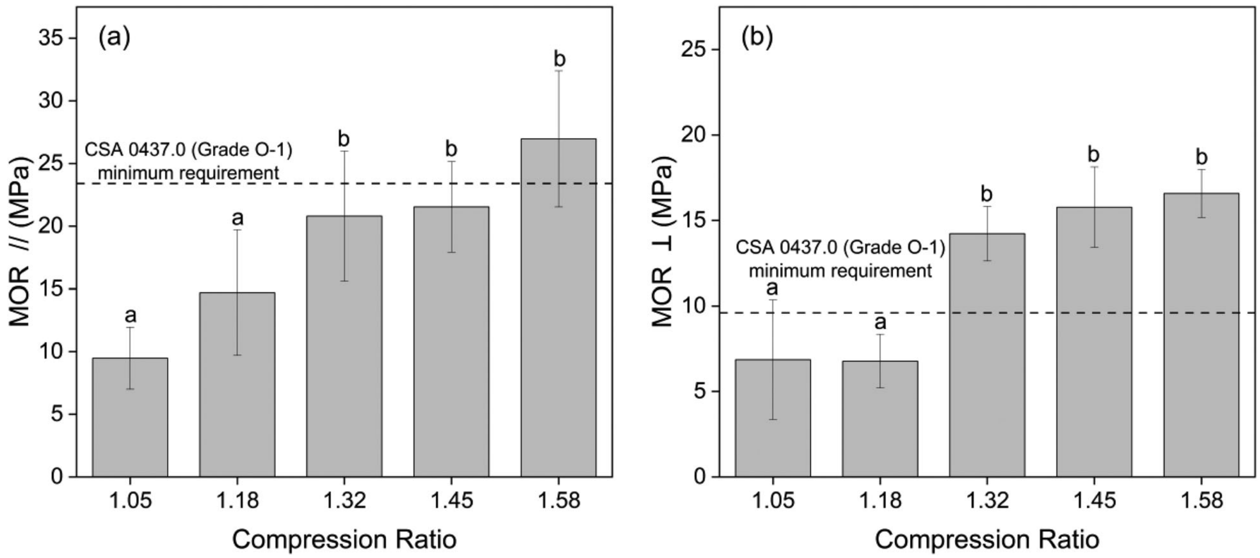

Figure 14. Steam pretreated sengon OSB at various compaction ratios (a) MOR // and MOR ⊥. The different letters show significant differences between treatments according to Duncan's multiple range test at a significant level of 5%. Error bars show standard deviations.

CRs. While the MOE (⊥) of sengon OSB at a CR of 1.58, 1.45, and 1.32 significantly different with CRs 1.05 and 1.18.

MOR (||) and (⊥) of sengon OSB at various CRs also showed the similar trend as MOE (Figure 14). MOR (||) increases with increasing CR with values ranging from 9.5 MPa to 27 MPa. However, only panels with a CR of 1.58 have a value above the requirements of the CSA 0437.0 standard (Grade O-1). Meanwhile, the MOR (⊥) were ranged from 7 MPa to 16.5 MPa. Sengon OSB with CRs of 1.32, 1.45, and 1.58 has a MOR (⊥) values that meets CSA 0437.0 standard (Grade O-1). Analysis of variance shows that the CR has a significant effect on MOR (||) and (⊥). Duncan's multiple range test shows that OSB with CRs of 1.32, 1.45, and 1.58 has significantly different MOR (||) and (⊥) values than other CRs.

Increasing the CR above 1.32 does not significantly increase MOE and MOR, especially MOE (⊥) and MOR (⊥). A similar trend, MOE & MOR gradually slow down as density continues to increase, was also reported by previous studies (Chen *et al*. 2010, Maulana *et al*. 2021c). According to Dai *et al*. (2002) wood cell wall damage may occur in excessive compaction. The increase in MOE and MOR generally aligns with the existing literature. Sumardi *et al*. (2007) reported that moso bamboo (*Phyllostachys pubescens*) OSB with a higher density had higher MOE and MOR values. OSB with a higher CR has more strands bearing the load and better contact between strand surfaces, resulting in higher MOE values (Febrianto 2017). Hiziroglu (2009) reported that the MOR of eastern redcedar (*Juniperus virginiana*) strandboard with a density of 780 kg m^{-3} was higher than strandboard with a density of 650 kg m^{-3}. The difference in CR has affected the density profile of OSB. A decrease in the CR is accompanied by a decrease in panel density, resulting in a density profile with a steeper graph (Febrianto *et al*. 2010). The steeper gradient in the density profile can cause shear failure of the board, so that the MOR value decreases as the board density decreases (Kawai *et al*. 1986).

