

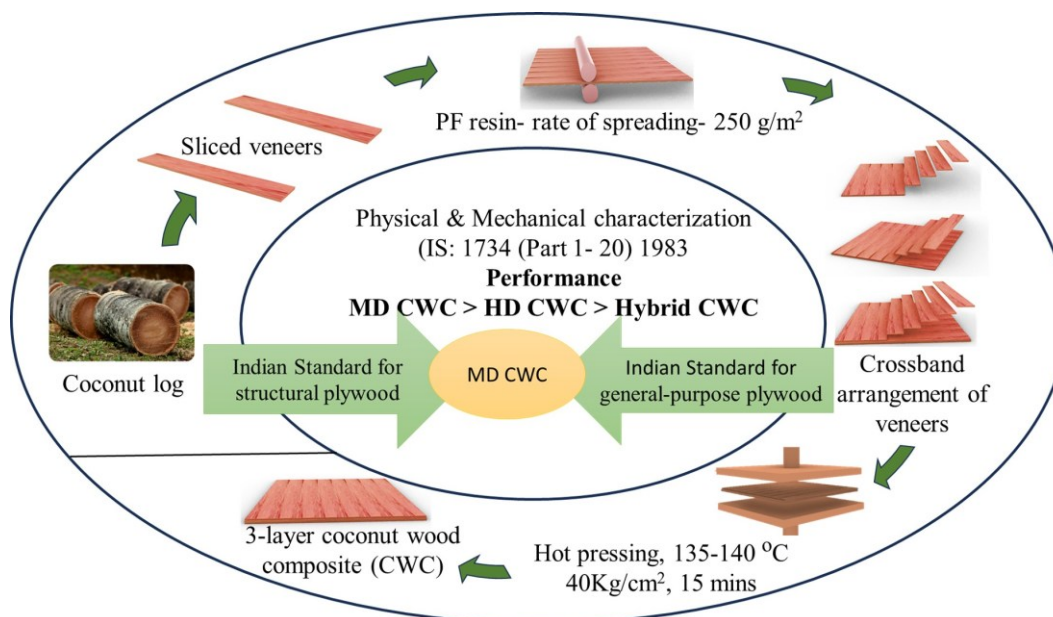
Performance Evaluation of Coconut Wood Veneer Composite for Sustainable Construction Material

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GRAPHICAL ABSTRACT



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The abundant coconut palm (*Cocos nucifera* L.) offers an appealing alternative to meet the increasing demand for wood panels, providing both functional and aesthetic benefits. However, the sclerenchymatous vascular bundle of coconut wood poses challenges for rotary peeling, and the high capital and operational costs associated with palm wood limit its practical use. Consequently, this preliminary study aimed to develop pure and hybrid coconut-sawn veneer composites (using *Macaranga peltata*). Veneers were bonded with phenol-formaldehyde resin in crossband orientation and hot-pressed (40 kg/cm², 135 to 140 °C, 15 min). Four types of 3-layer composites were produced: Pure medium-density coconut composite (Pure-MD), Pure high-density coconut composite (Pure-HD), coconut-*Macaranga* hybrid medium-density composite (Hybrid-MoD), and coconut-*Macaranga* hybrid high-density composite (Hybrid-HD). Physico-mechanical tests revealed that Pure-MD and Pure-HD met Indian standards (IS 303:1989), demonstrating good strength and stiffness. In contrast, high-density composites showed reduced glue adhesion. Hybrid-MD satisfied most criteria except bending stress, restricting high-load applications. Hybrid-HD failed in internal bonding and bending, limiting its utility. The study highlights the potential of pure coconut composites under optimized conditions. However, further improvements are needed for high-density and hybrid composites, focusing on adhesive type, surface modification, veneer alignment, and hot-pressing parameters.

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Keywords: Coconut plywood; Medium-density coconut wood; High-density coconut wood; Coconut hybrid composite

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INTRODUCTION

The coconut palm, often referred to as the “Tree of Life” or “Tree of Heaven”, is a multipurpose tree widely cultivated in over 90 tropical countries, primarily in coastal and island regions between 20° North and South latitudes (George 1985). The coconut palm, which is primarily grown for oil production, bears fruits continuously for 60 to 70 years (Gordon and Jackson 2016). After their economic lifespan, the trees comprise large quantities of lignocellulosic material, such as felled trunks, during replanting, offering a valuable resource for various applications.

In recent years, there has been an increasing shift towards utilizing sustainable materials, such as coconut wood. This shift is driven by the rising demand for eco-friendly products (Srivaro *et al.* 2022). It is estimated that approximately 20 million cubic meters of coconut lumber are produced annually from mature harvested trees (Srivaro *et al.* 2021). The construction industry remains the primary consumer of coconut lumber, where it is widely used for scaffolding and formwork in building construction (Arancon, Jr. 1997). Additionally, selected and graded coconut wood serves as a key material for structural components such as house posts, girders, trusses, door jambs, and sidings. Coconut wood is durable, hard, aesthetic, and exhibits significantly low volumetric shrinkage (Anoop *et al.* 2011). The trunk's outer edge is the strongest and densest, providing the tree with remarkable compressive strength parallel to the grain (CS), modulus of rupture (MOR), and modulus of elasticity (MOE) (Lu *et al.* 2024). Based on density, coconut wood is classified into three grades: high, medium, and low. Higher-density coconut wood is particularly suited for structural applications, including pillars, trusses, rafters, furniture, window and door frames, flooring, decking, and floor joists (Moreno *et al.* 2020; Srivaro *et al.* 2020b). According to Suprobo and Santosa (2017), coconut wood exhibits high strength, making it suitable for furniture production and decorative items such as picture frames and sculptures. Furthermore, high-density coconut wood can be used for load-bearing structures, including posts, power and telecommunication poles, trusses, parquet flooring, purlins, balustrades, and railings. However, a notable challenge in using high-density coconut wood for structural purposes is its difficulty in nailing, which may lead to splitting of finished surfaces (Arancon, Jr. 1997). Overcoming such challenges through appropriate wood processing techniques and fastening methods will enhance the usability of coconut wood in modern construction. Medium-density coconut wood is suitable for walls, studs, ceiling joists, and door or window frames. Both high and medium-density coconut wood can be used in load-bearing applications (Anoop *et al.* 2011). Low-density coconut wood is primarily employed for interior elements, such as ceiling and wall linings, boards, and shingles (Anoop *et al.* 2011).

