Exploring the Potential of *Gigantochloa levis* and *Gigantochloa scortechinii* Bamboo Species for Plybamboo Production

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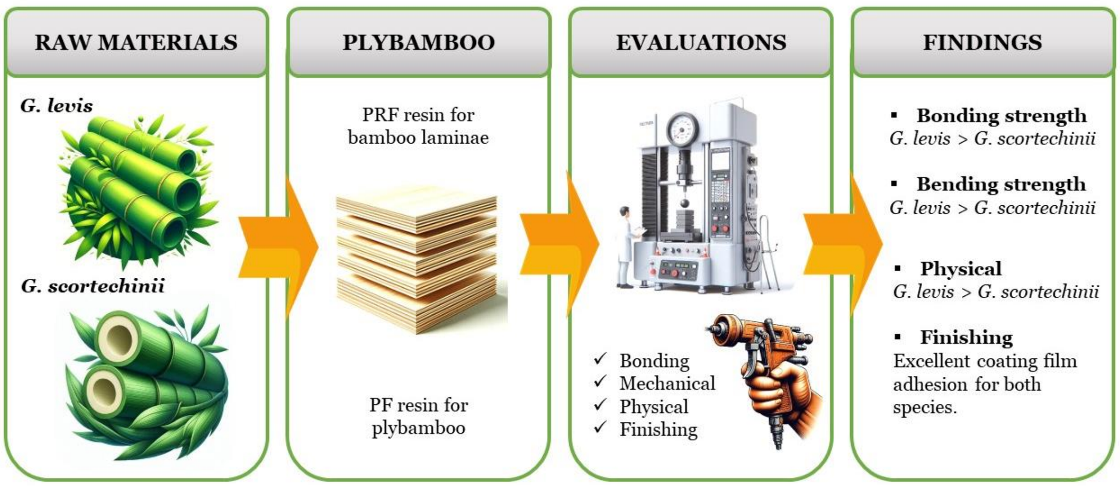
GRAPHICAL ABSTRACT



Exploring the Potential of *Gigantochloa levis* and *Gigantochloa scortechinii* Bamboo Species for Plybamboo Production

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Gigantochloa levis and *G. scortechinii* bamboo species were evaluated as material for plybamboo production. Plybamboo was composed of three layers with 12 mm thickness and used phenol formaldehyde (PF) as their binder. Representative samples were cut and tested for bonding, physical, mechanical, and finishing properties. Results indicated that *G. levis* plybamboo exhibited higher bending strength property compared to *G. scortechinii* plybamboo, as indicated by its higher modulus of rupture (121 N/mm^2) and modulus of elasticity (16300 N/mm^2). The *G. levis* plybamboo also displayed higher bond shear strength and was dimensionally stable compared to *G. scortechinii* plybamboo. The finishing properties revealed that all coatings performed well in the cross-cut tape and pull-off tests. Notably, plybamboo from both bamboo species showed excellent coating film adhesion. Based on minimum standard requirement, results revealed that both bamboo species were suitable to be used in plybamboo production for general use. The findings showed that those species are valuable renewable natural resources for plybamboo production and had potential to be utilized as a substitute for wood in board production.

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Keywords: Physical properties; Mechanical properties; Finishing properties; Plybamboo; Gigantochloa levis; G. scortechinii

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INTRODUCTION

Bamboo has gained popularity due to its short growth cycle and excellent physical and mechanical properties. It is known as an important non-wood forest product that serves as an alternative material in production of household products and industrial applications. Interest in bamboo as a raw material is growing because of its sustainable characteristics, thus helping to address the shortage of global timber resources.

Extensive research has been done to determine the feasibility of using bamboo in various shapes, sizes, and applications. However, bamboo's natural cylindrical and round form has inhibited its utilization efficiency (Hu and Pizzi 2013). Fortunately, the utilization efficiency of bamboo can be increased by converting its original form into thin flat laminae and gluing it together to form laminated composites. Apart from that, bulking treatment using phenolic resin followed by compressing at high temperature using a hot press has been known as an effective way to enhance the strength and dimensional stability of bamboo-based products (Lee and Zaidon 2015).

