

# EFFECT OF DIFFERENT CONFIGURATIONS ON THE PROPERTIES OF HYBRID LAMINATED BAMBOO-OIL PALM TRUNK COMPOSITES

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Advancements in hybrid laminated composite production have increased the value of bamboo and oil palm trunk (OPT) materials, enabling the development of renewable resource-based composites. This study evaluates the effect of bamboo-OPT configuration on the properties of hybrid laminated bamboo-OPT composites. Two Malaysian commercial bamboo species, namely semeliang (*Schizostachyum grande*) and semantan (*Gigantochloa scortechinii*), along with OPT veneer, were used. Various configurations of three-layer laminated mono-species bamboo, OPT, and hybrid bamboo-OPT composites specifically semeliang-OPT (SM-O) and semantan-OPT (SN-O) with dimensions of 9 mm (thickness) × 300 mm (width) × 300 mm (length) were fabricated using an impregnation modification method with low molecular weight phenol formaldehyde resin (LMwPF). The physical, bonding shear, and mechanical properties of the composites were evaluated. Results showed that the hybrid SM-O composite had the lowest thickness swelling of 1.55% and water absorption of 10.01% after 24 h immersion, indicating superior dimensional stability. In terms of bonding performance, SM-O achieved shear strengths of 2.94 N/mm<sup>2</sup> after 24 h soaking and 2.11 N/mm<sup>2</sup> after boil-dry-boil treatment, meeting the minimum standard requirement. For mechanical performance, SM-O displayed the highest modulus of rupture (MOR) at 189.08 N/mm<sup>2</sup> and modulus of elasticity (MOE) at 28,627 N/mm<sup>2</sup>, outperforming both mono-species bamboo and OPT composites.

Keywords: Bamboo, oil palm trunk veneer, impregnation modification, phenolic resin

## INTRODUCTION

The search for sustainable alternatives to conventional composite materials has led to a growing interest in non-timber forest products (NTFPs). Among these, bamboo and oil palm trunk (OPT) are particularly promising due to their abundance and versatility. Bamboo, in particular, is gaining traction in the composite market because of its exceptional strength and rapid growth. As a fast-growing and highly renewable resource, bamboo can be harvested just 3 to 4 years after planting, a significantly shorter time frame compared to the decades required for traditional timber species (Asniza et al. 2023).

This rapid growth not only makes bamboo an environmentally friendly option but also ensures a consistent and sustainable supply for various applications. Its high yield and durability further enhance its appeal as an alternative to

conventional wood materials (Balqis et al. 2024, Chaowana 2013, Chaudhary et al. 2024). Despite its many advantages, bamboo's structure, which includes numerous vessels and fibres, creates an environment that is non-durable due to its susceptibility to insects and fungi, potentially compromising its structural integrity and lifespan (Barrile & Genovese 2024, Sain et al. 2024, Yadav & Mathur 2021). It is essential to address these challenges in order to enhance the viability of bamboo in composite applications.

On the other hand, OPT, as a readily available by-product of the oil palm industry, shows significant potential use in composite materials (Suhaily et al. 2017), provided that its inherent weaknesses particularly its susceptibility to warping and shrinkage under fluctuating moisture conditions are addressed (Dungani et al. 2013, Sulaiman et al. 2012, Haslett 1990).

To overcome these challenges, a range of treatment methods has been investigated for non-wood forest products such as bamboo and OPT, including heat treatments, densification, and chemical modifications (Sain et al. 2024, Dungani et al. 2013, Rosli et al. 2016). Among these, impregnation modification stands out as a particularly effective approach. This method involves introducing stabilising agents such as phenol formaldehyde (PF), melamine-urea-formaldehyde (MUF), or polymer blends into the porous structure under vacuum or pressure. Impregnation by filling voids, reducing water uptake, and strengthening the cell walls will improve dimensional stability, durability, and resistance to environmental factors (Dungani et al. 2013, Gabrielli & Kamke 2010). Unlike traditional preservatives, which primarily protect against biological degradation, impregnation also enhances intrinsic physical and mechanical properties, increasing resilience to changes in moisture content and temperature fluctuations. Several studies have demonstrated that PF resin impregnation significantly improves modulus of rupture (MOR), modulus of elasticity (MOE), hardness, and anti-swelling efficiency (ASE) in OPT, while also enhancing resistance to termites and fungal decay (Che Ismail et al. 2022, Dungani et al. 2016, Bhat et al. 2010). In bamboo, phenolic resin impregnation has likewise proven effective. For example, Sobrinho et al. (2012) reported that treating *Bambusa vulgaris* with PF resin provided strong protection against insect attack. This dual benefit strengthening the material and extending its lifespan and makes resin impregnation especially relevant for OPT, where addressing dimensional stability and pest resistance is critical for composite applications.

Recent research has extended impregnation techniques to engineered OPT products. Laminated “compreg” composites made from OPT veneers impregnated with low molecular weight PF resin (LMwPF) have shown substantial gains in density, dimensional stability, and mechanical performance (Ahamad et al. 2023, Aizat et al. 2017, Wahab et al. 2012). These advances demonstrate that with appropriate impregnation treatments, OPT can be transformed from a low-value by-product into a viable raw material for high-value applications such as flooring, furniture components, marine-grade panels, and other engineered wood products, contributing to the sustainable utilisation of oil palm biomass resources.

In order to produce high-performance laminated products using bamboo and OPT veneer, the impregnation modification method must be employed. However, the impact of this modification on laminated bamboo and OPT composites is not yet fully understood. Therefore, this study will utilise semeliang (*Schizostachyum grande*) and semantan (*Gigantochloa scortechinii*) bamboo, together with OPT veneer, as raw materials for impregnation modification to create laminated bamboo and OPT composites, as well as hybrid bamboo-OPT composites. The modification process has the potential to enhance the physical, bonding, and mechanical properties of these materials; thereby adding value to both bamboo and oil palm industry. Furthermore, the laminated samples will undergo SEM analysis to examine changes in the modification mechanism and microstructure resulting from LMwPF resin treatment.

