Several Properties of Oil-Palm-Based Hybrid Laminated Veneer Lumber (LVL) Glued with Phenol Formaldehyde Resin

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Physical and mechanical properties were measured of oil-palm-based hybrid laminated veneer lumber (LVL) from pressed oil-palm wood veneer (*Elaeis guineensis* Jacq.) combined with jabon (*Anthocephalus cadamba* Miq.) or mahogany (*Swietenia macrophylla* King) veneers. Jabon and mahogany veneers were applied as the surface (face and back) and center-core of a 5-layer oil-palm-based hybrid LVL and glued with phenol-formaldehyde at a spread amount of 200 g/m^2. Different combinations of veneer layers were used to make oil-palm-based hybrid LVL. The hot-pressing phase occurred at 140 °C under a specific pressure of 10 kg/cm^2 for 7 min. All hybrid LVLs exhibited better properties than the oil-palm LVL. Specifically, the density, moisture content, horizontal shear flat, horizontal shear vertical, modulus of rupture, modulus of elasticity, compression strength, and hardness of all hybrid LVLs were higher than those of the oil-palm LVLs, showing improvements of about 7.8 to 19.6%, 8.8 to 17.6%, 35.0 to 44.9%, 35.4 to 79.4%, 35.7 to 76.1%, 5.3 to 46.8%, 19.9 to 68.4%, and 9.6 to 56%, respectively. Their thickness swelling and water absorption decreased 10.7 to 24.7% and 2.9 to 27.7%, respectively. The oil-palm-based hybrid LVL incorporating three mahogany veneers possessed the most favorable physical and mechanical properties among other LVLs.

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INTRODUCTION

Laminated Veneer Lumber (LVL), another form of structural composite lumber, is manufactured by arranging the dried veneer layers parallel to its length and adhering them with adhesive. Hybrid LVL has garnered significant interest in the field of composite materials due to its potential to combine the advantageous properties of different wood species, including those of underutilized resources. The utilization of oil-palm trunks as a material for manufacturing LVL has emerged as a compelling and environmentally sound solution to address the mounting waste produced by the palm oil sector.

The National Statistic Centre reported that Indonesia produced 45.1 million tons of palm oil in 2020 from 14.62 million hectares of oil-palm plantations. The exponential growth of this industry has led to substantial amounts of waste in the form of oil-palm trunks, which are often discarded or left to decompose, contributing to environmental concerns. In 2030, it is anticipated that 54 million tons of fresh fruit bunches, 30.7 million tons of mesocarp fiber, 14.8 million tons of palm kernel shell, 130 million tons of palm oil mill effluent, 129 million tons of fronds, and 59.7 million tons of trunks would be produced (Hambali and Rivai 2017).

Previous research in this area has shed light on the mechanical, physical, and structural properties of hybrid LVLs manufactured using different wood species in combination. The properties of laminated products, including LVL, are affected by wood species, wood quality, adhesive type, layer thickness and arrangements used during the material production (Arabi *et al.* 2024, Sulastiningsih *et al.* 2020, Prabuningrum *et al.* 2020, Wei *et al.* 2019, McGavin *et al* 2019; Muller *et al.* 2015; Wahab *et al.* 2013; Erdil *et al.* 2009; Wahab *et al.* 2008; Wong *et al.* 1996). Mixing various wood species with different properties could improve the LVL quality. Studies have demonstrated that making LVL with two different veneer types, *i.e.* "hybridization," can lead to enhanced strength, stiffness, and dimensional stability compared to single-species LVLs (Nordin *et al.* 2004a; Wei *et al*. 2019; Bal 2016; Liew and Grace 2016; Suhaily *et al.* 2019; Sulastiningsih *et al.* 2020). For instance, the 30-mm-thick LVLs consisting of 8 layers of beech and poplar veneers in various arrangements had shown better specific gravity, bending strength, and modulus of elasticity (parallel to glue line) than solid poplar and LVL made of merely poplar veneers (Burdurlu *et al.* 2007). According to Sulastiningsih *et al.* (2020), hybrid LVL made of oil-palm and mahogany veneers and glued with urea-formaldehyde adhesive had better mechanical strength than those made of merely oil-palm veneers. Similarly, Nordin *et al.* (2004a) reveal superior bending and compression strength of hybrid LVLs made from oil-palm trunk and rubberwood compared to conventional LVLs made from oil-palm trunk or rubberwood alone. San *et al.* (2007) observed an increase in the flexural properties of LVL derived from oil-palm trunk as the glue spread rate increased and the oil-palm veneer used as the LVL' outer-layers.

Jabon and mahogany are two wood species that have better properties than oil-palm trunk, and therefore they could be useful in improving the properties of oil-palm-based LVL. Both jabon and mahogany are developed in the plantation forest in Indonesia, but they have different properties. Jabon is a fast-growing species and native plant to Indonesia (Purwoko *et al.* 2023; Herawati *et al.* 2024; Rahayu *et al.* 2024; Suhaya *et al.* 2024). Jabon wood has a specific gravity range of 0.29 to 0.56, strength class of III to IV, and durability class of V (Martawijaya *et al.* 2005b).