A variety of bamboo composites have been developed, such as bamboo scrimber (Yu *et al.* 2015), bamboo strand-based composites (Malanit *et al.* 2011), laminated bamboo (Nugroho and Ando 2001), plybamboo (Anwar *et al.* 2012), and hybrid bamboo-wood composites (Yong *et al.* 2012; Semple *et al.* 2015). Plybamboo is one of the potential green-construction materials that can be used in both residential and industrial structures (Xiao *et al.* 2014). In addition to having renewable characteristics, the mechanical properties of plybamboo are comparable to those of common wood, making it competitive as commonly used building materials (Ahmad and Kamke 2011; Verma and Chariar 2012). Moreover, plybamboo and laminated panels using bamboo were reported to produce plybamboo with strength and stiffness comparable to plywood (Anwar *et al.* 2005; Rahman *et al.* 2012). Plybamboo is fabricated by assembling and gluing bamboo strips together. It can be done either in a crosswise or lengthwise direction, in alternate manner, with a hot-pressing technique using adhesive (Qisheng *et al.* 2002).

The inherent variations in bamboo's density, chemical composition, and permeability pose unique challenges for achieving strong adhesion with adhesive materials. A thorough understanding of the interaction between bamboo and different adhesives, along with the appropriate preparation and application techniques, is essential. Common adhesives used for wood-based composites can be applied to bamboo-based composites. For example, as the exterior-grade wood adhesive, phenol formaldehyde (PF) is normally used for bamboo structural panels (Nkeuwa *et al.* 2022; Huang *et al.* 2020). The majority of bamboo-based composites are made from PF resins, as they are commercially available, relatively inexpensive, and durable. Apart from allowing co-addition of crosslinking agents and fillers, PF also enables customization of viscosity and molecular weight distribution. It can be used and pressed in liquid, dry film, or powder form and cured to obtain a thermally stable, strong, and moisture proof bonding (Xiao 2016).

Peninsular Malaysia is endowed with more than 63 bamboo species. Among these, only 13 species are commercially exploited. The genus *Gigantochloa* is one of the most utilized bamboos in Malaysia because of its uniformity in size, thick culms wall, and ease of cultivation, which makes this bamboo genus a good choice for industrial usage (Nordahlia *et al.* 2019; Asniza *et al.* 2022). The species identified and highly recommended are *G. levis* (beting) and *G. scortechinii* (semantan) because they have higher density and modulus of rupture (MOR) compared to other species. In the literature, *G. scortechinii* bamboo is reported suitable for making particleboard, laminated bamboo boards, plybamboo, and bamwood (Zaidon *et al.* 2004; Roziela Hanim *et al.* 2010; Anwar *et al.* 2011, 2012). This study aimed to explore the potential of 3-plybamboo using *G. levis* and *G. scortechinii* bamboo species, employing PF resin as the adhesive. The properties of the plybamboo, such as bond shear strength, physical properties, mechanical properties, and finishing properties of plybamboo, were determined and compared.

EXPERIMENTAL

Materials

Gigantochloa levis (beting) and *Gigantochloa scortechinii* (semantan) were used to produce plybamboo. The bamboo species were harvested from the bamboo plantation in Forest Research Institute Malaysia (FRIM), Kepong, Selangor, Malaysia. The matured bamboo culms aged *ca.* three years were cut into 4 parts with 1.7 m length each. Phenol resorcinol formaldehyde (PRF) and phenol formaldehyde (PF) resin were used as binders.

Fabrication of Plybamboo

The bamboo culms were cut into splits of 20 mm wide (based on outer layer) using sizing and splitting machines. The bamboo splits were soaked in 2% borax solution for two weeks to prevent the bamboo from borer attack. The treated splits were then dried in a kiln until the moisture content of 12% was reached. Then, treated splits were planed using a planer machine to produce a strip with a final thickness of 4 mm. The final dimension of the prepared strip was 4 mm thickness, 20 mm width, and 300 mm length. The PRF resin was used to bond the edge of bamboo strips to produce laminae.

The PF resin was double spread on the laminae surface with glue spread of 215 g/m^2 on top of each layer of bamboo laminae. Three layers of bamboo laminae were glued together in perpendicular direction to produce a plybamboo. Cold pressing was initially performed at a pressure of 5 kg/cm^2 for approximately 15 minutes. Subsequently, the assembled laminae underwent hot pressing at 140 °C with a pressure of 14 kg/cm^2 for an additional 15 minutes to produce a 12 mm thick plybamboo.