## MATERIALS AND METHODS

### Preparation of raw materials

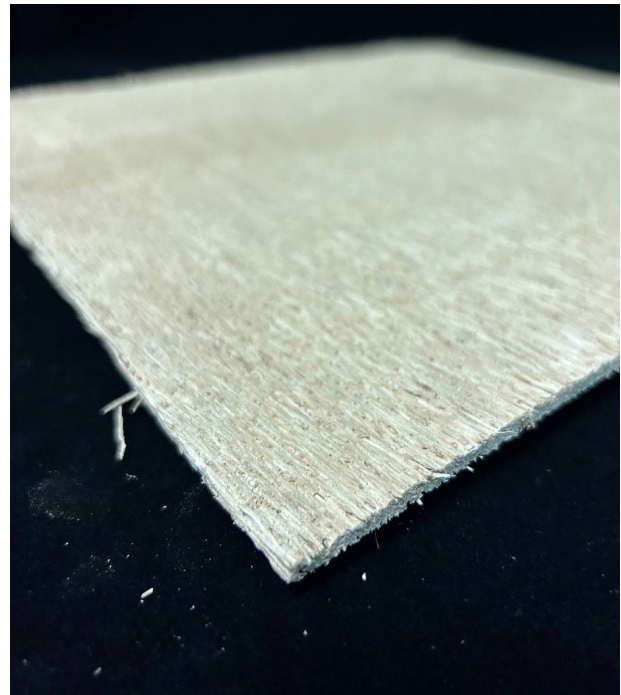
Crushed bamboo veneer, specifically made from *S. grande* (semeliang) and *G. scortechinii* (semantan), both aged 3-4 years was supplied by a local supplier in Selangor, Malaysia. The bamboo crushed veneer (Figure 1) was 5 mm thick, 1 m long, and its width depended on the diameter of the bamboo culms after the crushing process. Additionally, OPT veneer (Figure 2) with dimensions of 5 mm (thickness) × 100 mm (width) × 1 m (length) was obtained from a plywood manufacturer in Kluang, Johor, Malaysia. The resin used in this study, a low molecular weight phenol formaldehyde (LMwPF), was sourced from a resin supplier in Seremban, Negeri Sembilan, Malaysia. To ensure proper preparation for the next stages of the study, both the bamboo crushed veneer and the OPT veneer were kiln-dried to a moisture content below 12%.

### Impregnation modification

Bamboo crushed veneer and OPT veneer were impregnated with LMwPF resin using a vacuum-pressure treatment. The LMwPF resin, with a molecular weight of 1500 g/mol and a 30% concentration, was used for the process. The veneers were immersed in resin within a



**Figure 1** Planing process of bamboo veneer



**Figure 2** Oil palm trunk (OPT) veneer

container and placed in a vacuum chamber, as illustrate in Figure 3. The impregnation process started with a 1-hour vacuum application, followed by an additional hour of pressure treatment at 650 mmHg.

### Determination of Weight Percent Gain (WPG)

The Weight Percent Gain (WPG) of bamboo and OPT veneer were determined after impregnation with LMwPF resin through a vacuum-pressure process. 10 The samples were subsequently rinsed, wiped with a cloth, and weighed before setting to dry at 80 °C for 24 hours. Once dried, the oven-dried samples were weighed again, and the WPG was calculated using Equation 1:

$$WPG (\%) = \frac{(Final\ weight - Initial\ weight)}{Initial\ weight} \times 100 \quad (1)$$

### Fabrication of laminated bamboo, OPT and hybrid bamboo-OPT composites

Following the impregnation process, the treated bamboo crushed and OPT veneer underwent a pre-curing stage by being placed in an oven at



**Figure 3** Impregnation modification process by using vacuum chamber

60 °C for 8 hours. The final dimensions of the treated veneers were set to 3 mm (thickness) × 300 mm (width) × 300 mm (length). Pre-cured phenolic-treated bamboo crushed and OPT veneer were then assembled perpendicular to the grain to form three-layer hybrid laminated

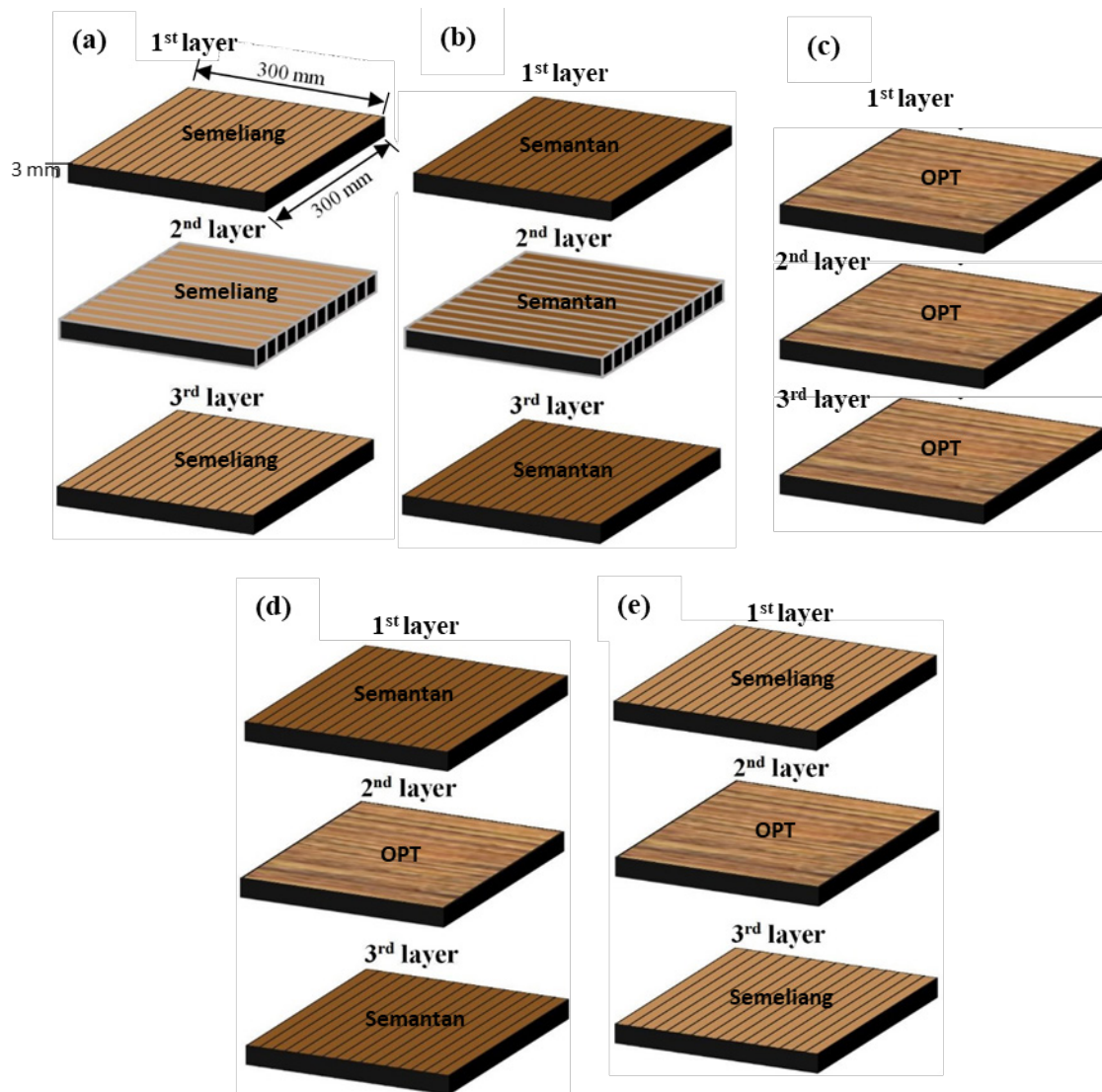
bamboo-OPT composites. To evaluate the effect of using OPT as the core layer, laminated composites consisting of a mono-species were also fabricated for comparison. The configuration and lay-up pattern of the three-layer laminated composite are shown in Figure 4.