In contrast, even though mahogany (*Swietenia macrophylla* King) is not as fast growing as jabon, it has a specific gravity range of 0.56 to 0.72, a strength class of II to III, and durability class of III (Martawijaya *et al.* 2005a). This species is native to Central and South America. It is largely planted in Asia, Southeast Asia, and the Pacific regions (Krisnawati *et al.* 2011). Its dense and strong wood has been used extensively as raw materials for furniture, doors, boats, musical instruments, and others (Borah *et al.* 2022). Mahogany wood also has average tangential shrinkage of 1.3%, average radial shrinkage of 0.9%, and anisotropy coefficient ranged from 1.02 to 1.27 (De Carvalho 2021; Martawijaya *et al.* 2005a). Overall, the wood has strong dimensional stability, which reduces potential defects during future use. For LVL products to retain their structural integrity, this stability is essential (De Carvalho 2021).

Previous study on LVL fabrication from oil-palm, jabon, and mahogany veneers have been using urea-formaldehyde resin as its adhesive (Sulastiningsih *et al.* 2020). According to Erdil *et al*. (2009), adhesive types could also affect LVL's performance due to differences in bonding. Masseat *et al.* (2018) showed that LVLs made from PF-treated oil-palm veneer had superior physical properties to LVLs made from untreated oil-palm veneer. Composite products made with phenol-formaldehyde, resorcinol-formaldehyde, and phenol-resorcinol-formaldehyde adhesives have proven to be more durable than solid wood when exposed to mild and humid conditions, water, alternating wetting and drying, and temperatures high enough to char wood (Frihart and Hunt 2021). Therefore, this study was designed to investigate the suitability of phenol-formaldehyde resin (PF) for fabricating hybrid LVL from oil-palm, jabon, and mahogany veneers with different layers arrangement. Considering the bonding ability of PF resin' with the three veneer types could affect the LVL properties, thus, the study also examined morphological and other physical and mechanical properties of the fabricated LVLs, *i.e.*, density, moisture content, thickness swelling, water absorption, bending strength, compression strength, hardness, and shear strength.

EXPERIMENTAL

Materials

The 32-year-old oil-palm trunk (*Elaeis guineensis* Jacq.) was collected from Malimping in Banten Province, while 6-year-old jabon wood (*Anthocephalus cadamba* Miq.) and 25-year-old mahogany wood (*Swietenia macrophylla* King.) were sourced from Sukabumi in West Java Province. The density of oil-palm trunk, jabon wood, and mahogany wood used in this research were 0.43, 0.45, and 0.56 g/cm^3, respectively. Additionally, a commercially available liquid phenol-formaldehyde adhesive (solid content = 43%) together with filler was employed in the research. Both adhesive and filler were sourced from PT Palmolite Adhesive Industry, Probolinggo, Indonesia.

Methods

Wood veneer preparation

A rotary peeling machine was used to convert the oil-palm trunk logs, which had an average diameter of 360 mm and a length of 1400 mm, into veneers. The intended veneer thickness was 5.5 mm. While industrially produced LVL commonly utilizes veneers of approximately 3.2 mm thickness, this study employed 5.5 mm thickness for oil-palm veneers. The thicker veneers were selected to avoid tearing or distorting oil-palm veneer during the veneer peeling, drying, gluing, and hot-pressing processes. Following this, the rotary veneers were cut into pieces measuring 400 mm in length and 420 mm in width. The veneers were then air-dried at room temperature for one day, followed by sun-drying until they attained a moisture content of about 16%. To complete the procedure, the oil-palm veneers were hot-pressed at a temperature of 120 °C under a pressure of 10 kg/cm^2 for 3 min. This pre-pressing procedure was used to smooth the rough-textured surface of oil palm wood veneers (Fig. 1). Pre-pressing treatment not only reduces surface roughness but also helps cut down on the quantity of glue used in the making of plywood (Bekhta *et al.* 2012; Bekhta and Marutzky 2007). In addition, past experiments with different wood species have revealed that smoother surfaces consistently resulted in higher bonding strengths, indicating the importance of minimizing surface roughness for optimal adhesive performance in plywood or LVL production (Küreli and Doganay 2015; Söğütlü 2017).

The jabon and mahogany logs, which averaged 280 mm in diameter and 1250 mm in length, underwent a process to produce wood veneer. A rotary peeling machine was used to obtain the desired 2 mm veneer thickness. The rotary veneers were subsequently cut into pieces measuring 400 mm in length and 420 mm in width. The veneers were conditioned at room temperature for one day before being exposed to the sun until their moisture content reached approximately 16%. To ensure optimal moisture levels, the veneers were subsequently oven-dried at 80 °C for 72 h, reducing the moisture content to approximately 8%. The pre-pressing was not applied for mahogany and jabon veneers since their surface were already smooth, approximately R_a 8.77 µm and 11.58 µm, respectively (measured with Mitutoyo surface roughness tester type SJ-210).

Fig.1. Appearance of the veneer used for LVL fabrication

Laminated-veneer-lumber (LVL) fabrication

Using varying layer compositions, 400 mm (width) × 400 mm (length) × thickness hybrid LVL panels with five plies were manufactured. The panels consisted of five different layer compositions: five-ply LVL composed of oil-palm trunk veneers for each layer (C1); five-ply LVL with face and back layers composed of jabon veneers (C2); five-ply LVL with face, center core, and back layers composed of jabon veneers (C3); five-ply LVL with face and back layers composed of mahogany veneers (C4); and five-ply LVL with face, center core, and back layers composed of mahogany veneers (C5) (Table 1).