Evaluation of Bonding Properties

Plybamboo was conditioned at 20 ± 2 °C and 60% relative humidity (RH) for a week before the testing was conducted. Ten test specimens from each interval were cut according to Malaysian Standard MS 2693 (2020). The dimensions of the sample were 12 mm thickness, 25 mm width, and 50 mm length. In this study, a series of pre-treatments (soak for 24 h, boil-dry-boil, vacuum pressure) are required for different bonding classes. In contrast, there was no pre-treatment required for control samples. The series of pre-treatments applied on the sample prior to testing were as follows:

i. Soak for 24 h
   Samples for bonding shear test were immersed for 24 h in water at 20 ± 3 ºC.
ii. Boil-dry-boil (BDB)
   This pre-treatment involved immersion for 6 h in boiling water followed by drying at room temperature for 1 h. The samples were then boiled for 4 h again followed by cooling in water at < 30 ºC for at least 1 h.
iii. Vacuum pressure (VP)
   The samples for vacuum pressure were immersed in water and vacuum of 85 kPa was applied for 30 min and followed by immediate application of a pressure of 450 to 480 kPa for 30 min.

After pre-treatment, the dimension of each test sample were measured and made ready for the shear bonding test. The test was conducted using the Shimadzu Universal Testing Machine at a rate of 7 mm/min for 30 ± 10 s until the sample failed. The percentage of bamboo failure was also evaluated.

Evaluation of Physical Properties

The samples were oven-dried at 103 ± 2 ºC until a constant weight was obtained prior for the determination of moisture content (MC). The initial weight and final oven-dried weight of each sample was determined, and its MC was calculated. The dimensions and weight of air-dry sample were measured, and the air-dry density was calculated. The dimensional stability of the sample was assessed by measuring its thickness and weight both before and after a 24 h immersion in distilled water at 25 ºC. The thickness swelling, linear expansion (parallel and perpendicular to the grain), and water absorption of the plybamboo were then calculated according to ASTM D 1037-96a (1996) standards.

Evaluation of Mechanical Properties

The mechanical properties of plybamboo were determined according to ASTM D3501 (1994) using a Shimadzu Universal Testing machine. All samples were conditioned at a temperature of 20 ℃ and RH of 65 ± 3% prior to the tests. For bending test, the constant load rate of 3500 N/min was applied on a 12-mm-thick, 25-mm-wide, and 300-mm-long sample. After the bending test, the MOR and MOE of the samples were determined. Following the test, the failure mode of the samples (%) was evaluated. In the compression test, the 12 mm thick, 50 mm wide, and 60 mm long samples were placed in a vertical position between two parallel metal plates. A constant load at a rate of 6.5 mm/min was introduced at the top of the samples to determine the compressive strength.

Application of Coatings on Plybamboo Substrate

Three types of lacquers were used: nitrocellulose (NC), acid catalyst (AC), and polyurethane (PU). The plybamboo (*G. levis* and *G. scortechinii*) produced earlier were used as substrates. After conditioning in room conditions, the plybamboo were cut into panels with final dimensions of 10 mm thick, 100 mm width, and 300 mm length. All samples were sanded using 180 grit, followed by 240 grit, and finally sanded with 320 grit sandpaper to ensure a smooth surface before finish application. Samples were coated at ambient temperature using a spray gun. Four distinct finishing systems, detailed in Table 1, were applied to the coatings. Three replicates were prepared for each system. The coated plybamboo was initially conditioned at room temperature for one week, followed by further conditioning in a controlled environment at 23 ± 2 °C and 50 ± 5% relative humidity (RH) prior to testing.

Table 1. Number of Coats for Different Finishing System

Plybamboo	Finishing System	Nitrocellulose (NC)		Acid Catalyst (AC)		Polyurethane (PU)	
		Sealer*	Top coat*	Sealer*	Top coat*	Sealer*	Top coat*
G. levis	1	1	1	1	1	1	1
	2	1	2	1	2	1	2
	3	2	1	2	1	2	1
	4	2	2	2	2	2	2
G. scortechinii	1	1	1	1	1	1	1
	2	1	2	1	2	1	2
	3	2	1	2	1	2	1
	4	2	2	2	2	2	2

*Number of coats

Evaluation of Finishing Properties

Cross-cut analysis

The adhesion of the coatings to the plybamboo substrate was tested using the cross-cut tape method in accordance with BS EN ISO 2409 (2013). The coatings were cut approximately at 45° to the grain direction using a 2 mm cross hatch cutter. The two series of parallel cuts were crossed at an angle of 90° to create a lattice pattern. Adhesive tape was placed over the lattice and was removed after 5 min. The cutting region was rated on the step classification given by the standard.