Due to the small diameter of the coconut stem, the optimal board width and thickness typically recovered from sawn lumber are 50 mm and 25 mm, respectively (Arancon, Jr. 1997). To address the limitation of small-sized lumber, coconut wood can be processed into composite materials, such as plywood and glued laminated timber, allowing for larger structural applications. Previously, many attempts have been made to develop coconut-based composite for structural applications such as plywood. Fahamy *et al.* (2011) created rubberwood-coconut plywood with enhanced physical and mechanical properties, highlighting the potential of coconut plywood. Faircloth *et al.* (2019) reported that coconut plywood panels offer superior mechanical performance and energy efficiency compared to conventional plywood, making them ideal for exterior wall systems. The extraction of high-quality peeled veneer is a challenging process in plywood manufacturing due to its hard fibrovascular bundle. Peeling coconut logs produces mostly low-quality veneer sheets. Additionally, peeling veneer thicker than 2.25 mm results in a noticeable decrease in quality. This process involves high manufacturing costs, and the peeler blade tends to wear out quickly (Arjun 2022). Peeling coconut wood requires substantial capital investment in machinery, as well as high processing and operational expenses. However, a high-quality veneer can be achieved through the sawn veneer. The sawn veneers with a thickness above 2.5 mm can be easily cut from logs and yield better quality (Arjun *et al.* 2022). Earlier studies on coconut plywood did not

account for the densities of coconut wood and their impact on mechanical properties, but this study specifically considers both medium and high-density coconut wood to assess the physical and mechanical properties of the composite accurately. This study also implies the potential of a hybrid composite using macaranga as a core veneer. This will help to better understand the effective utilization of coconut wood by producing high-quality products while also addressing the environmental impacts of over-logging and improving cost efficiency.

EXPERIMENTAL

Materials and Preparations

This study was conducted at the Coconut Wood Training and Demonstration Centre (CWTDC), College of Forestry, Kerala Agricultural University (KAU), Thrissur, India. Composite preparation was undertaken at the Institute of Wood Science and Technology field station, Kolkata, India. Coconut wood was sourced locally from Vellanikkara within Thrissur district, Kerala, India. Macaranga (*Macaranga peltata*) veneers, with thicknesses ranging from 1.5 to 2 mm, were obtained from Wood-X Ply and Boards Private Limited, Perumbavoor, Ernakulam district, India. Industrial-grade PF resin was utilized as an adhesive. The resin met the following standards: 50% solid content, 1:6 water tolerance, B4 22-second flow time, pH 9, and a shelf life of two weeks.

Coconut logs were initially cut into 1.5-m lengths. Subsequently, planks were produced from the subdermal portion of the logs using a portable Wood-Mizer® sawmill (Model: LX50SUPER, bandsaw blade: 335 cm, 32 mm wide, 1.07 mm thick, and with universal 10/30 profile; see supplementary material 1 in the Appendix). These planks had approximate cross-sectional dimensions of 15 cm x 8 cm. The planks were then kiln-dried for four days at 30 to 50 °C and 60% relative humidity (Shibu *et al.* 2023). Following this, the dried planks were further processed into sawn veneers with dimensions of 7 cm x 70 cm and thicknesses ranging from 3 to 3.25 mm using a Combi Planer Max-18 J1019 machine. The veneers were subsequently categorized based on density: high-density (800 to 1100 kg/m³) and medium-density (600 to 800 kg/m³). Phenol-formaldehyde adhesive was applied manually to both sides of core veneers at a 250 g/m² spreading rate. The veneers were then aligned perpendicular to the grain direction and subjected to hot pressing using a 19.5 HP hydraulic hot press (Bemco Hydraulics Limited, Belgaum, Karnataka, India). The specific conditions employed for composite preparation are detailed in Table 1.

Table 1. Three-layer Veneer Composite Preparation Conditions

Composite Types	Veneer Arrangements	Glue Spread Rate	Pressure	Temperature	Pressing Time	Dimensions
Pure-MD	CCC	250 g/m ²	40 kg/cm ²	135 to 140 °C	15 min	700 x 700 x 9 mm
Pure-HD	CCC					900 x 600 x 8 mm
Hybrid-MD	CMC					
Hybrid-HD	CMC					

C-Coconut veneer, M-Macaranga veneer

Three-layer veneer composites were developed using coconut (C) and Macaranga (M) veneers, arranged in specific configurations depending on the composite type. Pure

veneer composites, designated as Medium-Density Pure Coconut Composite (Pure-MD) and High-Density Pure Coconut Composite (Pure-HD), consisted solely of coconut veneers (CCC). Hybrid composites, including Medium-Density Hybrid Coconut Composite (Hybrid-MD) and High-Density Hybrid Coconut Composite (Hybrid-HD), incorporated Macaranga veneer as the core layer (CMC). A face veneer of *Gurjan* species with a thickness of 0.25 mm was used to enhance the surface finish. The dimensions of the Pure-MD and Pure-HD panels were 700 mm × 700 mm with a thickness of 9 ± 0.25 mm. Hybrid panels were fabricated with dimensions of 900 mm × 600 mm and a thickness of 8 ± 0.25 mm.