Table 1. Layer Composition of Oil-Palm-Based Hybrid LVL

LVL Type	Layer Number and Veneer Type				
	1	2	3	4	5
C1 (5S)	OPT (S)	OPT (S)	OPT (S)	OPT (S)	OPT (S)
C2 (2J3S)	Jabon (J)	OPT (S)	OPT (S)	OPT (S)	Jabon (J)
C3 (3J2S)	Jabon (J)	OPT (S)	Jabon (J)	OPT (S)	Jabon (J)
C4 (2M3S)	Mahogany (M)	OPT (S)	OPT (S)	OPT (S)	Mahogany (M)
C5 (3M2S)	Mahogany (M)	OPT (S)	Mahogany (M)	OPT (S)	Mahogany (M)

Note: C1 = five-ply LVL composed of oil-palm trunk veneers for each layer; C2 = five-ply LVL with face and back layers composed of jabon veneers; C3 = five-ply LVL with face, center core, and back layers composed of jabon veneers; C4 = five-ply LVL with face and back layers composed of mahogany veneers; and C5 = five-ply LVL with face, center core, and back layers composed of mahogany veneers

A phenol-formaldehyde adhesive mixture of PF resin and 20% filler was applied to each veneer face with a targeted distribution amount of 200 g/m^2 per glue line during the manufacturing process. After applying the adhesive, five veneer sheets were assembled in a parallel direction, and the assembly was cold-pressed at a specific pressure of 10 kg/cm^2 for 15 min to produce an LVL board with the targeted dimension. Subsequently, the assemblage was hot-pressed at a temperature of 140 °C and a specific pressure of 10 kg/cm^2 for 7 min. Each variety of LVL had five replications prepared. Before being subjected to testing, the manufactured LVL panels were conditioned for two weeks. Figure 2 shows samples of the oil-palm-based hybrid LVL fabricated in this study with five different layer compositions.

C1 C2 C3 C4 C5

Fig. 2. Samples of oil-palm-based hybrid LVL from each configuration

Evaluation of LVL properties

After conditioning for two weeks, several properties of LVLs, including morphological properties, moisture content (MC), density, thickness swelling (TS), water absorption (WA), bonding quality/delamination, horizontal shear strength, modulus of rupture (MOR), modulus of elasticity (MOE), compression strength (CS), and hardness were assessed. For morphological properties test, the samples used were the cross-section dimension of each LVL type, measuring 10 mm x 10 mm. The test was carried out using 3D Digital Microscope of Keyence (VHX 6000) with 20× magnification.

Except for bonding quality/delamination and horizontal shear strength, other tests were conducted in accordance with the American Standard ASTM D1037 (2006). The Japanese Agricultural Standard No. 683 (2018) was used to evaluate the bonding quality/delamination property and horizontal shear strength. All physical and mechanical properties data of LVL were analyzed using analysis of variance (ANOVA) with a completely randomized design, with the layer compositions as the treatment factor. Each physical and mechanical property of the LVLs was measured using five replicates

For the moisture content test, the samples' dimension was 100 mm × 100 mm. The samples were oven-dried for 24 h or until a constant weight was achieved at a temperature of 103 ± 2 °C. The moisture content was determined by subtracting the original weight from the weight obtained after oven drying. The moisture content values of LVL were calculated using Eq. 1 (ASTM D1037 2006).

The density evaluation was conducted by measuring the initial dimension of each specimen. The specimen for density evaluation had identical dimensions to the sample used for the moisture content test. The calculation of density was performed by dividing the specimen's weight by its original volume. The density values of LVL were calculated using Eq. 2 (ASTM D1037 2006)

The water absorption and thickness swelling tests were conducted by immersing the specimen in cool water for 24 h. The calculation of water absorption and thickness swelling of the LVL involved determining the discrepancy between the initial weight and thickness of the specimen and its weight and thickness after immersion in water. The water absorption (WA) and thickness swelling (TS), values of LVL were calculated using Eqs. 3 and 4 (ASTM D1037 2006),

$$MC\ (\%) = \frac{W_1 - W_0}{W_0} \text{ x } 100 \tag{1}$$

$$\rho\ (g/cm^3) = \frac{W_1}{V_1} \tag{2}$$

$$WA\ (\%) = \frac{W_2 - W_1}{W_1} \text{ x } 100 \tag{3}$$

$$TS\ (\%) = \frac{T_2 - T_1}{T_1} \text{ x } 100 \tag{4}$$

where MC is moisture content (%), ρ is density (g/cm^3), WA is water absorption (%), TS is thickness swelling (%), W_1 is LVL initial weight (g), W_0 is LVL oven dry weight (g), V_1 is LVL initial volume (mm^3), W_2 is LVL weight after 24 h-water immersion (g), T_1 is LVL initial thickness (mm), and T_2 is LVL thickness after 24 h-water immersion (mm).

The LVL's bonding quality was assessed using a delamination test and a horizontal shear test. The delamination test involved submerging a 75 mm × 75 mm LVL sample in boiling water at a controlled temperature of 100 ± 3 °C for 4 h and further cooled in water at room temperature for 1 h. Subsequently, the sample was subjected to oven drying at 70 ± 3 °C for 18 h. Following the completion of the treatment, it is necessary to quantify the extent of delamination present in each adhesive joint on all four sides of the test specimen, the ratio of delamination on four sides of the test specimen, and the total length of delamination on the same bonding layer shall be calculated. The ratio of delamination was calculated according to Eq. 5 (JAS No 683 2018),

$$RD\ (\%) = \frac{L_d}{L_b} \text{ x } 100 \tag{5}$$

where RD is ratio of delamination (%), L_d is the total length of delamination on four sides (mm), and L_b is the total length of the bonding layer on 4 sides.