Pull-off adhesion test

Pull-off adhesion test is another method to determine the adhesion properties of coatings on the substrate. This test method was assessed according to the standard BS EN ISO 4624 (2016). Aluminium dollies (20 mm) were glued on the finished plybamboo surface and allowed to cure for 24 h. The adhesion test was performed using a pull-off adhesion tester on a single coating or a multi-coat system of finished plybamboo. The adhesion strength properties of finished plybamboo were measured and the surface failure were evaluated accordingly.

Resistance to impact test

The impact resistance test was determined by dropping a steel ball from a height of 2.0 ± 0.01 m onto the surface of the test panel. Assessment was made by examining the appearance of the test panel impacted by the steel ball. The region was rated based on the assessment code in BS 3962: Part 6 (1980).

RESULTS AND DISCUSSION

Shear Strength and Failure Percentage

The shear strength and bamboo failure percentage of laminated bamboo were assessed in different conditions according to Malaysian Standard MS 2693 (2020). The shear strength and bamboo failure percentage for *G. levis* and *G. scortechinii* species are presented in Table 2. The shear strength for control, BDB, and VP from both bamboo species were not significantly different. Meanwhile, the shear strength of plybamboo from *G. levis* was significantly higher than *G. scortechinii* after soaking for 24 h.

Table 2. Mean Values of Bond Shear Strength and Bamboo Failure Percentage of *G. levis* and *G. scortechinii* Plybamboo

Pre-treatment	*G. levis*		*G. scortechinii*	
	Shear Strength (MPa)	B. Failure (%)	Shear Strength (MPa)	B. Failure (%)
Dry/Control	2.70^a (0.40)	73.00 (13.65)	2.69^a (0.46)	70.00 (10.57)
Soak 24 h	2.50^a (0.68)	37.00 (15.16)	1.53^b (0.34)	28.00 (12.65)
BDB	1.01^a (0.25)	40.00 (19.66)	1.26^a (0.20)	36.00 (5.47)
VP	1.27^a (0.40)	48.00 (11.26)	1.33^a (0.33)	34.00 (11.98)

Notes: B. failure = Percent of bamboo failure; BDB = Boiling-dry-boiling; VP = Vacuum pressure. Values in parentheses are standard deviations. Means followed with the same letters a, b in the same row is not significantly different at p ≤ 0.05 according to LSD.

The bond shear strength values of all samples after pre-treatment in wet conditions (24 h soaking, BDB and VP) were lower than those of the control samples. This reduction is likely due changes in dimensional stability, where the cell walls swelled or shrunk as moisture levels fluctuated during the wet treatment (Dong *et al.* 2023). The bond shear strength of pre-treated plybamboo from *G. levis* were higher compared to *G. scortechinii*, indicating that *G. scortechinii* absorbed more water compared to *G. levis*, contributing to the damage to the bonding and leading to the decrease of the bond shear strength.

Theoretically, optimal bonding is indicated by the simultaneously high values of both shear strength and the percentage of bamboo failure (Asniza *et al.* 2022). Conversely, when there is a high value in one aspect and a low value in the other, it signifies a deficiency either in the adhesive or in the bamboo (Anwar *et al.* 2004). The bamboo failure percentage values for all samples ranged from 28% to 73%. It is also notable that the bamboo failure percentage for both bamboo species was higher in the control samples compared to the pre-treated samples. This high percentage of bamboo failure in the control samples for both species is attributed to their high bond shear strength. This means the adhesive bonds between bamboo layers are very strong and resist breaking under stress. During testing, the adhesive bond remains intact, causing the bamboo material itself to fail instead. Control samples, which are untreated, maintain this high bond shear strength, leading to bamboo failure rather than adhesive failure. This highlights the effectiveness of the adhesive bond, regardless of the bamboo species.