Composite Characterization

Visual observation and physical properties

All the prepared samples of coconut veneer composites were stored under ambient environmental conditions for a duration of one month to assess potential deformities and monitor any changes in color. Density and moisture content (MC) were determined following the standardized procedures outlined in IS 1734 (Parts 1 to 20) (1983). The test sample (50 mm x 50 mm) was weighed initially (M_i) and then dried in an oven at a temperature of 103 ± 2 °C until a constant weight was obtained. Then, the dried sample was weighed (M_0), and the density and moisture content were calculated using Eqs. 1 and 2, respectively.

$$\text{Density (g/cm}^3\text{)} = M_0 / LWT \quad (1)$$

$$\text{Moisture content (\%)} = \frac{M_i - M_0}{M_0} \times 100 \quad (2)$$

Here, the length (L), width (W), and thickness (T) of the sample were measured in cm.

The thickness swelling (TS) and water absorption (WA) tests were conducted according to STN EN 317 (1995). Samples with dimensions 50 mm x 50 mm were used to measure the initial thickness (T_i) and weight (M_i), and then samples were submerged 10 cm below the water at a temperature of 20 ± 1 °C. The measurements of thickness (T_w) and weight (M_w) were taken after 2 h. These measurements were repeated 24 h later. Then, thickness swelling and water absorption were calculated using Eqs. 3 and 4, respectively,

$$\text{TS (\%)} = \frac{T_0 - T_i}{T_0} \times 100 \quad (3)$$

$$\text{WA (\%)} = \frac{M_w - M_i}{M_w} \times 100 \quad (4)$$

where TS is the thickness swelling (%), T_0 is the thickness of the sample after removal from water, T_i is the thickness of the sample before immersion in water, WA is the water absorption (%), M_w is the mass of the sample after removal from water, and M_i is the mass of the sample before soaking in water.

Volumetric shrinkage (VS) was estimated based on the green and oven-dry volume dimensions. Six samples, each measuring 60 mm x 20 mm, were used for volumetric shrinkage studies. These samples were oven-dried at 105 ± 2 °C until a constant weight was achieved. Volume is calculated by multiplying the three sides of the wood samples. The sides were accurately measured using a digital caliper. Volumetric shrinkage was obtained using Eq. 5,

$$VS = \frac{V_1 - V_0}{V_0} \quad (5)$$

where VS is the volumetric shrinkage (%), V_1 is the initial volume of the sample after its removal from water (kg), and V_0 is the oven-dry volume of the sample.

Mechanical properties

The properties, such as glue shear, tensile strength, static bending, and nail and screw withdrawal, were tested according to the standard IS 1734 (Parts 1 to 20) (1983) from NABL accredited Central Wood Testing Laboratory, The Rubber Board, Kottayam, Kerala. The size of samples used for each test is given in Table 2.

Table 2. Size of Specimen Used for Mechanical Tests

Sl no.	Mechanical Tests	Sample Size
1	Glue shear strength	150 mm x 25 mm, Notch distance 25 mm
2	Tensile strength	Cross section-12 mm x 6 mm
3	Static bending strength (parallel to face veneer)	432 mm x 50 mm x 9 mm (Pure composite) 384 mm x 50 mm x 8 mm (Hybrid composite)
4	Static bending strength (parallel to face veneer)	216 mm x 50 mm x 9 mm (Pure composite) 192 mm x 50 mm x 8 mm (Hybrid composite)
5	Nail and screw holding power	Composite strips measuring 250 mm x 50 mm are glued together to achieve a thickness exceeding 50 mm Screw dimensions: 4 mm in size and 50 mm in length Nail Dimension: 50 mm long and 2.5 mm

RESULTS AND DISCUSSION

Visual Observations

Unique patterns of sawn coconut wood, such as clear, continuous wood fibers uniformly aligned longitudinal direction, enhance its appeal (Dai *et al.* 2023). Figure 1 depicts visual qualities that make it a preferred material for furniture, wooden houses, and souvenirs (Mellolo *et al.* 2018). The study by Srivaro *et al.* (2020a) demonstrated that higher wood density is associated with a darker appearance. Additionally, the outer zone of the wood was found to be darker than the inner zone, while older trunks exhibited a darker colour compared to younger ones of similar density.

Three weeks after manufacture, the medium-density composite showed slight cupping compared to the high-density composite (Fig. 2). Cupping in plywood typically arises from moisture and temperature fluctuations, leading to uneven expansion and contraction of the wood tissues. The primary cause of this issue is the uneven distribution and variation of moisture content in veneers and plywood, which is closely linked to fluctuations in temperature and relative humidity in the surrounding atmosphere (Hrázský and Král 2011). This phenomenon can be attributed to the higher proportion of parenchymatous ground tissue in medium-density coconut wood (Fig. 3), which is more susceptible to dimensional changes in response to environmental factors such as relative humidity. In contrast, the higher proportion of sclerenchymatous fibrous tissue found in high-density coconut wood exhibits greater resistance to environmental fluctuations (Fathi 2014). Although both high-density and medium-density coconut woods were seasoned according to the same standard, these findings suggest that medium-density

wood may require extended seasoning or more precise conditioning to achieve optimal performance (Comath *et al.* 2023). To mitigate cupping, it is essential to implement proper storage and handling of veneers, along with maintaining consistent moisture content throughout the manufacturing process. These measures are crucial in minimizing dimensional instability and ensuring the long-term durability of the composite.



Fig. 1. The surface texture of coconut-sawn veneer plywood

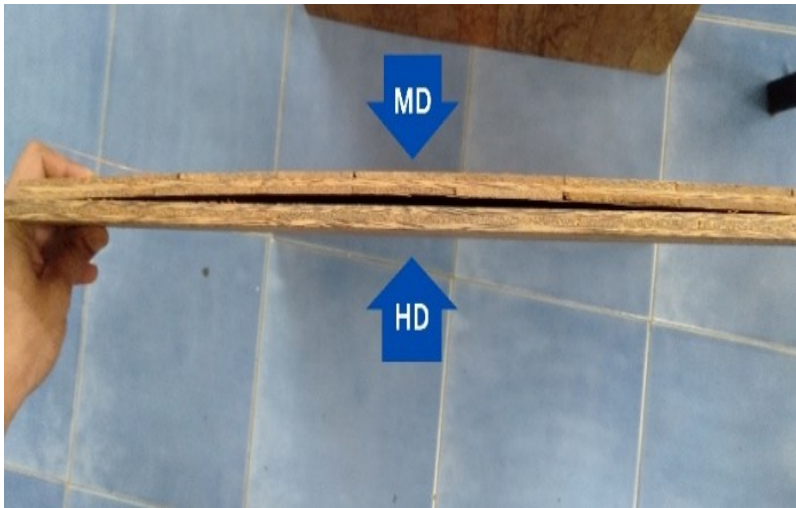


Fig. 2. The vertical view of thickness shows the cupping defect in MD (HD for reference)