The horizontal shear test was carried out in 2 directions, namely horizontal shear flat (HSF), indicating horizontal direction use, and horizontal shear vertical (HSV), indicating vertical direction use. For the HSF test, the sample's width was 40 mm, and the length was 6 times the thickness of the LVL sample. For the HSV test, the samples' width was the same with their thickness, and the length was 6 times of the LVL's sample thickness. The test was carried out like a bending test with the span length equal to 4 times the thickness of the sample LVL. The values of HSF and HSV were determined using equation 6. (JAS No 683 2018),

$$HSF, HSV\ (\text{MPa}) = \frac{3P}{4bt} \tag{6}$$

where HSF is horizontal shear strength flat (MPa), HSV is horizontal shear strength vertical (MPa), P is the maximum load (N), L is span length (mm), and b and t are the width and thickness of the LVL specimen (mm).

All mechanical properties were assessed utilizing a Universal Testing Machine (Shimadzu, UH-100A Series, Japan). The determination of the modulus of rupture (MOR) and modulus of elasticity (MOE) was conducted concurrently with grain in parallel direction and flat-wise bending tests. The dimensions of the MOR and MOE samples were

300 mm (length) × 50 mm (width) × 16.5 mm (thickness) for OPT LVL (C1), and 250 mm (length) × 50 mm (width) × 13.5 mm (average thickness) for hybrid LVL (C2, C3, C4, and C5). The experiment involved subjecting the test specimen to a continuous load at a speed of 10 mm/min, specifically at the center of the specimen. The span lengths used for the experiment were 250 mm and 200 mm for OPT LVL and hybrid LVL, respectively. The highest load observed at the site of fracture in the specimen was documented and used to determine the MOR. Conversely, to calculate the MOE, both the load at the proportional limit and the corresponding deflection were recorded. The values of MOR and MOE of LVL were determined using Eqs. 7 and 8 (ASTM D1037 2006).

The dimensions of the specimen used for measuring compression strength parallel to the grain (CS) were 25 mm in width × 60 mm in length × thickness. A progressive compressive load was steadily applied until the point of maximum load (P, in N) was attained. This resulted in the fracture of the test specimen. The CS of LVL was determined using Eq. 9,

$$MOR\ (MPa) = \frac{3PL}{2bt^2} \quad (7)$$

$$MOE\ (GPa) = \frac{\Delta PL^3}{4\Delta Ybt^3} \quad (8)$$

$$CS\ (MPa) = \frac{P}{bt} \quad (9)$$

where *MOR* is modulus of rupture (MPa), *MOE* is modulus of elasticity (GPa), *CS* is compression strength (MPa), *P* is the maximum load (N), *L* is span length (mm), *b* and *t* are the width and thickness of the LVL specimen (mm), ΔP is the load at the proportional limit (N), and ΔY is deflection at the proportional limit (mm).

For the hardness test, the samples used had a dimension of 50 mm (length) × 50 mm (width) × thickness. The hardness of the material was assessed using the Janka test, which involved applying an 11.28 ± 0.05 mm diameter hemispherical steel ball to the surface of the specimen. The test measured the load required for the ball to penetrate to a depth of half its diameter, specifically 5.64 mm, as indicated by the tightening of the collar against the specimen. The calculated surface area of the ball on the test specimen was 100 mm².

RESULTS AND DISCUSSION

Morphological Properties of Oil-palm-based Hybrid LVL

Figure 3 presents cross-section of LVLs captured using 3D Digital Microscope of Keyence (VHX 6000) with 20× magnification. The results demonstrated that the phenol formaldehyde (PF) glue could permeate the wood structure, allowing for mechanical interlocking. Consequently, this would eventually enable greater interaction between veneers and PF adhesive. As shown in Fig. 3, the glue line on the LVL using oil-palm veneer (C1) appeared to be thinner than that observed in the hybrid LVLs using jabon and mahogany veneers (C2-C5). A more visible and thicker glue line was observed in the C5 LVL compared to other LVL combinations. Khoo *et al.* (2021) stated that the glue line thickness formation could be influenced by the amount of adhesive applied to the veneer surface. The lack of adhesive in the glue line reduces cohesive strength, resulting in a thin and starved glue line (Frihart 2005).

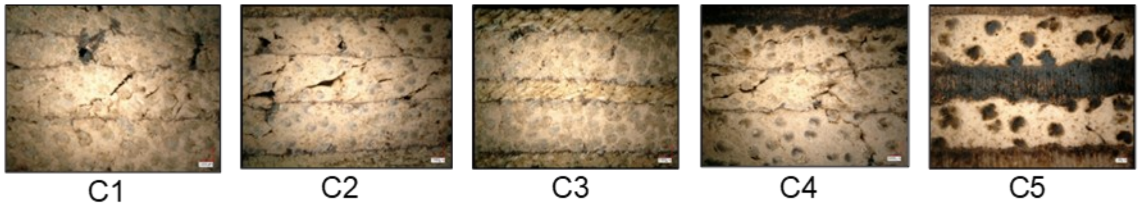

Fig. 3. Cross-section of LVLs captured using 3D Digital Microscope of Keyence (VHX 6000) with 20× magnification

The density, anatomy and surface condition of the lumber impacted the adhesive distribution on the veneer surface and its further penetration into wood structure. According to Wang *et al.* (2016), adhesive penetration into the wood's secondary cell wall can increase cell-wall connections and improve the elasticity of the bonding interphase. Generally, mahogany veneers have a greater density with a more complex anatomical structure compared to oil palm trunk and jabon veneer, which makes its glue lines thicker than others. Veneers with deep and frequent lathe checks may need a higher glue spread rate to provide a sufficient glue line thickness (Vick 1999; Daoui *et al.* 2011), thereby allowing better internal surface contact for mechanical interlocking, and transferring stresses efficiently between plies (Kurt and Ci 2012).