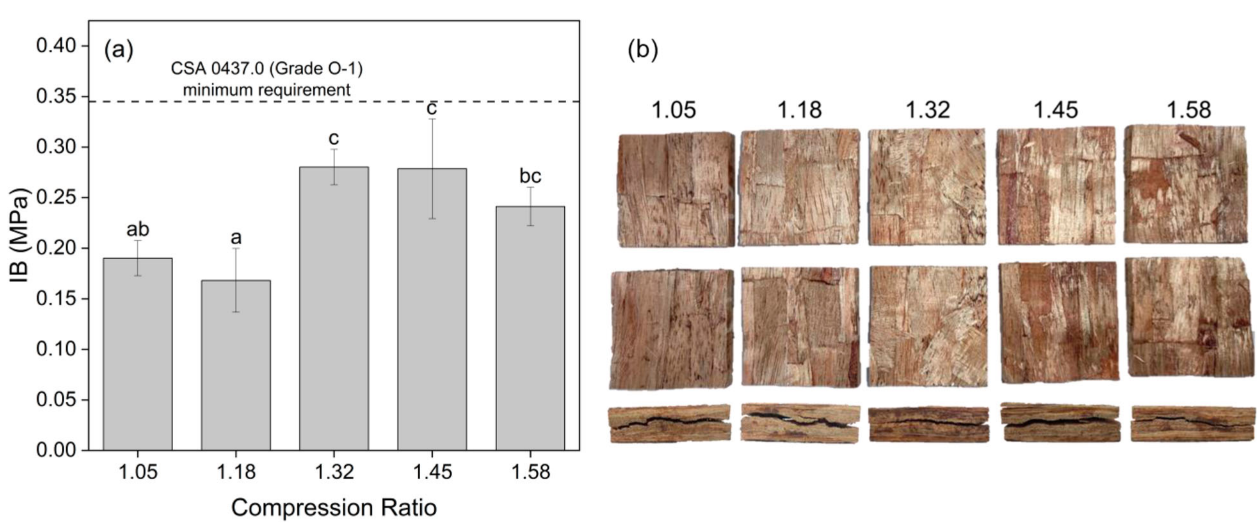

Figure 15. Steam pretreated sengon OSB at various compaction ratios (a) Internal bonding values and (b) failures on internal bonding specimen. The different letters show significant differences between treatments according to Duncan's multiple range test at a significant level of 5%. Error bars show standard deviations.

Figure 15 shows internal bonding values (a) and failures on internal bonding specimen (b) of sengon OSB at various CR. The IB values of sengon OSB were 0.15 MPa–0.27 MPa (Figure 15). None of the panels complies with CSA 0437.0 standard (Grade O-1). The highest value was obtained at a CR of 1.32, while the lowest was at a CR of 1.18. Analysis of variance shows that the CR has a significant effect on the IB values. The IB value of sengon OSB increased significantly by increasing the CR to 1.32. Greater strand contact when the mat with a higher CR was pressed allows the formation of more effective bond lines resulting in higher IB strength (Chen *et al*. 2010). The trend of non-linear IB values with increasing CR may be caused by failure during specimen testing. Panels with a low CR are made with a low target density, and this causes the IB specimens of low CR panels to tend to fail in the core layer. While, lower IB value at high CRs might be caused by strand damage. Although previous studies reported the trend of non-linear changes in IB with increasing density (Jin 2009, Chen *et al*. 2010), IB will generally increase with increasing panel density. A linear increase in IB with an increase in density was also reported by previous studies (Sumardi *et al*. 2007, Van 2021, Maulana *et al*. 2021c).

In this study, the IB value of OSB with CR 1.58 was lower than OSB with CR 1.45 and 1.32. Although insignificant, the low IB values can be caused by interstrand contact development during the hot-pressing, where the lower mat densities are more rapid than at higher mat density (Dai *et al*. 2007). In addition, the lower IB value at CR 1.58 could also be caused by the longer mat-forming time, whereas in this study, mat-forming for making laboratory scale panels was carried out manually. Longer mat-forming times may allow the pre-cured adhesive to occur, thereby reducing adhesive penetration during pressing.