Once assembled, the three-layer laminated composite underwent cold pressing for 10 minutes, followed by hot pressing at 140 °C for 20 minutes under a pressure of 20 kg/cm<sup>2</sup>. The laminated composites were conditioned for one week at a temperature of 20 ± 3 °C and a 60% relative humidity before testing. Figure 5 illustrates the final dimensions of the hybrid laminated bamboo-OPT composites. The overall

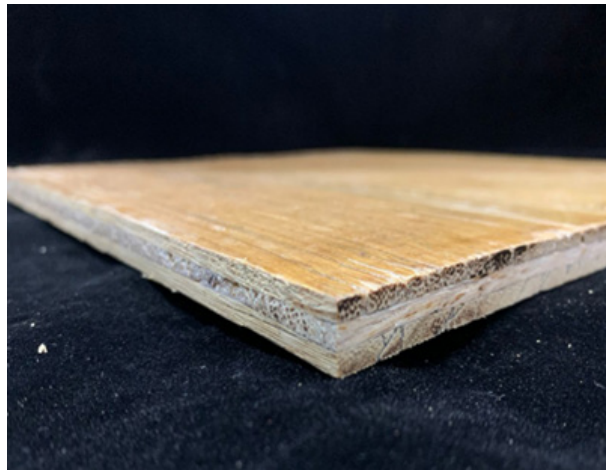
experimental matrix, showing the samples, composite types, and number of sample sets required for all tests, is presented in Table 1.

### Determination of physical properties and dimensional stability

The moisture content (MC) of the laminated composites was determined using the oven-drying method. Ten samples of each composite were dried at 103 ± 2 °C until a constant weight was recorded. The initial and final oven-dried weights were noted down to calculate the MC. Dimensional stability was assessed by measuring water absorption (WA), thickness



**Figure 4** Configurations of (a, b) three-layer laminated bamboo (SM, SN) and (c) laminated OPT, and (d, e) hybrid laminated bamboo-OPT composites (SN-O, SM-O)



**Figure 5** The hybrid laminated bamboo-OPT composites (9 mm thick × 300 mm width × 300 mm length)

**Table 1** Overall matrix of experiments

Sample	Veneer sheet/ Layer	Composite type	No of sample per test						
			MC	WA	TS	LE	MOR	MOE	CS
Semeliang (SM)	3 layers of SM	Laminated	10	10			30		30
Semantan (SN)	3 layers of SN	mono-species bamboo	10	10			30		30
OPT	3 layers of OPT	Laminated mono OPT	10	10			30		30
Hybrid Semeliang-OPT (SM-O)	1 <sup>st</sup> layer: SM 2 <sup>nd</sup> layer: OPT 3 <sup>rd</sup> layer: SM	Hybrid laminated bamboo-OPT	10	10			30		30
Hybrid Semantan-OPT (SN-O)	1 <sup>st</sup> layer: SN 2 <sup>nd</sup> layer: OPT 3 <sup>rd</sup> layer: SN		10	10			30		30

swelling (TS) and linear expansion (LE) after water immersion. The tests were conducted in accordance with ASTM D 1037-12 (ASTM 2020) standards. The dimensions and weight of the air-dried samples were measured, and their density was calculated before and after immersion in distilled water (30 mm below the surface) at 25 °C for 24 hours.

### Evaluation of bonding shear properties

The shear strength of the laminated composites was tested using 10 test specimens per treatment condition, measuring 9 mm (thickness) × 25 mm (width) × 50 mm (length), following Malaysian Standard MS 2693:2020 (MS 2693 2020). Testing was conducted using a Universal Testing Machine

at a speed of 7 mm/min for 30 ± 10 seconds until failure occurred. The bonding shear properties were assessed under different pre-treatment conditions (24-hour soak, boil-dry-boil cycles, and vacuum-pressure) to meet various bonding class requirements. Untreated samples served as control specimens.

The distribution of adhesive within the laminated composites was analysed using a scanning electron microscopy (SEM). Prior to imaging, the samples were dried overnight in a vacuum vessel to ensure a completely dry surface. They were then mounted onto specimen stubs with electrically conductive double-sided tape to prevent electrostatic charge build-up, thereby enhancing signal detection and reducing noise during SEM analysis.