The jabon and mahogany veneers appeared to be more intact than the veneer from oil-palm trunks following the pressing process. According to Li *et al.* (2019), the bonding strength of the bond lines is mostly responsible for the LVL's strength. The presence of lathe checks increases adhesive penetration and reduces bond line integrity. The strength of the bond is increased when the bond line is continuous. However, ultimate strength does not usually rely on extensive adhesive penetration because bond line shear strength is mostly determined by the weakest connection across the laminas (Liu *et al.* 2018). Thicker glue lines were observed for LVL with mahogany veneers (C4 and C5); however, the adhesive volume used was considered excessive as excess adhesive was squeezed out around the panel edges during pressing and appeared dark. It is also known that bonding strength will decrease as the glue line thickness increases. This is due to the fact that with a thicker glue line, higher internal stress is generated during glue shrinkage, which can lead to a lower shear strength (Pizzi and Mittal 2017).

Physical Properties of Oil-palm-based Hybrid LVL

The average density, moisture content, thickness swelling, and water absorption of hybrid LVL made of oil-palm trunk, jabon, and mahogany veneers are displayed in Table 2. The LVL made from oil-palm alone had the lowest average density (0.51 g/cm^3), while that hybrid LVL using 3 layers of mahogany veneers for the face, center core, and back layers (C5) had the highest density value (0.61 g/cm^3). The average density range for 5-plies LVLs made from a combination between oil-palm and jabon or mahogany veneer was 0.55 to 0.56 g/cm^3. The LVL density is affected by the types and density of the wood used, the amount of adhesive employed, the ply organization, and the manufacturing process. This statement agrees with the results of a previous study by Shukla and Kamdem (2008). In this study, the average density values of oil-palm and mahogany wood were the lowest (0.43 g/cm^3) and highest (0.56 g/cm^3), respectively, which explained the highest density of hybrid LVL using 3 layers of mahogany veneers.

The incorporation of 2 and 3 layers of mahogany and jabon veneers into oil-palm-based hybrid LVLs (C2−C5) increased the density values by 7.8 to 19.6% greater than oil-palm LVL (C1). Further statistical analysis confirmed significant differences in the density of C1 and those of C3 and C5, but not with C2 or C4. This result indicates that the inclusion of 3 layers of other hardwood veneers with higher density than oil-palm, such as jabon and mahogany, as the face, center core, and back layers of hybrid LVL (C3 and C5) potentially increases the density of oil-palm-based hybrid LVL. This result is in line with previous studies. Organizing veneers of a higher density species, such as beech, as the face and back of hybrid LVL helped increase the composite density from beech and poplar veneers (Burdurlu *et al.* 2007). When denser species, such as keruing, were used to reinforce low-density woods such as pulai, sesendok, and kekabu hutan, a stronger and denser LVL that met structural requirements was produced (H'ng *et al.* 2010). Nordin *et al.* (2004a) added that the combination of veneers used in the LVL structure increases the density values relative to LVL built solely with OPT veneers. The density values of seven-ply LVL with two layers and three layers of rubberwood veneers were 0.57 g/cm^3 and 0.59 g/cm^3, respectively, while the density value of entirely oil-palm layers LVL was 0.54 g/cm^3 (Nordin *et al.* 2004a). It could be argued that the more homogenous and higher density of solid rubberwood is responsible for enhancing the density of oil-palm-based hybrid LVL (Nordin *et al.* 2004a).

Table 2. Several Physical Properties of Oil-palm-based Hybrid LVL

Layer Compositions	Properties			
	Density (g/cm^3)	MC (%)	TS (%)	WA (%)
C1	0.51^c (0.01)	10.2^b (0.5)	9.3^a (1.0)	81.3^a (3.3)
C2	0.55^{bc} (0.05)	12.0^a (0.6)	8.2^{ab} (0.9)	78.9^a (2.5)
C3	0.56^{ab} (0.03)	11.8^a (0.8)	7.8^{ab} (0.4)	74.9^a (6.0)
C4	0.55^{bc} (0.02)	11.3^a (0.3)	8.3^{ab} (1.1)	66.1^b (3.7)
C5	0.61^a (0.03)	11.1^{ab} (0.4)	7.0^b (0.9)	58.8^b (6.1)
ANOVA results, P-value	0.001**	0.001**	0.013*	0.000**

Notes: C1= 5-ply LVL composed of oil-palm trunk veneers for each layer; C2 = 5-ply LVL with face and back layers composed of jabon veneers; C3 = 5-ply LVL with face, center core, and back layers composed of jabon veneers; C4 = 5-ply LVL with face and back layers composed of mahogany veneers; C5 = 5-ply LVL with face, center core, and back layers composed of mahogany veneers; MC = moisture content; TS = thickness swelling; WA = water absorption. Values in parentheses indicate standard deviation; values followed with the same letter within the same column are not significantly different; * = significant at 95%, ** = highly significant at 99%

Nevertheless, the density values of oil-palm-based hybrid LVLs with 2 layers of jabon (C2) or 2 layers of mahogany veneers (C4) were not significantly different from each other. This result could be linked to the structure of jabon, which has a lower density than mahogany wood. Therefore, jabon also has more internal void space, enabling it to possibly absorb and deposit more resin than mahogany wood. Ngabalin and Listyanto (2023) reported that jabon wood had a better intake of phenol formaldehyde than sengon (*Paraserianthes falcataria*), which has a lower density than jabon, indicating a good compatibility between this particular resin with jabon. Another study explained that higher uptake of phenol formaldehyde resin by certain hardwood species could be linked to their low density or better affinity to the resin molecules (Kupfernagel *et al.* 2023).