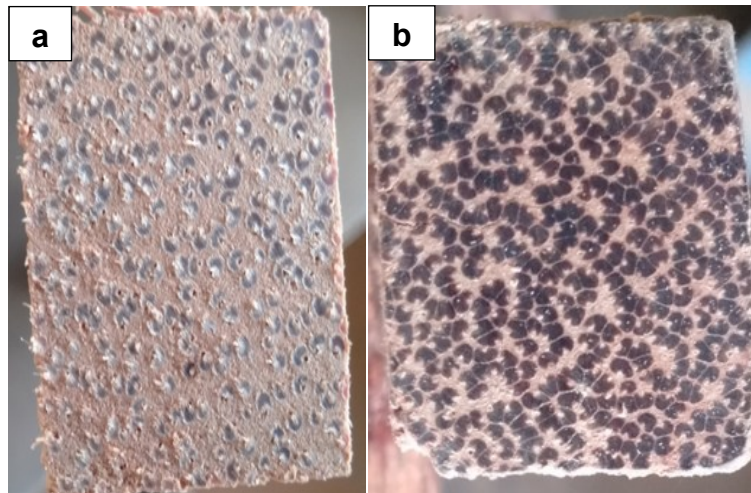


Fig. 3. Cross-sectional image of medium density (a) and high density (b) coconut wood

Density and Moisture Content

The variations in wood density are influenced by factors such as the distribution and proportion of fibers to other cell types within vascular bundles and the thickness of cell walls in fibers and ground parenchyma (Fathi *et al.* 2023). The high-density coconut wood contained more fibers and less parenchymatous tissue, hence it also showed good strength. The adhesive used may also have influenced the density variations because the relative adsorption and absorption of glue at the interphase of a two-density class composite might have varied. However, the type and rate of adhesive used were the same in all treatments. The core veneer was less dense than the coconut veneer. The variation in density between pure and hybrid composites was attributed to differences in the density of the core veneer used.

Moisture content plays a critical role in determining the dimensional stability and performance of plywood across various applications. Plywood, being a wood-based material, is inherently hygroscopic. It tends to absorb moisture from its environment, with its equilibrium moisture content rising as relative humidity increases (Sonderegger and Niemz 2009). Exposure to conditions of high relative humidity or direct contact with water further elevates the moisture content of plywood. Table 3 illustrates the moisture content of the composite boards studied. When comparing pure-MD with pure-HD, the former exhibited higher moisture content, which can be attributed to the higher proportion of parenchyma and higher porosity of the wood used in medium-density wood.

Low-density woods generally contain fewer vascular bundles and more parenchyma cells, resulting in higher water storage capacity or moisture content. This relationship between wood density and moisture content is especially relevant for coconut wood compared to other hardwoods (Fathi 2014). The medium-density composite, with higher moisture content, is more susceptible to water absorption and dimensional instability. The medium-density board exhibits slight cupping (Fig. 2), suggesting inferior dimensional stability compared to high-density boards. In contrast, the high-density composite demonstrates lower moisture content, indicating superior moisture resistance and improved dimensional stability. The pure composite and the hybrid composite showed a significant difference in moisture content. This was due to the

macaranga wood used in the hybrid composite, which increased the moisture content compared to its counterpart.

Table 3. Physical Properties of the Coconut Composite

Composite Type	Density (g/cm ³)	MC (%)	TS (%)	WA (%)	VS (%)
Pure-MD	0.73 ^b (0.02)	14.55 ^c (0.41)	3.76 (0.29)	16.92 ^b (1.24)	5.28 (3.69)
Pure-HD	0.85 ^a (0.03)	13.30 ^d (0.27)	4.06 (1.09)	12.82 ^b (0.89)	4.91 (1.68)
Hybrid-MD	0.70 ^b (0.04)	18.45 ^a (0.27)	3.28 (1.67)	21.85 ^a (4.64)	4.93 (1.17)
Hybrid- HD	0.82 ^a (0.02)	15.82 ^b (0.61)	4.99 (0.51)	14.66 ^b (3.53)	4.17 (0.60)

MD-Medium density, HD-High density, Hybrid – combination of Macaranga and coconut veneer, Pure- Only with coconut veneer

Water Absorption and Thickness Swelling

The composite samples with varying densities were tested for water absorption after 2 h and 24 h, as well as for thickness swelling. The average values for water absorption and thickness swelling were calculated using Eqs. 3 and 4, and the results are summarized in Table 3. The density of the composite correlates with water absorption, with the lowest density found in the hybrid medium-density samples, resulting in the highest water absorption. In contrast, pure high-density samples exhibited lower water absorption due to a higher concentration of vascular bundles and reduced parenchymatous tissue content. Either way, medium-density composites, the highest water absorption was observed in the hybrid composite, followed by the pure medium-density composite. These values reflect the inherent structure of coconut wood, where medium-density samples contain a higher proportion of parenchymatous tissue and fewer sclerenchymatous vascular bundles (Robert *et al.* 2019). The parenchymatous ground tissue retains more water compared to the vascular bundles, which directly affects the absorption capacity.