Conclusions

Steam and steam pre-treatment followed by washing with 1% NaOH increased the extractive content of sengon in sengon wood. FTIR analysis showed bond improvement between strand and resin by both pretreatments. Morphological observations showed an improvement in the strand surface after pretreatments. Steam and steam followed by washing with 1% NaOH pretreatments increase the dimensional stability of sengon OSB. Steam followed by washing with 1% NaOH pretreatment produced sengon OSB with highest dimensional stability. The pretreatment did not significantly affect the mechanical properties of sengon OSB. Both steam treated and steam followed by washing with 1% NaOH treated OSB have met the CSA 0437.0 standard (Grade O-1) for thickness swelling, MOE (⊥), and MOR (⊥) but did not have meet MOE (||), MOR (||), and IB. Therefore, even though steam followed by washing with 1% NaOH has better stability, for economic reasons only steam treatment is sufficient to be recommended for further development. Sengon OSB at various compaction ratios was successfully made and was meet the target mat density. OSB at high CR has better dimensional stability, MOE, and MOR than a lower CR. The board with a CR of 1.58 has the most optimal physical and mechanical properties and meets the CSA 0437.0 standard (Grade O-1) on thickness swelling, MOE perpendicular, and MOR parallel and perpendicular.

Acknowledgements

This study was supported by the RIIM-PRN project No. 65/II.7/HK/2022, the fiscal year 2022–2023, titled "Pengembangan Produk Oriented Strand Board Unggul dari Kayu Ringan dan Cepat Tumbuh Dalam Rangka Pengembangan Produk Biokomposit Prospektif".

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

This work was supported by the RIIM-PRN, Badan Riset dan Inovasi Nasional, Indonesia, project No. 65/II.7/HK/2022.

ORCID

Muhammad Iqbal Maulana http://orcid.org/0000-0002-4470-2157
Sena Maulana http://orcid.org/0000-0002-3864-4210
Muhammad Adly Rahandi Lubis http://orcid.org/0000-0001-7860-3125
Wahyu Hidayat http://orcid.org/0000-0002-6015-1623
Rita Kartika Sari http://orcid.org/0000-0001-5377-1384

References

Aisyah, S, Haryadi, J, Maulana, MI, Marwanto, Prasetia, D, Hidayat, W, Lubis, MAR, Kim, N-H and Febrianto, F, 2021. Effects of strands pre-treatment and adhesive type on the properties of oriented strand board made from Gmelina (Gmelina arborea). *Jurnal Sylva Lestari*, 9, 475–487. doi:10.23960/jsl.v9i3.532

Alia-Syahirah, Y, Paridah, MT, Hamdan, H, Anwar, U and Lee, SH, 2019. Effects of anatomical characteristics and wood density on surface roughness and their relation to surface wettability of hardwood. *Journal of Tropical Forest Science*, 31, 269–277. doi:10.26525/jtfs2019.31.3.269

Anwar Uyup, MK, Sahari, SH, Jalaludin, Z, Husain, H, Lee, SH and Yusoh, AS, 2021. Water vapour sorption behaviour and physico-mechanical properties of methyl methacrylate (MMA)- and MMA–styrene-modified batai (*Paraserianthes falcataria*) wood. *Holzforschung*, 75, 444–451. doi:10.1515/hf-2020-0005

APA, 2017. *Oriented Strand Board*. Washington: American Plywood Association (APA), The Engineer Wood Association.

Báder, M, 2020. FTIR analysis of chemical changes in wood induced by steaming and longitudinal compression. *Cellulose*, 27, 6811–6829. doi:10.1007/s10570-020-03131-8

Baskara, MIA, Hapsoro, D, Maulana, MI, Marwanto, Prasetia, D, Hidayat, W, Lubis, MAR, Kim, N-H and Febrianto, F, 2022. Physical and mechanical properties of oriented strand board from three species of plantation forests at various resin contents. *Jurnal Sylva Lestari*, 10, 49–62. doi:10.23960/jsl.v10i1.519

Beck, K, 2009. Effect of strand geometry and wood species on strandboard mechanical properties. *Wood and Fiber Science*, 41, 267–278.

Bowyer, JL, Shmulssky, R, and Haygreen, JG, 2007. *Forest Products and Wood Science: An Introduction*. Iowa: A Blackwell Publishing Company.

[BPS] Badan Pusat Statistik, 2016. *Statistik Produksi Kehutanan 2015*. Jakarta: Badan Pusat Statistik.

[BPS] Badan Pusat Statistik, 2020. *Statistik Produksi Kehutanan 2019*. Jakarta: Badan Pusat Statistik.