## Evaluation of mechanical properties

Due to the absence of established testing methods for bamboo plywood, the static bending and compression parallel-to-grain tests were conducted based on ASTM D3501-05a Standard (ASTM 2018) for wood-based structural panels. Laminated bamboo, OPT and hybrid bamboo-OPT specimens were tested using a Universal Testing Machine with a capacity of 100 kN. Before testing, all specimens were conditioned in a controlled environment at  $20 \pm 3$  °C and  $65 \pm 3\%$  relative humidity (EMC 12%). For the static bending test, 30 test samples with dimensions of 9 mm (thickness)  $\times$  30 mm (width)  $\times$  300 mm (length) were tested under a constant load rate of 3500 N/min. The modulus of rupture (MOR) and modulus of elasticity (MOE) were then determined. For the compression test, 30 test specimens measuring 9 mm (thickness)  $\times$  50 mm (width)  $\times$  60 mm (length) were positioned vertically between two parallel metal plates in the testing machine. A constant load was applied from above at a rate of 6.5 mm/min until failure occurred.

## Statistical analysis

Statistical analysis was conducted using the Statistical Analysis Software (SAS). The least significant difference (LSD) method was employed to discern the primary factors and their interactions that significantly influence the mean values at a confidence level of  $p \leq 0.05$ . This approach ranks the means and determines the minimum difference required for statistical significance. Through this analysis, variations in the bonding and mechanical properties of the impregnated laminated composites were thoroughly examined, providing a clear understanding of the factors contributing to their performance.

## RESULTS AND DISCUSSION

### Weight Percent Gain (WPG) of bamboo and OPT veneer

Table 2 presents the WPG of semantan, semeliang, and OPT treated with a 30% concentration of LMwPF. The choice of non-wood material significantly affects WPG. OPT displayed a higher WPG than both bamboo species, which suggests that OPT has a greater ability to absorb and retain

**Table 2** Weight percent gain (WPG) of semeliang, semantan and OPT treated with LMwPF

Sample	WPG (%)
Semeliang	42.65 <sup>a</sup> (6.76)
Semantan	36.66 <sup>a</sup> (1.98)
OPT	56.37 <sup>b</sup> (5.29)

Values in parentheses are standard deviations. Means followed with the same letters are not significantly different at  $p \leq 0.05$  according to LSD

resin during impregnation. The higher WPG in OPT is mainly attributed to its anatomical structure, which contains a larger number of parenchyma cells. These cells provide sufficient space for resin uptake, facilitating more efficient absorption (Rosli et al. 2016). Additionally, the larger openings and interconnected nature structure of the parenchyma allow easier resin penetration, leading to a higher WPG compared to bamboo.

Among the bamboo species, no significant difference in WPG was observed, although semeliang bamboo showed a slightly higher value than semantan. According to Nordahlia et al. (2019), the frequency of vascular bundle in semeliang ranges from 7 to 19 mm<sup>2</sup>, whereas in semantan, it varies from 6 to 26 mm<sup>2</sup>. The variation in vascular bundle distribution may influence WPG, as species with fewer vascular bundles tend to have more continuous parenchyma, allowing for greater resin penetration. In contrast, a higher density of vascular bundles may restrict resin flow, resulting in lower WPG. Additionally, semeliang has thinner culm walls, which increase its permeability and facilitate faster penetration of LMwPF. Thinner walls offer a larger surface area and reduce flow resistance, resulting in more efficient resin absorption.

### Physical properties and dimensional stability of laminated composites

The average values of the physical properties, including moisture content (MC), density, water absorption (WA), thickness swelling (TS), and linear expansion (LE) of the composites, are presented in Table 3. Laminated composites made from both bamboo species exhibited significantly lower MC, with semeliang at

**Table 3** Physical properties of the laminated composites

Sample	MC (%)	Density (kg/m <sup>3</sup> )	WA (%)	TS (%)	LE (%)
Semeliang (SM)	7.29 <sup>b</sup> (0.22)	889.07 <sup>a</sup> (37.15)	7.24 <sup>c</sup> (2.17)	1.38 <sup>b</sup> (0.56)	0.22 <sup>a</sup> (0.14)
Semantan (SN)	7.19 <sup>b</sup> (0.24)	827.84 <sup>b</sup> (38.69)	9.64 <sup>b</sup> (1.16)	1.30 <sup>b</sup> (0.44)	0.21 <sup>a</sup> (0.12)
OPT	8.48 <sup>a</sup> (1.21)	750.38 <sup>c</sup> (25.79)	19.90 <sup>a</sup> (6.82)	2.20 <sup>a</sup> (1.85)	0.21 <sup>a</sup> (0.09)
Hybrid Semeliang-OPT (SM-O)	7.36 <sup>b</sup> (0.24)	856.40 <sup>a</sup> (35.45)	10.01 <sup>b</sup> (1.87)	1.55 <sup>b</sup> (0.49)	0.32 <sup>a</sup> (0.11)
Hybrid Semantan-OPT (SN-O)	8.44 <sup>a</sup> (0.36)	815.98 <sup>b</sup> (28.29)	17.32 <sup>a</sup> (6.91)	3.38 <sup>a</sup> (1.11)	0.46 <sup>a</sup> (0.12)
Untreated laminated veneer OPT <sup>10</sup>	7.90–9.90	320–610	80–170	5.0–14.0	NA

Values in parentheses are standard deviations. Means followed with the same letters in the same column are not significantly different at  $p \leq 0.05$  according to LSD; MC = Moisture content, WA = Water absorption, TS = Thickness swelling, LE = Linear expansion, NA = Not available

7.29% and semantan at 7.19%. In contrast, the OPT composite had a significantly higher MC of 8.48%. This finding corresponds with the significantly higher WA (19.90%) and TS (2.2%) observed in OPT mono-species laminated composites compared to those made from bamboo. Among the composites, semeliang-based laminated boards had the highest density, which was not significantly different from the hybrid semeliang-OPT (SM-O) composite. However, the percentage of LE for all composites showed no significant differences.

The lower MC in laminated bamboo composites compared to OPT composites can be attributed to the natural compositions of the materials. During resin treatment, the resin penetrates the spaces around the vascular bundles, particularly within the surrounding parenchyma cells. This penetration restricts the moisture transport through the vascular bundles. As a result, treated laminated bamboo composites retain less moisture. Additionally, resin impregnation reduces the water absorption capacity of bamboo's parenchyma cells by filling their cell walls, thereby limiting their ability to retain moisture.