Unlike water absorption, thickness swelling demonstrates a distinct trend relative to density. Hybrid-HD samples exhibit higher thickness swelling than pure-HD samples, as indicated in Table 3. However, the difference in thickness swelling is not statistically significant between densities or between hybrid and pure composites. In high-density composites, increased average thickness swelling was not because of water absorption rates but because of improper glue adhesion. As a result, when the sample is immersed in water, the water enters the vacant spaces, causing it to bulge. These findings indicate that enhancing adhesive application is crucial for reducing swelling and improving the dimensional stability of high-density composite materials (Del Menezzi and Tomaselli 2006).

Volumetric Shrinkage

The lowest shrinkage value among the composites, as shown in Table 3, was observed in the hybrid-HD composite, followed by the pure-HD composite. This trend is consistent with the findings of Fathi (2014), who demonstrated that volumetric shrinkage is higher in the inner, medium-density regions of wood and nearly half as much in the outer, high-density areas. In hybrid composites, the thickness of the core veneer is very low, so it does not have much effect on shrinkage value. The variation in shrinkage behaviour can be attributed to differences in tissue distribution within the wood structure. The denser outer portion contains a higher proportion of fibers per unit area (Fig. 3),

while the inner portion consists of more parenchymatous ground tissue. This difference in tissue composition results in lower shrinkage in the outer portion, which has a greater concentration of vascular bundles.

Similar findings were reported by Killmann (1983), who also observed lower shrinkage in the higher-density regions of wood. Furthermore, the study by Sonderegger and Niemz (2009) highlights the critical role of moisture content in the shrinkage behaviour of plywood. As moisture content increases, shrinkage tends to rise in wood-based materials. These consistent observations across studies reinforce the understanding that both density and moisture content are key factors influencing the shrinkage characteristics of wood composites.

Mechanical Properties

Mechanical properties of developed plywood were evaluated according to Indian standards IS 1734 (Parts 1 to 20) (1983).

Bending Properties

The key mechanical properties of plywood are bending and tensile strength, both of which are directly influenced by its construction. A change in one typically affects the other. The bending test is performed on plywood to evaluate its flexural strength and stiffness, ensuring the material can withstand loads without excessive deformation or failure in structural applications (Kljak and Brezovic 2007).

The bending test results are presented in Table 4. Pure-MD had the highest MOR along the grain, fulfilling the structural plywood requirements for bending, except for bending stress across the grain. In comparison, pure-HD had a lower MOR than pure-MD but exhibited a significantly higher MOE. It also met the structural plywood standards for bending, although the bending stress across the grain fell slightly below the specified threshold. Both pure and hybrid-HD complied with the general-purpose plywood standards IS 303 (1989) for both BWR and MR grades. However, hybrid-HD and MD did not meet the requirements of IS 10701 (2012) for structural plywood or the BWR grade for general-purpose plywood. Nevertheless, Hybrid-HD satisfied the MR grade bending requirement along the grain.

Table 4. Static Bending Properties of Coconut Veneer Composites

Composite Type	Parallel to Face Veneer		Perpendicular to Face Veneer	
	MOR (N/mm ²)	MOE (N/mm ²)	MOR (N/mm ²)	MOE (N/mm ²)
Pure-MD	120.86 ^a (3.80)	13203.00 ^a (1349.07)	20.17 ^a (0.98)	2643.16 ^a (535.56)
Pure-HD	71.20 ^b (30.46)	16552.43 ^a (1608.01)	25.70 ^a (5.79)	1897.00 ^a (943.01)
Hybrid-MD	22.55 ^c (0.21)	6344.95 ^b (3278.64)	3.02 ^b (1.70)	235.87 ^b (46.18)
Hybrid- HD	30.01 ^c (2.83)	7775.13 ^b (1669.48)	7.90 ^b (6.57)	497.39 ^b (236.41)
Average minimum strength requirements for structural purposes				
IS 10701 (2012)	50	7500	30	4000
Average minimum strength requirements for general purposes				
IS 303 (1989)	BWR	MR	BWR	MR
	40	30	5000	4000
			20	15
			2500	2000

BWR: Boiling Water Resistant, MR: Moisture Resistant

The pure-HD was expected to show a higher MOR value than the pure-MD; however, it exhibited a lower value. This discrepancy may be attributed to fractures along the glue line, as illustrated in Fig. 4. Nevertheless, it achieved an average bending strength of 71.2 N/mm², which reflects the mechanical strength of coconut wood as its density increases. In contrast, the hybrid-HD displayed a lower bending strength. This was likely influenced by several factors, such as the reduced thickness and inferior mechanical properties of the Macaranga veneer, higher moisture content, and lower adhesive strength, all of which are less favourable compared to the pure composites. Macaranga is a lightweight wood with a density of 270 to 495 kg/m³ and a MOR of around 49.6 N/mm² (Nordahlia *et al.* 2018). However, the MOR of air-dried coconut wood ranges from 28.4 N/mm² (inner) to 85.4 N/mm² (outer), spanning from very weak to very strong (Khairul 2009). The variation in veneer density and the corresponding changes in MOR may have substantial influence on the bending properties of the prepared composite.