In contrast, after pre-treatment, the samples normally fail due to adhesive or glue failure which contribute to the low percentage of bamboo failure. Therefore, from the results obtained from both bamboo species, the low percentage of bamboo failure does not represent low bond shear strength. The results indicated that all samples in this study met the minimum shear strength requirement of the Malaysian Standard MS 2693 (2020), which was 0.35 to 2.5 N/mm^2 for dry condition.

Physical Properties

Thickness swelling test was performed to explore the dimensional stability of *G. levis* and *G. scortechinii* plybamboo caused by water absorption. Table 3 shows the thickness swelling behavior of the plybamboo. Plybamboo from *G. levis* showed a lower thickness swelling percentage compared to *G. scortechinii* plybamboo. The thickness of *G. levis* plybamboo swelled 5.08%, while *G. scortechinii* plybamboo swelled 9.22% after 24 h of soaking. Plybamboo from *G. scortechinii* absorbed more water (29.01%) than *G. levis* plybamboo (23.59%) when soaked in water. Additionally, *G. scortechinii* plybamboo exhibited higher linear expansion parallel to the grain compared to *G. levis* plybamboo. However, the value of linear expansion perpendicular to grain was not significantly different for both *G. levis* plybamboo (1.02%) and *G. scortechinii* plybamboo (1.00%).

Table 3. Physical Properties of *G. levis* and *G. scortechinii* Plybamboo

Species	Thickness Swelling (%)	Linear Expansion Parallel to Grain (%)	Linear Expansion Perpendicular to Grain (%)	Water Absorption (%)
G. levis	5.08^a (1.77)	0.13^a (0.22)	1.02^a (0.25)	23.59^a (2.02)
G. scortechinii	9.22^b (1.92)	0.48^b (0.59)	1.00^a (0.82)	29.01^b (2.71)

Notes: Values are mean. Values in parentheses are standard deviations. Means followed with the same letters ^{a,b} in the same column are not significantly different at $p \leq 0.05$ according to LSD.

The relationship between thickness swelling and water absorption in bamboo is closely linked to its hygroscopic nature. When bamboo absorbs water, its cell walls swell, leading to an increase in thickness. This swelling is a direct result of water molecules penetrating the bamboo's structure, causing it to expand. Therefore, higher water absorption generally results in greater thickness swelling, reflecting the bamboo's response to changes in moisture content. This relationship highlights the importance of controlling moisture levels to maintain the dimensional stability of bamboo products (Anokye *et al.* 2014). Furthermore, the water uptake of the plybamboo can be influenced by the variation of density and proportions of cellulose and hemicellulose. The degree of swelling and shrinkage depends on factors such as the species of bamboo, density, and the duration and extent of exposure to water. The density of bamboo affects how much water plybamboo can absorb. High density bamboo tends to have fewer void spaces within its structure, such that it does not let water soak in easily. Conversely, lower density bamboo may have more open spaces or pores, allowing water to infiltrate more easily. *G. levis* is noted to have a higher density (751 kg/ m^3) compared to *G. scortechinii* (690 kg/m^3) (Nordahlia *et al.* 2019). As a result, plybamboo made from higher density bamboo was less likely to soak up as much water compared to plybamboo made from less dense bamboo.

Both *G. levis* and *G. scortechinii* bamboo are from the genus *Gigantochloa*, thus having similar anatomical structure with type III vascular bundles (Nordahlia *et al.* 2019). Their composition of cellulose and hemicellulose are different. This primary constituent has a large number of hydroxyls (-OH) and an amorphous nature, which contribute to the absorption of water (Mochane *et al.* 2019; Taib and Julkapli 2019). *G. levis* is reported to have lower cellulose content (33.81%) compared to *G. scortechinii* (46.87%) (Aprilia *et al.* 2018; Hamid *et al.* 2023). As a result of this, *G. levis* plybamboo exhibit the lowest water uptake. In contrast, higher cellulose and/or hemicellulose content in *G. scortechinii* contribute to the poor water resistance of the plybamboo due to the presence of more hydroxyl group in the fibers (Ashori and Sheshmani 2010). This behavior is triggered by the water molecules that were attracted *via* hydrogen bonding, causing the moisture accumulation in the cell wall and around fiber-matrix interface and leading to dimensional changes caused by the reversible and irreversible swelling of the plybamboo (Abdul Khalil *et al.* 2007). A study by Osman *et al.* (2022) reported that *G. levis* exhibited excellent dimensional stability when compared to wood species with high shrinkage when dried from green to oven dry.