In contrast, OPT mono-species laminated composites exhibit high MC, WA, and TS, despite having a high percentage of WPG after impregnation treatment. This phenomenon is likely attributed to the higher proportion of parenchyma tissues within the OPT structure. Parenchyma tissue is soft, spongy, and highly

hygroscopic (Rosli et al. 2016, Zaini et al. 2024). Even after resin impregnation, the structure retains considerable void spaces, allowing water to penetrate and remain trapped. As a result, moisture uptake and swelling increase, notwithstanding the high WPG (Abdullah et al. 2012).

Sitti Fatimah et al. (2012) reported that the parenchyma tissue in OPT can retain moisture content equivalent to approximately 1.5 to 2.5 times its dry weight. These structural variances account for the elevated MC, WA, and TS in OPT mono-species laminated composites compared to bamboo composites. Additionally, the higher density of bamboo-based composites, particularly those made from semeliang and semantan, suggests a more compact and robust fibre structure in bamboo relative to OPT.

The impregnation of LMwPF resin effectively fills the porous structures of both bamboo and OPT, creating a protective barrier that reduces WA and improves dimensional stability. By infusing the OPT cells with resin, this approach significantly lowers the WA of OPT mono-species laminated composites from 19.90% to 10.01% in hybrid semeliang-OPT (SM-O) and to 17.32% in hybrid semantan-OPT (SN-O). The reduction in WA of the hybrid composites may be attributed to their lay-up configuration, where OPT serves as the core while bamboo forms the outer layers. The resin-impregnated bamboo acts as a protective shield, limiting moisture penetration into the composite. This design takes advantage

of bamboo's excellent moisture resistance to protect the more hygroscopic OPT core, which remains less exposed to external moisture.

A strong correlation between WA and TS has been widely reported, as absorbed moisture causes the cell walls to swell, leading to dimensional changes in the composite (Abdullah et al. 2012, Rowell 2012). Consistent with this, the hybrid SM-O composite not only shows reduced WA but also demonstrates notable improvements in TS, decreasing from 2.20% in OPT-only composites to 1.55%. These results highlight the effectiveness of the resin impregnation technique in addressing the inherent dimensional instability of untreated OPT, which has been a limitation in previous works (Sulaiman et al. 2012). Nevertheless, this improvement in TS was accompanied by a slight compromise in dimensional stability in terms of linear expansion (LE), which increased from approximately 0.21% in mono-species bamboo and OPT composites to 0.31% in SM-O hybrids and 0.42% in SN-O hybrids.

The findings of this study align with the general understanding that lower WA leads to lower TS and better dimensional stability. When compared with the work of Sulaiman et al. (2012), who investigated the MC, density, TS, and WA of laminated veneer lumber made from OPT using various resins including urea formaldehyde (UF), phenol formaldehyde (PF), melamine-urea-formaldehyde (MUF), and

phenol resorcinol formaldehyde (PRF), without any pre-treatment at different adhesive spread levels, the present results show markedly lower dimensional instability. The higher instability reported in the earlier study is likely due to the absence of resin impregnation, which in our case proved critical for controlling both WA and TS and producing a more stable and moisture-resistant composite.

### Bonding shear properties

Evaluating the bonding shear properties of laminated composites is essential to determine the strength, performance, and durability of the adhesive bonds, which directly affect overall composite quality. The impregnation process plays a role in enhancing bonding effectiveness, contributing to improve composite performance. The test results, shown in Table 4, indicate that all samples, except for the SN-O samples subjected to the 24-hour soak and BDB treatment, met the minimum standard requirements outlined in MS 2693 (2020).

Among the tested materials, the SM composite consistently exhibited the highest shear strength across all treatment types compared to SN and OPT composite. The observed variation in bond shear strength between SM and SN laminated composites can be attributed to the inherent differences in their fibre characteristics, including fibre length, fibre diameter, cell wall

**Table 4** Bonding shear properties of the laminated composites

Shear strength (N/mm <sup>2</sup> )	Pre-treatment			
	Control	Soak 24h	Boil-dry-boil (BDB)	Vacuum- pressure
Semeliang (SM)	2.39 <sup>a</sup> (0.25)	2.48 <sup>b</sup> (0.27)	1.95 <sup>a</sup> (0.26)	2.45 <sup>b</sup> (0.49)
Semantan (SN)	1.60 <sup>c</sup> (0.37)	1.79 <sup>c</sup> (0.63)	1.31 <sup>b</sup> (0.09)	1.52 <sup>b</sup> (0.16)
OPT	1.98 <sup>b</sup> (0.38)	1.81 <sup>c</sup> (0.36)	1.46 <sup>b</sup> (0.12)	1.74 <sup>b</sup> (0.65)
Hybrid Semeliang-OPT (SM-O)	2.41 <sup>a</sup> (0.14)	2.94 <sup>a</sup> (0.11)	2.11 <sup>a</sup> (0.35)	2.87 <sup>a</sup> (0.21)
Hybrid Semantan-OPT (SN-O)	1.42 <sup>c</sup> (0.27)	0.82 <sup>d</sup> (0.45)	0.94 <sup>c</sup> (0.59)	1.70 <sup>b</sup> (0.73)

Values in parentheses are standard deviations. Means followed with the same letters in the same column are not significantly different at  $p \leq 0.05$  according to LSD

thickness, microfibril angle, and lumen diameter. According to Nordahlia et al. (2019), the mean lumen diameter of semeliang ranges from 2.4 to 5.8  $\mu\text{m}$ , whereas that of semantan is between 2.2 and 4.1  $\mu\text{m}$ . A larger lumen diameter facilitates greater resin penetration into bamboo strips, thereby forming a stronger anchorage between the layers (Anwar et al. 2004). This finding aligns with the results of this study, where semeliang samples exhibited higher bond shear strength than those made from semantan.

Oil palm trunk (OPT) contains a higher proportion of parenchyma tissue, which significantly affects WA in OPT mono-species laminated composites. Although these composites tend to absorb more water, the resin is able to penetrate the parenchyma cells, filling the voids and reducing internal stresses caused by moisture uptake. This process strengthens the adhesive bonds, enabling the bonding shear strength of the OPT mono-species laminated composites to meet the minimum standard requirements after undergoing a series of pre-treatments.