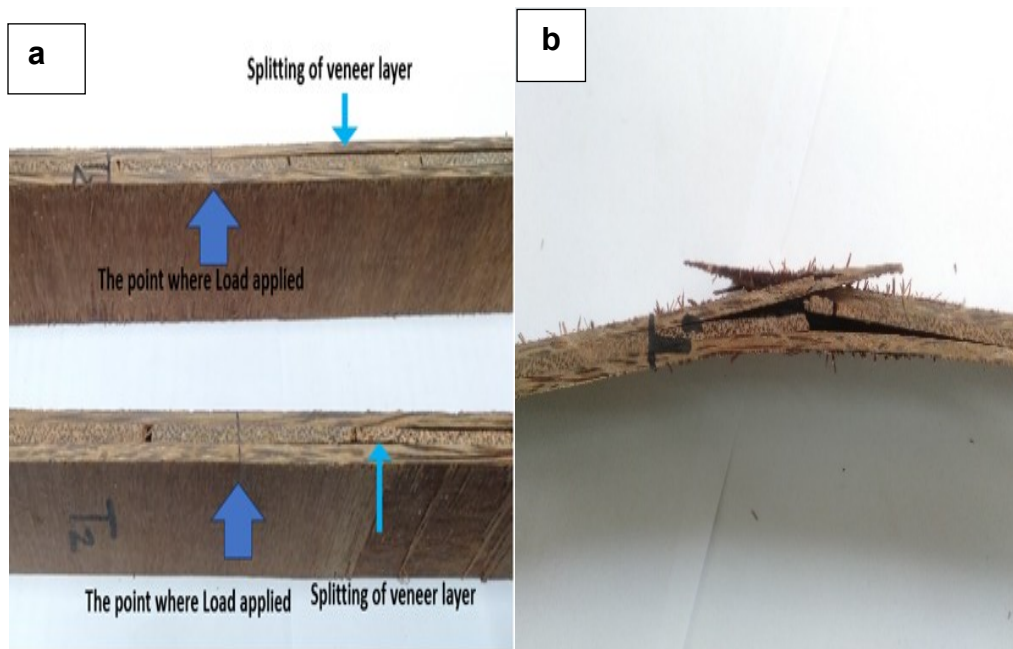


Fig. 4. Coconut plywood after bending test: (a) High-density pure coconut, (b) Medium-density pure coconut

Tensile Strength

The tensile strength values for both pure and hybrid coconut composites exhibited variability, reflecting their capacity to resist tensile forces, which is critical for load-bearing applications and ensuring structural integrity in plywood. The tensile strength results for the four composite types are presented in Table 5.

Table 5. Mechanical Properties (Tensile Strength, Glue Shear, Nail and Screw) of Coconut Veneer Composites

Composite Type	Tensile Strength (Parallel) (N/mm ²)	Glue Shear Strength (N)	Nail and Screw Withdrawal (N)	
			Nail (Face)	Screw (Face)
Pure-MD	59.86 (13.48)	1515.16 (402.47)	2950.90 (204.29)	4072.26 ^b (154.68)
Pure-HD	65.33 (13.75)	1143.76 (61.07)	2081.50 (735.00)	4823.86 ^a (179.93)
Hybrid-MD	58.06 (0.51)	1016.86 (126.38)	1359.70 (66.59)	2309.27 ^d (166.48)
Hybrid- HD	68.36 (20.77)	799.20 (447.38)	2020.86 (24.53)	3168.01 ^c (46.64)
Average minimum strength requirements for structural purposes				
IS 10701 (2012)	55	1350	Not specified	Not specified
Average minimum strength requirements for general purposes				
IS 303 (1989)	Not specified	BWR	Not specified	Not specified
		1350		

All the composites prepared for this study demonstrated promising performance, meeting and exceeding the minimum tensile strength requirement of 55 N/mm² for structural plywood, making them suitable for load-bearing applications. The tensile strength results did not show a significant difference among the composites. The hybrid-HD composite demonstrated the highest average tensile strength, while the pure-HD composite also achieved satisfactory tensile strength. In contrast, the Hybrid-MD composite, which includes Macaranga and medium-density coconut veneer, recorded the lowest average tensile strength.

The higher average tensile strength observed in high-density composites, compared to medium-density ones, is attributed to the greater presence of sclerenchymatous fibers, which enhance the material's tension-bearing capacity. A similar positive correlation between density and tensile strength was reported by Said *et al.* (2022). This trend aligns with the general principle that denser materials tend to exhibit increased strength due to higher material compaction and fewer void spaces. It is worth mentioning that the hybrid composites revealed a more pronounced difference in tensile strength between the medium- and high-density variants. The hybrid-MD composite displayed a slightly lower tensile strength than its pure counterpart, while the hybrid-HD composite achieved the highest tensile strength among all composites. This suggests that hybridization may have a more complex influence on tensile properties, likely resulting from interactions between the coconut fibers and other reinforcing materials (Satheesh and Pugazhivadivu 2019; Nwigbo. *et al.* 2022). The superior performance of the hybrid-HD composite over the other variants suggests that combining high density with hybridization can lead to synergistic improvements in tensile strength. This observation is consistent with studies indicating that the effective hybridization of coconut fibers with other materials can enhance mechanical properties (Raman *et al.* 2022; Okpe and Folorunso 2023). However, a detailed understanding of the performance

of these hybrids would require careful consideration of their specific composition and the processing methods employed.

Nail and Screw Withdrawal Test

The withdrawal resistance of a screw shank from plywood is influenced by several key factors, including the plywood's density, the screw's diameter, and the depth of its penetration into the material. Additionally, the surface condition of the screw during installation affects the initial withdrawal resistance. The withdrawal strength is also dependent on variables, such as the type of wood species used, the moisture content, grain orientation, section alignment, extraction duration, and the method of screw insertion, as noted by Celebi and Kilic (2007). Furthermore, factors such as glue type and layer thickness notably affect the withdrawal strength of both nails and screws, as highlighted by Abdul *et al.* (2010).

In this study, the glue type and application rate were consistent across all treatments; however, the thickness of the composite layers, which ranged from 8 to 9 mm, was slightly reduced in the hybrid composite. The nail and screw withdrawal strengths were measured, and the results are summarized in Table 5. All of the composite showed better results in screw and nail holding capacity as compared to cross-laminated timber made of poplar and fir (Abdoli *et al.* 2022) and oil palm plywood (Abdul *et al.* 2010). Pure-HD demonstrated the highest screw withdrawal strength at 4820 N. This indicates that pure-HD was highly suited for applications that rely on screw-based fastenings, especially those requiring durability and stronghold, such as in heavy furniture or structural components. The pure-MD also showed higher screw-holding performance (4070 N). The difference between pure-HD and pure-MD may be due to the denser structure of pure-HD, which provides more material for screws to grip. Hybrid composite also showed a similar trend. The high-density composite showed greater screw withdrawal properties. A similar observation was found in hybrid-HD, with a screw withdrawal strength of 3170 N, which performed better than hybrid-MD but did not reach the level of the pure composites. Hybrid-MD showed the lowest screw withdrawal strength of 2310 N. The study conducted by Abdul *et al.* (2010) on oil palm trunks (OPT) reported the highest screw withdrawal value of 1226 (± 72.16) achieved for hybrid plywood compared to pure plywood. It can be concluded that the density of types of core veneers greatly influences the nail and screw holding capacity of composite.