BSN, 2004. *Badan Standardisasi Nasional SNI 06-6989.11-2004pH meter*. Jakarta: National Standardization Institution.

Carvalho, AG, Zanuncio, AJV, Vital, BR, Carneiro, ACO, da Silva, CMS and Tonoli, GHD, 2018. Hydrothermal treatment of strand particles of pine for the improvement of OSB panels. *European Journal of Wood and Wood Products*, 76, 155–162. doi:10.1007/s00107-017-1234-3

Chen, S, Du, C, and Wellwood, R, 2010. Effect of panel density on major properties of oriented strandboard. *Wood and Fiber Science*, 42, 177–184.

Cheng, R, Zhang, Q, and Sui, S, 2006. Improvement of softening treatment technology of bamboo. *Wood Science and Technology*, 40, 327–335. doi:10.1007/s00226-005-0034-9

CSA, 2011. CAN/CSA-O437 Standards on OSB and waferboard.

Dai, CP, Mei, C, and Korai, H, 2002. Density and property relationships of wood strand composites. In: *Proceedings 6th Pacific Rim Bio-Based Composites Symposium*, Nov 10–13.

Dai, C, Yu, C, and Zhou, X, 2005. Heat and mass transfer in wood composite panels during hot pressing. Part II. Modeling void formation and mat permeability. *Wood and Fiber Science*, 37, 242–257.

Dai, C., Yu, C., and Zhou, C., 2007. Theoretical modeling of bonding characteristics and performance of wood composites. Part I. Inter-element contact. *Wood and Fiber Science*, 1, 48–55.

Donohoe, BS, Decker, SR, Tucker, MP, Himmel, ME and Vinzant, TB, 2008. Visualizing lignin coalescence and migration through maize cell walls following thermochemical pretreatment. *Biotechnology and Bioengineering*, 101, 913–925. doi:10.1002/bit.21959

FAO, 2023. Forestry production and trade. License: CC BY-NC-SA 3.0 IGO. Extracted from: https://www.fao.org/faostat/en/#data/FO. Data of Access: 12-05-2023.

Fatrawana, A, Maulana, S, Nawawi, DS, Sari, RK, Hidayat, W, Park, SH, Febrianto, F, Lee, SH and Kim, N-H, 2019. Changes in chemical components of steam-treated betung bamboo strands and their effects on the physical and mechanical properties of bamboo-oriented strand boards. *European Journal of Wood and Wood Products*, 77, 731–739. doi:10.1007/s00107-019-01426-7

Febrianto, F, 2017. *Bamboo Oriented Strand board: Superior Materials for Structural Building Material Components*. Bogor: IPB Press.

Febrianto, F, Hidayat, W, Samosir, TP, Lin, CH and Soong, HD, 2010. Effect of strand combination on dimensional stability and mechanical properties of oriented strand board made from tropical fast growing tree species. *Journal of Biological Sciences*, 10, 267–272. doi:10.3923/jbs.2010.267.272

Febrianto, F, Jang, JH, Lee, SH, Santosa, IA, Hidayat, W, Kwon, J-H and Kim, N-H, 2015. Effect of bamboo species and resin content on properties of oriented strand board prepared from steam-treated bamboo strands. *Bioresources*, 10, 2642–2655. doi:10.15376/biores.10.2.2642-2655

Febrianto, F, Sahroni, and Hidayat, W, Bakar, ES, Kwon, G-J, Kwon, J-H, Hong, S-I and Kim, N-H, 2012. Properties of oriented strand board made from Betung bamboo (*Dendrocalamus asper* (Schultes.f) Backer ex Heyne). *Wood Science and Technology*, 46, 53–62. doi:10.1007/s00226-010-0385-8

Hidayat, W, Qi, Y, and Jang, J-H, 2017. Carbonization characteristics of juvenile woods from some tropical trees planted in Indonesia. *Journal of the Faculty of Agriculture, Kyushu University*, 62, 145–152. doi:10.5109/1801799

Hiziroglu, S, 2009. Properties of strandboard panels manufactured from eastern redcedar. *Materials*, 2, 926–933. doi:10.3390/ma2030926

Hornus, N, Cheng, G, and Erramuspe, IBV, 2020. Oriented strand board with improved dimensional stability by extraction of hemicelluloses. *Wood and Fiber Science*, 52, 257–265. doi:10.22382/wfs-2020-024

Huang, Y, Lin, Q, and Yang, C, 2020. Multi-scale characterization of bamboo bonding interfaces with phenol-formaldehyde resin of different molecular weight to study the bonding mechanism. *Journal of The Royal Society Interface*, 17, 20190755. doi:10.1098/rsif.2019.0755