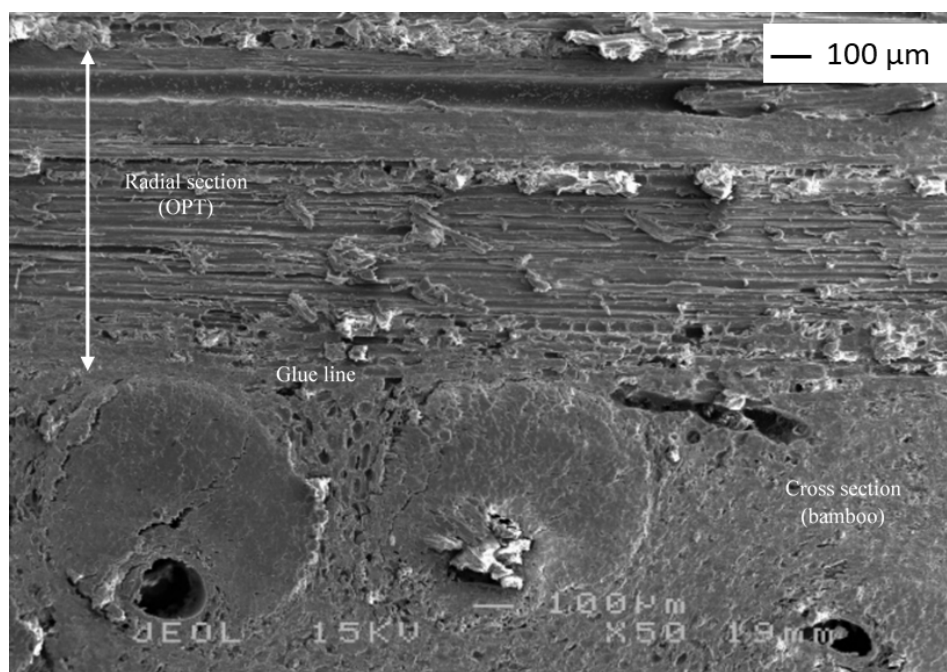
The SN-O hybrid composite exhibited weaker bond shear strength, particularly after the 24-hour soak treatment, suggesting that semantan may be less suitable for hybrid composites with OPT. In contrast, the SM-O hybrid composite showed improved bond shear strength, particularly following the 24-hour soak and vacuum-pressure

treatment, suggesting that this configuration is more resistant to wet conditions.

Figure 6 illustrates the interaction between the adhesive and the composite materials. It was noted that LMwPF resin sufficiently penetrated the laminated composite, enhancing the bonding strength between veneer surfaces. Dungani et al. (2013) indicated that resin impregnation process served as an effective barrier against water molecule diffusion into cell walls and lumens by sealing the lumen openings. LMwPF resin impregnation also caused cell bulking, reducing additional water swelling and preserving the bond shear strength under wet conditions (Anwar et al. 2004, Rabiatal Adawiyah et al. 2020).

### Mechanical properties

The strength, stiffness, and compressive strength of the laminated composites are summarised in Table 5. The results indicate that SM and SN composites have higher bending strength, with greater MOR and MOE values compared to those made from OPT. MOE is an important parameter as it reflects the material's stiffness and resistance to deformation. Both semeliang and semantan composites demonstrate higher MOE values, making them more resistant to deformation under stress and suitable for high-performance applications.



**Figure 6** Penetration of adhesive in SM-O hybrid laminated composite (50 × magnification)

**Table 5** Mechanical properties of the laminated composites

Sample	Bending strength (N/mm <sup>2</sup> )		Compressive strength (N/mm <sup>2</sup> )
	MOR	MOE	
Semeliang (SM)	168.88 <sup>b</sup> (12.73)	26524 <sup>b</sup> (1237)	89.68 <sup>a</sup> (13.40)
Semantan (SN)	169.11 <sup>b</sup> (16.74)	26967 <sup>b</sup> (1157)	58.16 <sup>c</sup> (21.11)
OPT	68.43 <sup>c</sup> (9.17)	7368 <sup>c</sup> (1686)	36.02 <sup>d</sup> (7.52)
Hybrid Semeliang-OPT (SM-O)	189.08 <sup>a</sup> (11.16)	28627 <sup>a</sup> (575)	82.56 <sup>a</sup> (4.71)
Hybrid Semantan-OPT (SN-O)	163.58 <sup>b</sup> (20.28)	28452 <sup>a</sup> (1585)	73.34 <sup>b</sup> (10.32)

Notes: Values in parentheses are standard deviations. Means followed with the same letters in the same column are not significantly different at  $p \leq 0.05$  according to LSD, OPT = Oil palm trunk, MOR = Modulus of rupture, MOE = Modulus of elasticity

The hybridisation of semeliang with OPT (SM-O) results in significant enhancements in mechanical strength and elasticity. The bending strength (MOR) is augmented by approximately 12%, rising from 168.88 N/mm<sup>2</sup> to 189.08 N/mm<sup>2</sup>, while the MOE improves by around 8%, increasing from 26,524 N/mm<sup>2</sup> to 28,627 N/mm<sup>2</sup>. These improvements underscore the efficacy of incorporating OPT with semeliang to enhance the mechanical properties, making the composite both stronger and more elastic. Conversely, hybridisation of semantan with OPT (SN-O) does not produce substantial improvements in mechanical strength or elasticity, suggesting that semantan may be less effective in enhancing hybrid composite performance when combined with OPT.

In terms of compressive strength, both SM and SN composites significantly outperform OPT, which exhibits a much lower compressive strength of 36.02 N/mm<sup>2</sup>. The SM-O hybrid composite achieves a compressive strength of 82.56 N/mm<sup>2</sup>, while the SN-O hybrid composite records 73.34 N/mm<sup>2</sup>. These results indicate that integrating bamboo laminates with OPT not only enhances the compressive strength but also improves its suitability for applications requiring both bending and compression resistance.