The pure-MD treatment exhibited the highest nail withdrawal strength at 2950 N, followed by pure-HD with 2080 N. Both hybrid composites also demonstrated notable nail-holding capacities, with hybrid-HD showing a withdrawal strength of 2020 N and hybrid-MD at 1360 N. These findings highlight the influence of wood density on nail withdrawal properties, as higher-density woods, are typically expected to offer greater resistance to nail withdrawal (Barcık *et al.* 2014). However, this study revealed an unexpected trend: the pure-HD composites exhibited lower nail withdrawal strength than the pure-MD composites. The diminished performance in both high-density composites and hybrids could be attributed to differences in surface texture and fiber structure, factors that are known to influence nail grip. Additionally, this deviation may also be attributed to variations in adhesive properties, which considerably influence plywood performance, as noted by Okuma (1976). In the current study, glue shear strength was also observed to be lower in the high-density composites, potentially contributing to the reduced nail withdrawal resistance.

A similar trend was observed in the hybrid composites, where reduced thickness and weaker adhesive bonds appeared to negatively impact withdrawal performance. In the case of hybrid-MD, the lower density may have further contributed to the reduction in withdrawal strength. Nonetheless, the nail withdrawal strength of pure-HD, at 2080 N, remains within acceptable limits for medium-to-heavy load applications and is considered reliable for specific fastening requirements.

Glue Shear Strength

The variations resulting from the distribution and size of vascular bundles, as well as differences in the cell wall thickness of parenchyma and fiber cells, greatly affects the mechanical properties of the material. However, the glue shear strength is determined by glue and surface interaction. The glue shear strength of test samples under dry conditions is shown in Table 5. According to Indian Standards IS 10701 (2012), in the dry state, structural plywood needs to satisfy an average glue shear strength of 1350 N. Out of four prepared samples, pure-MD got an average value of 1520 N, which exceeded the highest required glue shear strength. According to IS 303 (1989), the glue shear strength of pure-MD (1520 N) exceeded the minimum requirements for both BWR (Boiling Water Resistant) and MR (Moisture Resistant) grades in the dry state, while pure-HD (1140 N) met the MR grade standards and surpassed the minimum individual strength for BWR grade but fell short of its minimum average. Hybrid-MD (1020 N) met the MR grade requirements but did not meet the BWR grade standards, and hybrid-HD (799 N) met the minimum individual requirement for the MR grade but failed to meet other standards.

The silica content in the coconut wood was found to be high, enhancing the structural properties (Fathi 2014); however, it might have played a significant role in hindering glue adhesion. The study conducted by Dušek *et al.* (2021) observed that natural silica content in wood or rice straw can potentially hinder glue adhesion. Similarly, there is a strong possibility of finding higher silica content in high-density coconut wood due to the presence of sclerenchyma tissues. This might hinder glue adhesion in high-density composites, and is shown in the correlation chart (Fig. 6). A similar observation was made by Gurr *et al.* (2022), who found that medium-density coconut veneers (600 to 700 kg/m³) achieved higher bond strength with shorter pressing times. Meanwhile, high-density veneers (900 to 1,000 kg/m³) required longer pressing times for optimal bonding. In this study, the high-density composite exhibited lower glue shear strength than the medium-density composite, suggesting that the pressing time was more suitable for the latter. Extending this duration could enhance the performance of the high-density composite. Additionally, challenges can be mitigated through innovative solutions such as surface treatments, including water or sodium hydroxide, to improve fiber-adhesive adhesion.

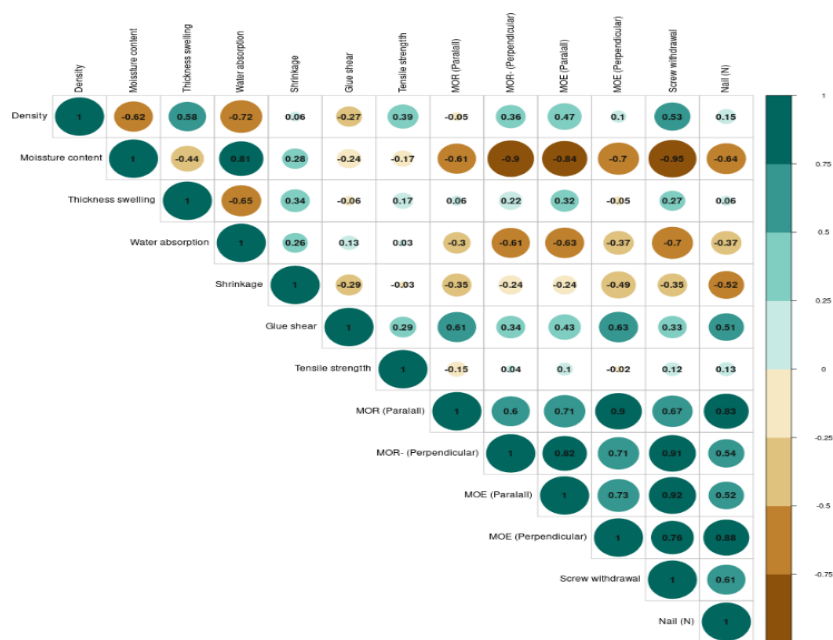
A similar trend was observed in the hybrid composites, where hybrid-MD exhibited higher glue shear strength compared to hybrid-HD. However, both hybrid composites failed to meet the optimum strength values outlined in Indian standards. The reduction in glue shear strength may be attributed to the use of different veneers and the variation in their thicknesses, potentially influenced by the hot-pressing process, which can impact bonding efficiency. As noted by Demirkir *et al.* (2013), factors such as wood species, adhesive type, wood density, veneer peeling temperature, veneer drying temperature, and relative moisture content play a critical role in determining plywood bonding strength. In the case of hybrid composites, the elevated moisture content likely impeded effective bonding, particularly in medium-density composites. This issue may

have arisen from uneven drying of the logs prior to hot pressing or moisture absorption from the environment. To mitigate this, it is essential to ensure proper moisture levels are maintained before the hot-pressing process.