The moisture content range of hybrid LVL manufactured in this study was 10.2 to 12%. The hybrid LVL with the inclusion of jabon veneers on its face and back layers (C2) showed the highest value of 12% followed by C3 (11.8%), C4 (11.3%), and C5 (11.1%). These values were 8.8 to 17.6% higher than the moisture content of C1. A few variables, such as the wood species used, the veneer lay-up and bonding methods, and the production and storage environments, could affect the moisture content of LVL. Higher MC levels observed in LVL types C2 to C5 from this study could be the result from using denser veneers than oil-palm wood, *i.e.* jabon and mahogany. According to Li *et.al* (2020) denser veneers have more compact structure, which can limit moisture transport and retention, leading to higher moisture content in LVL. Statistical analysis with a 95% confidence interval showed that the arrangement of veneer layers of the hybrid LVL had a very significant effect on moisture content values. In addition to this, moisture content values of all LVL in this study satisfied the Japanese Agricultural Standard for LVL (JAS No 683 2018).

Thickness swelling and water absorption are the parameters used to provide insight into the dimensional stability of LVL. The thickness swelling and water absorption values of hybrid LVL manufactured in this study were approximately 7.0 to 9.3% and 58.8 to 81.3%, respectively (Table 2). In general, the incorporation of mahogany or jabon veneers into the structure of oil-palm-based hybrid LVL increased the LVL's dimensional stability as the thickness swelling and water absorption were reduced 10.8 to 24.7% and 2.9 to 27.7%, respectively. Furthermore, oil-palm-based hybrid LVL made of two layers of jabon veneers as the surface had the highest thickness swelling and water absorption. In contrast, the lowest values of both parameters were observed in LVL, which comprised 3 layers of mahogany veneers as the surface and centre-core (C5). The high density of mahogany veneer may be attributed to the superior performance of the dimensional stability of the hybrid LVL. Vick (1999) stated that high-density wood typically has a denser cell wall and a smaller lumen, which correlates to a smaller volume for water absorption compared to low-density wood. Further statistical analysis revealed that the thickness swelling and water absorption of oil-palm-based hybrid LVLs made with mahogany veneers (C4 and C5) were significantly different from other types of hybrid LVL or oil-palm LVL, indicating the significant influence of wood species being used and/or their densities.

In addition, the highest water absorption value observed in C1 could be attributed to the predominant influence of the intrinsic permeability of oil-palm trunk veneer employed in the LVL structure. Bal (2016) pointed out a similar trend for the correlation between water absorption and permeability of the veneers used in the LVL. Choo *et al.* (2013) reported that the permeability of oil-palm trunks ranged from 4.3 to 7.9 Darcys. Nevertheless, mahogany has limited permeability due to its anatomical characteristics, characterized by short and wide vessels, small inter-vessel pits, short fibers, and the occlusion of the vessels due to the excretion of tannins or gum-like compounds inside its small pits (Listyanto *et al.* 2010). The use of mahogany and jabon veneers has been observed to be beneficial in mitigating water absorption in hybrid oil-palm LVL. The observed decrease in water absorption of hybrid LVLs was hypothesized to be attributed to the density of the materials.

The bonding quality of composite materials is of utmost significance. In this study, the bonding quality of multilayer composite products was assessed by the delamination and horizontal shear tests, and the results are presented in Table 3. The outcomes of the boiling water delamination test indicated the absence of delamination in all specimens. In contrast to this, Jamaludin *et al.* (2010) reported that seven-layer, six-layer, and five-layer oil-palm trunk LVL glued with urea formaldehyde (UF) did not pass the boiling water test. They argued that UF LVL exhibited a certain degree of resistance to moisture, while it did not possess waterproof properties. One notable drawback of amino resins is their susceptibility to bond degradation resulting from exposure to water and moisture. This phenomenon can be attributed to the hydrolysis of the amino-ethylenic link present in these compounds. Consequently, adhesive formulations consisting solely of urea-formaldehyde (UF) are exclusively employed for interior applications. Nonetheless, Wahab *et al*. (2013) demonstrated that oil palm composite boards glued with urea–formaldehyde resin when produced under specific configurations can satisfy delamination requirements, suggesting that bond durability is strongly dependent on processing parameters.