Mechanical Properties

The results of the bending and compression parallel to grain tests of both *G. levis* and *G. scortechinii* plybamboo samples bonded using PF (flat surface) and PVAc (edge surface), are shown in Table 4. The *G. levis* and *G. scortechinii* plybamboo samples showed similar mean density and moisture content. The bending properties of *G. levis* plybamboo samples were higher than those of *G. scortechinii* plybamboo. The ANOVA test results indicated statistically significant difference at 95% confidence level between the mean values of both MOE and MOR of the *G. levis* and *G. scortechinii* plybamboo samples. The mean MOR of *G. levis* was 26% higher than *G. scortechinii*, while the mean MOE was 14% higher. Nevertheless, the MOE and MOR mean values of *G. scortechinii* plybamboo samples in this present study were higher than the *G. scortechinii* plybamboo recorded by Anwar *et al.* (2004). In their study, PF was used to bond the flat surface and PVAc on the edge surface, and the 3-ply bamboo samples exhibited mean MC of 9.97% and density of 719 kg/m^3.

The study showed that the mean compressive stress of *G. levis* was lower than *G. scortechinii* plybamboo samples by 8%. The ANOVA was also conducted, and the results indicated statistically significant difference at 95% confidence level between the mean compressive stress of *G. levis* and *G. scortechinii* plybamboo. The mean compressive stress *G. scortechinii* plybamboo was higher than the results (35 N/mm^2) obtained by Anwar *et al.* (2004).

A study by Fadhlia *et al.* (2017) used PF as bonding medium at the flat surface and PRF at the edge surface to produce 3-ply phenolic-treated *G. scortechinii* plybamboo samples with different treatment methods as well as untreated plybamboo. The results showed that the mean MOR of phenolic-treated plybamboo samples ranged from 130 to 167 MPa, while the untreated plybamboo was 126 MPa, which was higher than the mean MOR of *G. scortechinii* plybamboo treated with boric acid in this study. The MC of the plybamboo in their study was lower (6.19% to 6.65%), with higher density ranged from 732 to 860 kg/m^3, except for untreated plybamboo with MC of 8.30% and density of 645 kg/m^3.

Another study by Yeh and Lin (2012) indicated that the MOR of laminated bamboo members were higher for samples with high density values. In reference to solid wood, it is also commonly known that there are high correlations between density and strength properties of the timber (Dinwoodie 2000). Nevertheless, further study can be conducted to determine the relationship between density and bending properties of the plybamboo by taking into consideration various factors such as bonding medium, effect of processing methods, number of plies, treatment, MC, and bamboo age.

Table 4. Mean Values of Physical and Mechanical Properties of *G. levis* and *G. scortechinii* Plybamboo

Species	MC (%)	Density (kg/m^3)	Compression Parallel to Grain (N/mm^2)	Bending (N/mm^2)	
				MOR	MOE
G. levis	12.83 (1.72)	771.01 (12.33)	48.83^a (4.53)	121.10^a (21.72)	16348^a (1941)
G. *scortechinii*	12.77 (1.89)	719.21 (15.44)	52.78^b (4.38)	95.64^b (14.88)	14253^b (3253)

Notes: Values in parentheses are standard deviations. Means followed with the same letters ^{a,b} in the same column are not significantly different at $p \leq 0.05$ according to LSD.

Comparing these results with other studies, it can be concluded that one key influencing property is density, which is crucial for producing high-quality bamboo composites (Yu *et al*. 2015). Xie *et al.* (2016) found that increased density in bamboo composites leads to improved dimensional stability and mechanical strength. Zhang *et al.* (2021) also highlight that bamboo density significantly enhances mechanical properties, dimensional stability, and overall serviceability of bamboo composite products.

Apart from this, factors such as MC, adhesive types, bamboo species, treatment, size of bamboo strip, machining, and gluing processes would have contributed to the bending and compressive properties of the plybamboo (Sharma *et al.* 2015; Penellum *et al.* 2018; Nkeuwa *et al.* 2022). This is expected because the middle layer of the plybamboo consists of edge-glued bamboo strips with the grain perpendicular to the face grain, which might have weakened its bending strength. In contrast, the mean MOE of the plybamboo were higher than the bamboo strips of *G. levis* (13,185 N/mm^2) and *G. scortechinii* (10,039

N/mm^2) mainly due to the reinforcement by the adhesive used to bond the layers in plybamboo, which increases its stiffness.