The relatively lower mechanical properties observed in laminated OPT composites are

primarily attributed to their intrinsically lower density compared to bamboo (Nuryawan et al. 2022). Numerous studies have established a strong positive correlation between density and mechanical strength in wood and lignocellulosic composites, as higher density often indicates a greater proportion of load-bearing fibres, thicker cell walls, and reduced void volume (Fadhli et al. 2017, Abdul Khalil et al. 2010). Bamboo possesses a higher proportion of fibres and vascular bundles relative to parenchyma cells, which contribute significantly to its superior MOR, MOE and compressive strength. This unique anatomical structure of bamboo results in higher density, which in turn translates to greater stiffness, tensile capacity and overall mechanical performance.

Furthermore, the strategic configuration of veneers plays a pivotal role in enhancing the mechanical performance of laminated composites. Positioning lower-density veneers at the core and placing higher-density veneers on the outer layers significantly improves the overall strength and stiffness of OPT-based composites (Ghani et al. 2022, Kamke & Lee 2007). This arrangement takes advantage of the fact that outer layers bear the highest tensile and compressive stresses during bending, making high-density veneers particularly beneficial in these zones. Empirical studies

have indicated that lay-up patterns profoundly affect both bending strength and bond integrity, highlighting the importance of precise veneer placement in composite fabrication (Rosli et al. 2016).

By leveraging the inherent density-related properties of bamboo and optimising the lay-up sequence, high-performance and cost-effective laminated composites can be developed for various structural and industrial applications. This approach not only enhances mechanical properties but also promotes the sustainable use of natural resources, aligning with environmental conservation goals.

## CONCLUSIONS

The findings of this study indicate that laminated composites made from semeliang (SM) and hybrid semeliang-OPT (SM-O) exhibited lower moisture content and thickness swelling compared to semantan (SN), OPT, and hybrid semantan-OPT (SN-O). Additionally, the SM composite demonstrated significantly lower water absorption than the other composites, reflecting superior dimensional stability and enhanced resistance to moisture-related changes. Hybridising OPT with semeliang bamboo significantly improved the bonding shear, stiffness and strength performance of the laminated composites. Specifically, the bonding shear strength of SM-O composites increased by approximately 0.84%, 18.55%, and 8.21% under control, 24-hour soak, and boil-dry-boil (BDB) treatments, respectively, as compared to SM composites. Moreover, the modulus of rupture (MOR) and modulus of elasticity (MOE) of the SM-O hybrid composite were 12% and 8% higher, respectively, than those of the SM composite. Overall, integrating semeliang bamboo with OPT offers a promising and cost-effective solution to enhancing the bonding and mechanical properties of laminated composites. Given the abundance and lower cost of OPT compared to bamboo, this hybridization offers an economical alternative without compromising strength and elasticity. This combination delivers a high-performance solution for structural applications, striking a balance between affordability and superior composite properties.

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## REFERENCES

- ABDUL KHALIL HPS, BHAT AH, JAWAID M, AMOUZGAR P, RIDZUAN R & SAID MR. 2010. Agro-wastes: Mechanical and physical properties of resin impregnated oil palm trunk core lumber. *Polymer Composites*. 31: 638–644. <https://doi.org/10.1002/pc.20841>
- ABDULLAH CK, JAWAID M, KHALIL HPS, ZAIDON A & HADIYANE A. 2012. Oil palm trunk polymer composite: morphology, water absorption, and thickness swelling behaviours. *BioResources*. 7: 3. DOI:10.15376/biores.7.3.2948-2959
- AHAMAD WN, SALIM S, LEE SH ET AL. 2023. Effects of compression ratio and phenolic resin concentration on the properties of laminated compreg inner oil palm and sesenduk wood composites. *Forests*. 14: 83. <https://doi.org/10.3390/f14010083>
- AIZAT G, ZAIDON A, LEE SH, EDI SB & PAIMAN B. 2017. A comparison between the properties of low and medium molecular weight phenol formaldehyde resin-treated laminated compreg oil palm wood. *International Forestry Review*. 19: 1–11. <https://doi.org/10.1505/146554817828562305>
- ANWAR UMK, ZAIDON A, PARIDAH MT & RAZAK W. 2004. The potential of utilising bamboo culm (*Gigantochloa scortechinii*) in the production of structural plywood. *Journal of Bamboo and Rattan*. 3: 393–400.
- ASNIZA M, ALIA SYAHIRAH Y, MOHD FAHMI A, LEE SH & ANWAR UMK. 2023. Properties of plybamboo manufactured from two Malaysian bamboo species. *Physical Science Review*. 9: 75–83. <https://doi.org/10.1515/psr-2022-0049>
- ASTM D1037-12. 2020. *Annual book of ASTM standard, standard test methods for evaluating properties of wood-based fiber and particle panel material*. ASTM International, West Conshohocken, PA, USA.
- ASTM D3501-05a. 2018. *Annual book of ASTM standard, standard test methods for wood-based structural panels in compression*. ASTM International, West Conshohocken, PA, USA.
- AUGUSTINA S, DWIANTO W, WAHYUDI I, SYAFII W, GÉRARDIN P & MARBUN SD. 2023. Wood impregnation in relation to its mechanisms and properties enhancement. *BioResources*. 18: 4332–4372. <https://doi.org/10.15376/biores.18.2.Augustina>
- BALQIS NMJ, JAFFAR N, JAAFAR AS, ISHAK N, ISMAIL N & MD ZAIN N. 2024. Potential of bamboo as green building element. *International Journal of Business and Technology Management*. 6: 350–359. <http://dx.doi.org/10.6007/IJARBS/v12-i8/14490>
- BARRILE V & GENOVESE E. 2024. Bamboo structures: Innovative methods and applications for structural health monitoring and dissemination. *Advances in*