Table 3. Bonding Quality of Oil-Palm-Based Hybrid LVL

Layer Compositions	Properties		
	Delamination (%)	HSF (MPa)	HSV (MPa)
C1	0	2.3^b (0.2)	2.4^c (02)
C2	0	3.4^a (0.7)	3.4^b (0.4)
C3	0	3.2^a (0.3)	3.3^b (0.3)
C4	0	3.2^a (0.3)	3.6^b (0.3)
C5	0	3.4^a (0.3)	4.4^a (0.6)
ANOVA results, P-value		0.001**	0.000**

Notes: C1= 5-ply LVL composed of oil-palm trunk veneers for each layer; C2 = 5-ply LVL with face and back layers composed of jabon veneers; C3 = 5-ply LVL with face, centre core, and back layers composed of jabon veneers; C4 = 5-ply LVL with face and back layers composed of mahogany veneers; C5 = 5-ply LVL with face, centre core, and back layers composed of mahogany veneers. HSF is horizontal shear strength flat. HSV is horizontal shear strength vertical. Values in parentheses indicate standard deviation. Values followed with the same letter within the same column are not significantly different, ** = highly significant at 99%

The absence of delamination observed in the experiment indicates that the layers possess compatible stiffness and exhibit a favorable interface combination. Consequently, the bonding integrity of the LVL derived from oil-palm trunk, in conjunction with jabon veneer and mahogany veneer, was deemed satisfactory and compliant with the LVL standard set by the Japanese Agricultural Standard for structural application. This finding further verifies that the bonding connections are potentially compatible with outdoor conditions.

The information on LVL horizontal shear, both flat (HSF) and vertical (HSV), is critical as the parameter affects the overall stability of LVL in structural applications. The average values of HSF and HSV of all LVLs from this study were in the range of 2.3 to 3.4 MPa and 2.4 to 4.4 MPa, respectively (Table 3). Based on these values, the oil-palm-based hybrid LVLs manufactured in this study met the criteria set for A type structural LVL as stipulated in the Japanese Agricultural Standard No 683 (2018).

The lowest and highest HSF and HSV values were both observed in C1 and C5. All oil-palm-based hybrid LVLs (C2-C5) had higher HSF and HSV than oil-palm LVL (C1), with approximate increases of 35.0 to 44.9% and 35.4 to 79.4%, respectively. The results indicated that combining oil-palm with jabon or mahogany veneers increased the horizontal shear strength of oil-palm-based hybrid LVL and were confirmed by statistical analysis. According to Gaff *et al.* (2015), the shear strength of LVL is significantly impacted by the wood species used and layers composition, as different species exhibit different mechanical characteristics that can affect LVL performance.

Mechanical Properties of oil-palm-based Hybrid LVL

The mechanical properties and statistical analysis results of the oil-palm-based hybrid LVL are summarized in Table 4. Bending strength tests were performed in a flatwise direction. The average values of bending strength were 25.3 to 44.6 MPa for MOR and 3.4 to 5.0 GPa for MOE. The highest values of MOE (5.0 GPa) and MOR (44.6 MPa) were found in C5, while their lowest values were observed in C1 (LVL made of oil-palm veneers only).

Table 4. Several Mechanical Properties of Oil-palm-based Hybrid LVL

Layer Compositions	Properties			
	MOR (MPa)	MOE (GPa)	CS (MPa)	HD (MPa)
C1	25.3^{c} (4.0)	$3,4^{c}$ (0.5)	18.6^{d} (1.4)	20.7^{c} (0.9)
C2	34.4^{bc} (6.37)	3.6^{bc} (0.6)	22.3^{cd} (1.9)	22.7^{c} (0.3)
C3	43.7^{b} (5.8)	4.9^{ab} (0.8)	27.7^{ab} (5.0)	24.7^{b} (0.8)
C4	33.9^{bc} (4.5)	3.9^{abc} (0.9)	24.1^{bc} (2.3)	22.7^{c} (1.0)
C5	44.6^{a} (5.7)	5.0^{a} (0.6)	31.4^{a} (1.9)	32.3^{a} (1.7)
ANOVA results, P-Value	0.000**	0.003**	0.000**	0.000**

Notes: C1 = 5-ply LVL composed of oil-palm trunk veneers for each layer; C2 = 5-ply LVL with face and back layers composed of jabon veneers; C3 = 5-ply LVL with face, centre core, and back layers composed of jabon veneers; C4 = 5-ply LVL with face and back layers composed of mahogany veneers; C5 = 5-ply LVL with face, centre core, and back layers composed of mahogany veneers; MOR = modulus of rupture; MOE = modulus of elasticity; CS = Compression strength; HD = Hardness; Values in parentheses indicate standard deviation; values followed with the same letter within the same column are not significantly different; ** = highly significant at 99%

The MOR and MOE values from hybrid LVLs that incorporate 2 and 3 layers of jabon or mahogany veneers in the structure were higher than those of LVL from oil-palm veneers only. The increases in MOR and MOE of all hybrid LVLs were approximately 35.7 to 76.1% and 5.3 to 46.8%, respectively. Incorporating 3 layers of mahogany veneers into the structure of oil-palm-based hybrid LVL markedly enhanced its MOR and MOE by approximately 76.1% and 46.8%, respectively. Furthermore, hybrid LVL with 3 layers of jabon/mahogany veneers had higher MOR and MOE than the hybrid LVL with 2 layers of jabon/ mahogany veneers. In other words, as the layers of denser veneers increased, the bending properties values also increased. This result is also in agreement with the existing studies (Nordin *et al.* 2004a; Sulastiningsih *et al.* 2020; Arabi *et al.* 2024). In addition, this result could also be due to the thickness of mahogany and jabon veneers which was thinner than that of the oil-palm veneers. According to Blomqvist *et al*. (2022), thinner veneers generally lead to more uniform stress distribution and better mechanical performance than the thicker ones. Therefore, incorporating 3 layers of mahogany or jabon veneers in the hybrid LVL could lead to a more uniform stress distribution which ultimately increased the LVL's bending strength.