Correlation of Properties

The correlation chart provides insights into the relationships between various properties of the developed composite material (Table 6). The influence of density is notable, as it enhanced mechanical strength, such as MOR, MOE, and tensile strength and screw holding power. It helped to reduce water absorption and moisture content, reflecting its importance in composite performance. However, the density negatively impacted the glue adhesion, which however can be improved by adjusting hot pressing conditions, glue type, and surface modification. Water absorption and moisture content showed a positive correlation, which indicates that the parenchymatous cells and pores hold water from the surrounding environment. Moisture content was negatively correlated with major mechanical properties, considerably reducing most mechanical properties, including MOR, MOE, and screw-holding strength. Thickness swelling did not have much significance with the mechanical properties. However, increased swelling showed a slight reduction in mechanical properties, especially nail-holding power and MOE. Fastening properties, including screw withdrawal and nail holding strength, also showed a positive correlation with static bending properties. Glue shear strength is an important parameter that shows a positive correlation with all mechanical properties except tensile strength. This is evident in the higher static bending stress observed in pure-MD. However, in tensile strength, which measures the maximum resistance to tearing along the grain, it showed a low correlation with glue shear. Conversely, moisture content negatively affected mechanical properties, demonstrating that higher moisture levels weaken the material's strength and stability. Similarly, water absorption adversely impacted bending strength, highlighting the need for moisture-resistant treatments.

Table 6. Correlation Chart of Physical and Mechanical Properties of Developed Composite



CONCLUSIONS

1. In this study, the pure-MD (medium density) composite performed well, meeting nearly all the requirements of the Indian Standard for structural plywood and fully complying with the standards for general-purpose plywood.
2. The reduced bonding strength of pure-HD (high density) may have notable influence on its mechanical and physical properties. However, Pure-HD still met nearly all the requirements of the Indian Standards for general-purpose plywood (IS 303 1989). Compared to the high-density board, the medium-density board exhibited slight cupping.
3. Hybrid high-density (HD) and medium-density (MD) composites did not meet several standards for structural plywood and fell short in key characteristics, such as bending strength (MOR and MOE), required for general-purpose plywood standards.
4. The reduction in bonding strength, moisture content, uneven layer thickness, and gaps between adjacent sawn veneers may greatly influence their overall properties. Optimising veneer standards, hot-pressing conditions, adhesive type, and layup patterns can improve the mechanical strength and performance of pure-HD and hybrid composites in future research.

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APPENDIX

Supplementary material 1

LX50SUPER Portable Band Sawmill – Working and Specifications

The LX50SUPER is a compact and efficient portable band sawmill designed for converting saw logs into lumber, slabs, and other wood products with precision and ease. Unlike circular sawmills, the LX50SUPER uses a horizontal band saw blade that moves through the log in a straight line, allowing for accurate and smooth cuts across various hardwood and softwood species.

Working Mechanism

- Operates using a horizontal band blade that travels on guide rollers.
- Logs are securely positioned on a laser-cut steel bed and advanced side supports.
- The sawhead is raised and lowered with a quick-adjust mechanism, enabling precise control of cutting depth.
- A gravity-fed blade lubrication system reduces friction and enhances cutting performance.
- Sawdust is directed away from the cut through a dedicated sawdust port for cleaner operation.

Key Specifications

- **Maximum log diameter:** 26 inches (660 mm)
- **Maximum width of cut:** 23.5 inches (597 mm)
- **Maximum depth of cut:** 8 inches (203 mm)
- **Standard cutting length:** 12 feet 5 inches (3.78 meters)
- **Extendable cutting length:** Optional 5-foot (1.52-meter) bed extensions can be added for longer logs with no practical limit
- **Engine:** 14 HP KOHLER gas engine – reliable and powerful for consistent operation
- **Blade guide system:** High-performance guide rollers for accurate blade alignment
- **Frame:** Heavy-duty bent steel frame with diagonal crossbars for enhanced stability
- **Log handling:** Includes multiple side supports, extra log clamp, and bed leveling feet for precise log positioning

The LX50SUPER is built for serious woodworking tasks in a portable format, offering high-capacity cutting, robust construction, and user-friendly operation. Its rectangular throat design ensures full-width cutting at any depth, making it a versatile and dependable choice for small-scale sawmilling operations.

Specifications LX50SUPER Portable Sawmill Specifications	
POWER	
Power Selections	10.4kW (14HP) petrol
CUTTING CAPACITY	
Max Width of Cut	60cm (23 1/2")
Max. Log Diameter	66 cm
Max Cant Width	55cm (21 1/2")
Max Depth of Cut	20cm (8")
Max Log Length	3.78m (12' 5")
Max Log Length (with extensions)	Unlimited
BLADE	
Blade dimension	3.35m (132"); 32mm wide;; 1.07mm thick,
Blade Lubrication System	1 Gal. (3.8L) Water Tank with On/Off Valve
BLADE WHEELS	
Blade Wheel Diameter	400mm (16")
Blade Wheel Type	Belted Cast Iron
HEAD FEATURES AND OPTIONS	
Head Forward/Reverse	Push Feed
Head Up/Down	Hand Crank
Blade Engagement	Mechanical Clutch
BED FEATURES AND OPTIONS	
Side Supports	2 Quick-Set
Trailer Package	N/A
Log Clamping	2 Quick-Set
Additional Bed Options	Optional 1.5m Bed Extension
MACHINE DIMENSIONS AND REQUIREMENTS	
Delivery Methods	Pallet
Weight (heaviest power option)	447kg (985 lbs)