- Bamboo Science*. 7: 100079. <https://doi.org/10.1016/j.bamboo.2024.100079>
- BHAT IUH, ABDULLAH CK, ABDUL KHALIL HPS, HAKIMI IBRAHIM M & NURUL FAZITA MR. 2010. Properties enhancement of resin impregnated agro waste: oil palm trunk lumber. *Journal of Reinforced Plastics and Composites*. 29: 3301–3308. <https://doi.org/10.1177/0731684410372262>
- CHAOWANA P. 2013. Bamboo: An alternative raw material for wood and wood-based composites. *Journal of Materials Science Research*. 2: 90. <https://doi.org/10.5539/jmsr.v2n2p90>
- CHAUDHARY U, MALIK S, RANA V & JOSHI G. 2024. Bamboo in the pulp, paper and allied industries. *Advances in Bamboo Science*. 7: 100069. <https://doi.org/10.1016/j.bamboo.2024.100069>
- CHE ISMAIL A, SALIM S, MD TAHIR P ET AL. 2022. Properties enhancement of oil palm trunk plywood against decay and termite for marine applications. *Polymers*. 14: 2680. <https://doi.org/10.3390/polym14132680>
- DUNGANI R, ABDUL KHALIL HPS, ISLAM N, SUMARDI I, ADITIAWATI P & HADIYANE A. 2016. Soil burial degradation of oil palm shell (OPS) nanofiller and phenol formaldehyde (PF) resin-impregnated oil palm trunk lumber (OPTL): Dimensional stability and mechanical properties. *Journal of Biobased Materials and Bioenergy*. 10: 258–264. <https://doi.org/10.1166/jbmb.2016.1585>
- DUNGANI R, JAWAID M, ABDUL KHALIL HP ET AL. 2013. A review on quality enhancement of oil palm trunk waste by resin impregnation: Future materials. *BioResources*. 8: 3136–3156.
- FADHLIA FARN, PARIDAH MT, ANWAR UMK, JULIANA AH & ZAIDON A. 2017. Enhancing mechanical properties and dimensional stability of phenolic resin-treated plybamboo. *Journal of Tropical Forest Science*. 29: 19–29. <http://www.jstor.org/stable/44028271>
- GABRIELLI CP & KAMKE FA. 2010. Phenol-formaldehyde impregnation of densified wood for improved dimensional stability. *Wood Science and Technology*. 44: 95–104. <https://doi.org/10.1016/j.jclepro.2020.121022>
- GHANI A, LEE SH, SABARUDDIN FA, SAIFULAZRY SOA & PARIDAH MT. 2022. Laminated veneer lumber from oil palm trunk. Pp. 241–251 in *Oil Palm Biomass for Composite Panels*. Elsevier, New York.
- HASLETT AN. 1990. Suitability of oil palm trunk for timber uses. *Journal of Tropical Forest Science*. 2: 243–251.
- KAMKE FA & LEE JN. 2007. Adhesive penetration in wood - A review. *Wood and Fiber Science*. 39: 205–220.
- MS2693. 2020. *Laminated bamboo - Specifications for general use*. Department of Standards Malaysia, Cyberjaya, Selangor, Malaysia.
- NORDAHLIA AS, ANWAR UMK, HAMDAN H, ABDUL LATIF M & MOHD FAHMI A. 2019. Anatomical, physical, and mechanical properties of thirteen Malaysian bamboo species. *BioResources*. 14: 3925–3943. <https://doi.org/10.15376/biores.14.2.3925-3943>
- NURYAWAN A, SUTIAWAN J, RAHMAWATY MASRUCHIN N & BEKHTA P. 2022. Panel products made of oil palm trunk: a review of potency, environmental aspect, and comparison with wood-based composites. *Polymers*. 14: 1758. <https://doi.org/10.3390/polym14091758>
- RABIATOL ADAWIAH MA, ZAIDON A, LEE SH, ANWAR UMK, EDI SUHAIMI B & NUR IZREEN FA. 2020. Low viscosity melamine urea formaldehyde resin as a bulking agent in reducing formaldehyde emission of treated wood. *BioResources*. 15: 2195–2211. <https://doi.org/10.1007/s13196-020-00270-0>
- ROSLI F, GHAZALI CM, ABDULLAH MM & HUSSIN K. 2016. A review: Characteristics of oil palm trunk (OPT) and quality improvement of palm trunk plywood by resin impregnation. *BioResources*. 11: 5565–5580. <https://doi.org/10.15376/biores.11.2.Rosli>
- ROWELL RM. 2012. *Handbook of Wood Chemistry and Wood Composites* (2nd ed.). CRC Press, New York.
- SAIN A, GAUR A, KHICHAD JS & SOMANI P. 2024. Treatment of bamboo for sustainable construction practise: a comprehensive review. In: *IOP Conference Series: Earth and Environmental Science*. 1326: 012049. <https://doi.org/10.1088/1755-1315/1326/1/012049>
- SITTI FATIMAH MR, OTHMAN S, ROKIAH H ET AL. 2012. Characterization of parenchyma and vascular bundle of oil palm trunk as function of storage time. *Lignocellulose*. 1: 33–44. <https://doi.org/10.1063/1.5089338>
- SOBRINHO A, TORRES SM, BARBOSA NP, ORTIZ SR & GHAVAMI K. 2012. Impregnation of *Bambusa vulgaris* with polymeric resins. *Key Engineering Materials*. 517: 27–33. <https://doi.org/10.4028/www.scientific.net/KEM.517.27>
- SUHAILY SS, ABDUL KHALIL HPS, ASNIZA M ET AL. 2017. Design of green laminated composites from agricultural biomass. Pp 291–311 in Mohammad Jawaid NS and Paridah MT (eds) *Lignocellulosic Fibre and Biomass-Based Composite Materials*. Woodhead Publishing, London.
- SULAIMAN O, AWALLUDIN MF, HASHIM R & IBRAHIM H MONDAL MD. 2012. The effect of relative humidity on the physical and mechanical properties of oil palm trunk and rubberwood. *Cellulose Chemistry and Technology*. 46: 401–407. <https://doi.org/10.1179/2042645311Y.0000000011>
- WAHAB NHA, TAHIR PM, BENG HOONG YET ET AL. 2012. Adhesion characteristics of phenol formaldehyde pre-preg oil palm stem veneers. *BioResources*. 7: 4545–4562. <https://doi.org/10.15376/BIORES.7.4.4545-4562>
- YADAV M & MATHUR A. 2021. Bamboo as a sustainable material in the construction industry: An overview. *Materials Today: Proceedings*. 43: 2872–2876. <https://doi.org/10.1016/j.matpr.2021.01.125>
- ZAINI LH, GINDL-ALTMUTTER W, GUSENBAUER C ET AL. 2024. Nanofibrils from oil palm trunk: effect of delignification and fibrillation technique. *Journal of Wood Science*. 70: 19. <https://doi.org/10.1186/s10086-024-02133-5>