Further statistical analysis showed significant difference in the bending properties of oil-palm LVL and hybrid LVL with 3 layers of mahogany veneers used as its face, center core, and back. The findings demonstrated that the incorporation of mahogany veneer layers enhanced bending characteristics in comparison to oil-palm LVL. This could be linked to the fact that mahogany wood itself already has higher MOR and MOE values (635.3 kg/cm^2 and 9.4 × 10^4 kg/cm^2) than jabon (412.4 kg/cm^2 and 3.4 × 10^4 kg/cm^2) and oil-palm trunk (199.9 kg/cm^2 and 1.6 × 10^4 kg/cm^2) (Yu *et al.* 2020; Cabral *et al.* 2022). In addition to this, the density of raw materials of the LVL had a strong correlation with the bending properties of manufactured products. Among the wood species used in this study, mahogany outperformed the density value, while oil-palm trunk had the smallest density value. The increased density resulted in elevated bending strength values. Hence, it can be observed that the robustness and flexibility of plywood or other veneer products are influenced not solely by the inherent strength of the wood species and the dimensions of the constituent elements, as seen in solid wood, but also by the layer numbers, thickness, and the veneer quality (Dungani *et al.* 2019). These results agree with the previous studies that show the increase in the mechanical properties of LVL from fast-growing species as the wood species and product densities increase (Alamsyah *et al.* 2023; Arabi *et al.* 2024).

Table 4 shows that the average compression strength range of LVLs in this study was 18.6 to 31.4 MPa, with the highest value found in C5 (31.4 MPa). As expected, combining oil-palm and jabon or mahogany veneers resulted in hybrid LVLs (C2-C5) with an approximate compression strength increase of 19.9 to 68.4% from oil-palm LVL (C1). The inclusion of 3 layers of mahogany (C5) and jabon veneers (C3) improved the compression strength of oil-palm LVL up to 68.4% and 48.7%, respectively. Further statistical analysis confirmed that the compression strength of oil-palm LVL (C1) was significantly lower and different from the hybrid LVL made with 3 layers of jabon or mahogany veneers as the face, back, and center core. This result supports the previous study of Nordin *et al.* (2004a,b), who reported that including 3 layers of Malaysian oak (*Hevea brasiliensis*) veneers greatly increased the compression strength of 9-layer-LVL (322 kg/cm^2), in comparison to that of LVL made from only oil-palm veneers (215.2 kg/cm^2) or using only two layers of Malaysian oak veneers in the hybrid LVL structure (271 kg/cm^2).

In addition to the incorporation of higher-density veneers, the application of high-press pressure could also increase compression strength. Kurt *et al.* (2012) recorded a higher compression strength value of LVL (648 kg/cm^2 to 912 kg/cm^2) due to the application of high pressure during the manufacturing process (2.5 kg/cm^2 to 12.5 kg/cm^2). They argued that press pressure affects the degree of adhesive penetration into the substrate (Kurt *et al.* 2012).

The measurement of surface hardness (indentation) indicates the wood composite's ability to withstand abrasion, which is relevant for its potential use in veneer-laminated flooring (Shukla and Kamdem 2008). As shown in Table 4, the average value range of the hardness of all LVLs from this study was 20.7 to 32.3 MPa. The lowest and highest values were observed in C1 and C5, respectively. As expected, the inclusion of two and three layers of mahogany and jabon veneers (construction types of C2 to C5) improved the hardness of oil-palm-based hybrid LVL by approximately 9.6 to 56%. Further statistical analysis confirmed the integration of three layers of jabon or mahogany veneers as the face, back, and center core of the hybrid LVL (C3 and C5) significantly improves the hardness of hybrid LVLs. In general, the hardness of veneer-based composite is affected by the surface strength of the outer veneer. However, this study revealed that the addition of veneer from stronger wood material than oil-palm, such as mahogany, as both surface and core for oil-palm LVL significantly increased the panel hardness. This result could be linked to the structure of mahogany wood that has a dense fiber structure and thick-cells wall, thus allowing the wood to be more resistant to external forces than oil-palm wood that is dominantly occupied by soft parenchymal tissue (Lim and Gan 2005; Martawijaya *et al.* 2005a). In addition, the densities of hybrid LVLs composed of oil-palm and 3 layers of jabon or mahogany veneers (C3 and C5) were also higher than other hybrid or oil-palm LVLs (see Table 2) and potentially contribute to their high hardness values.

CONCLUSIONS

The incorporation of jabon and mahogany veneers markedly improved the performance of the laminated veneer lumber (LVL). Compared with the original oil palm LVL (C1), the hybrid LVLs (C2 to C5) exhibited increases in density (8 to 20%), horizontal shear strength (39 to 83%), modulus of rupture (34 to 76%), modulus of elasticity (6 to 47%), compression strength (20 to 69%), and hardness (10 to 56%). In contrast, thickness swelling and water absorption decreased by 11 to 25% and 3 to 28%, respectively. Among the tested configurations, the C5 arrangement—comprising three layers of mahogany veneers at the face, back, and core—showed the most superior overall performance. These findings demonstrate the potential of hybrid LVL using jabon and mahogany veneers to enhance the structural quality of oil palm LVL. Future research should investigate the durability, dimensional stability, and cost-effectiveness of theC5 configuration for potential industrial-scale applications.

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