Ishiguri, F, Hiraiwa, T, and Iizuka, K, 2012. Radial variation in microfibril angle and compression properties of paraserianthes falcataria planted in Indonesia. *IAWA Journal*, 33, 15–23. doi:10.1163/22941932-90000076

Iswanto, AH, Febrianto, F, and Wahyudi, I, 2010. Effect of pre-treatment techniques on physical, mechanical and durability properties of oriented strand board made from sentang wood (*Melia excelsa* Jack). *Journal of the Faculty of Agriculture, Kyushu University*, 55, 371–377. doi:10.5109/18854

Jin, J, 2009. Properties of strand boards with uniform and conventional vertical density profiles. *Wood Science and Technology*, 43, 559–574. doi:10.1007/s00226-009-0248-3

JSA, 2003. JIS A 5908: Japanese industrial standard: Particle board.

Kaida, R, Kaku, T, and Baba, K, 2009. Enzymatic saccharification and ethanol production of Acacia mangium and Paraserianthes falcataria wood, and Elaeis guineensis trunk. *Journal of Wood Science*, 55, 381–386. doi:10.1007/s10086-009-1038-0

Kawai, S, Sasaki, H, and Nakaji, M, 1986. Physical properties of low-density particleboard. *Wood Research: Bulletin of The Wood Research Institute Kyoto University*, 72, 27–36.

Kojima, M, Yamamoto, H, and Okumura, K, 2009. Effect of the lateral growth rate on wood properties in fast-growing hardwood species. *Journal of Wood Science*, 55, 417–424. doi:10.1007/s10086-009-1057-x

Kuklewski, KM, Blankenhorn, PR, and Rishel, LE, 1985. Comparison of selected physical and mechanical properties of Red Maple (Acer Rubrum L.) and Aspen (Populus Grandidentata Michx.) Flakeboard. *Wood and Fiber Science*, 17, 11–21.

Laskowska, A, and Kozakiewicz, P, 2017. Surface wettability of wood species from tropical and temperate zones by polar and dispersive liquids. *Drvna industrija*, 68, 299–306. doi:10.5552/drind.2017.1704

Maloney, TM, 1993. *Modern particleboard and dry-process fibreboard manufacturing*. San Fransisco: Miller Freeman Publications.

Maulana, S, Busyra, I, and Fatrawana, A, 2017. Effects of steam treatment on physical and mechanical properties of bamboo oriented strand board. *Journal of the Korean Wood Science and Technology*, 45, 872–882. doi:10.5658/WOOD.2017.45.6.872

Maulana, S, Gumelar, Y, and Fatrawana, A, 2019. Destructive and non-destructive tests of bamboo oriented strand board under various shelling ratios and resin contents. *Journal of the Korean Wood Science and Technology*, 47, 519–532. doi:10.5658/WOOD.2019.47.4.519

Maulana, S, Hidayat, W, and Sumardi, I, 2021c. Properties of dual-species bamboo-oriented strand boards bonded with phenol formaldehyde adhesive under various compression ratios. *Bioresources*, 16, 5422–5435. doi:10.15376/biores.16.3.5422-5435

Maulana, MI, Murda, RA, and Purusatama, BD, 2021a. Properties of oriented strand board from alkali-washed bamboo strands after steam treatment. *Bioresources*, 16, 987–996. doi:10.15376/biores.16.1.987-996

Maulana, MI, Murda, RA, and Purusatama, BD, 2021b. Effect of alkali-washing at different concentration on the chemical compositions of the steam treated bamboo strands. *Journal of the Korean Wood Science and Technology*, 49, 14–22. doi:10.5658/WOOD.2021.49.1.14

Moya, R, Tenorio, C, and Torres, JDC, 2021. Steaming and heating dipteryx panamensis logs from fast-grown plantations: Reduction of growth strain and effects on quality. *Forest Products Journal*, 71, 3–10.

Nawawi, DS, 2017. Characteristic of β-O-4 structures in different reaction wood lignins of *Eusideroxylon zwageri* T. et B. and four other woody species. *Holzforschung*, 71, 11–20. doi:10.1515/hf-2016-0100

Rahimi, S, Singh, K and Devallanc, D, 2019. Effect of Different Hydrothermal Treatments (Steam and Hot Compressed Water) on Physical Properties and Drying Behavior of Yellow-Poplar (Liriodendron tulipifera). *Liriodendron Tulipifera*, 69, 42–52. doi:10.13073/FPJ-D-18-00028

Riedl, B, and He, G, 2004. Curing kinetics of phenol formaldehyde resin and wood-resin interactions in the presence of wood substrates. *Wood Science and Technology*, 38, 69–81. doi:10.1007/s00226-003-0221-5

Saiful Islam, M, Hamdan, S, and Jusoh, I, 2012. The effect of alkali pretreatment on mechanical and morphological properties of tropical wood polymer composites. *Materials & Design*, 33, 419–424. doi:10.1016/j.matdes.2011.04.044

Sannigrahi, P, 2011. Pseudo-lignin and pretreatment chemistry. *Energy & Environmental Science*, 4, 1306–1310. doi:10.1039/C0EE00378F

Selig, MJ, Viamajala, S, and Decker, SR, 2007. Deposition of lignin droplets produced during dilute acid pretreatment of maize stems retards enzymatic hydrolysis of cellulose. *Biotechnology Progress*, 23, 1333–1339. doi:10.1021/bp0702018

Stewart, HTL, 2021. Growth and profitability of smallholder sengon and teak plantations in the Pati district, Indonesia. *Forest Policy and Economics*, 130, 102539. doi:10.1016/j.forpol.2021.102539

Sumardi, I, Ono, K, and Suzuki, S, 2007. Effect of board density and layer structure on the mechanical properties of bamboo oriented strandboard. *Journal of Wood Science*, 53, 510–515. doi:10.1007/s10086-007-0893-9

Susilawati, D, and Kanowski, PJ, 2021. Sustainability certification and legality verification in Indonesian natural forest-based wood products value chains. *International Forestry Review*, 23, 365–391. doi:10.1505/146554821833992839

Susilawati, D, Kanowski, P, and Setyowati, AB, 2019. Compliance of smallholder timber value chains in East Java with Indonesia's timber legality verification system. *Forest Policy and Economics*, 102, 41–50. doi:10.1016/j.forpol.2019.02.005

TAPPI, 1999. *Technical Association of the Pulp and Paper Industry T-207 Water Solubility of Wood and Pulp*. Atlanta: TAPPI.

TAPPI, 2002. *Technical Association of the Pulp and Paper Industry T-212 One Percent Sodium Hydroxide Solibility of Wood and Pulp*. Atlanta: TAPPI.

Timar, MC, 2016. Color and FTIR analysis of chemical changes in beech wood (Fagus sylvatica L.) after light steaming and heat treatment in two different environments. *Bioresources*, 11. doi:10.15376/biores.11.4.8325-8343

Tsutsumi, Y, 1995. The difference of reactivity between syringyl lignin and guaiacyl lignin in alkaline systems. *Holzforschung*, 49, 423–428. doi:10.1515/hfsg.1995.49.5.423

Van, TP, 2021. Effect of wood and panel density on the properties of lightweight strand boards. *Wood Material Science & Engineering*, 16, 237–245. doi:10.1080/17480272.2019.1705906

Van, TP, Biziks, V, and Mai, C, 2022. Effects of low and high molecular weight of phenol-formaldehyde (PF) on the properties of strand boards from kiri wood (Paulownia tomentosa). *Wood Material Science & Engineering*, 17, 337–344. doi:10.1080/17480272.2020.1867239

Vital, BR, Lehmann, WF, and Boone, RS, 1974. How species and board densities affect properties of exotic hardwood particleboards. *Forest Products Journal*, 24, 37–45.

Wang, X, Deng, Y, and Li, Y, 2016. In situ identification of the molecular-scale interactions of phenol-formaldehyde resin and wood cell walls using infrared nanospectroscopy. *RSC Advances*, 6, 76318–76324. doi:10.1039/C6RA13159J

Yusoh, AS, Md Tahir, P, and Anwar Uyup, MK, 2021. Effect of wood species, clamping pressure and glue spread rate on the bonding properties of cross-laminated timber (CLT) manufactured from tropical hardwoods. *Construction and Building Materials*, 273, 121721. doi:10.1016/j.conbuildmat.2020.121721

Zhou, D, 1990. A study of oriented structural board made from hybrid poplar. *Holz als Roh- und Werkstoff*, 48, 293–296. doi:10.1007/BF02626522

Zhuang, B, Cloutier, A, and Koubaa, A, 2022. Physical and mechanical properties of oriented strand board made from eastern canadian softwood species. *Forests*, 13, 523. doi:10.3390/f13040523