Finishing Properties

A coating protects the wood and other wood-based materials from the natural weathering process, UV radiation, and moisture, and to help maintain its appearance. To provide protection and aesthetics properties, finishes have to be carefully selected in function of the end use (Philipp 2010; Mishra *et al.* 2018). Moreover, to perform durably, the finishing products require good adhesion, flexibility, water resistance, and resistance to other damage-causing parameters (Cheumani Yona *et al.* 2021). The finishing properties (adhesion strength and impact resistance) of the plybamboo fabricated from *G. levis* and *G. scortechinii* bamboo species are discussed in the following section.

Cross-cut adhesion properties

The significance of adhesion as a coating parameter lies in its role in determining the coating's ability to remain firmly attached to the substrate. It correlates with the coating's quality, its interactions with the surface in terms of both physicochemical and mechanical aspects, as well as the level of surface preparation before the painting process (Meijer 2005). The adhesion of the NC, AC, and PU coatings to the plybamboo substrate that was assessed by cross-cut test method are shown in Table 5.

Table 5. Cross-cut Adhesion Rating* of Coated Plybamboo with Different Finishing System

Plybamboo	Finishing System	NC	AC	PU
G. levis	1	1	1	1
	2	1	1	1
	3	1	1	1
	4	1	1	1
G. scortechinii	1	1	1	1
	2	1	1	1
	3	1	1	1
	4	1	1	1

Notes: *Rating 0 to 5, where 0 is very good and 5 very poor

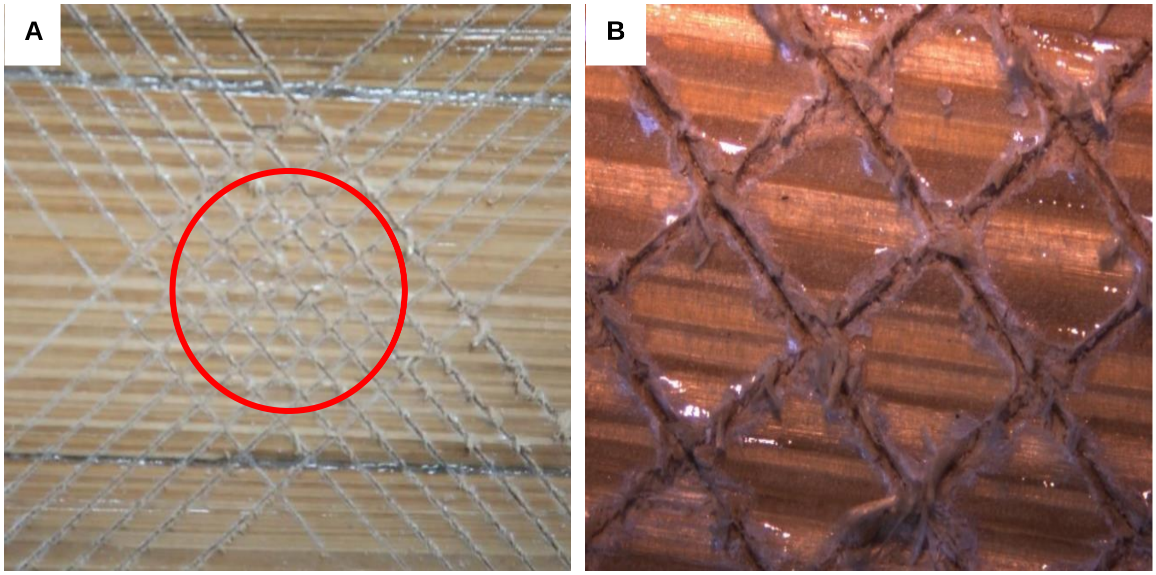

Fig. 1. Affected cross-cut area for test panel with AC lacquer (A) and at magnification of 18X (B)

The affected area on both *G. levis* and *G. scortechinii* plybamboo coated with NC, AC, and PU for finishing systems 1, 2, 3, and 4 did not exceed 5%. Each type of coating applied through all four coating systems exhibited excellent adhesion properties and received a rating of “1”. Rating 1 is generally well accepted for commercial organic coatings (Pavlic *et al.* 2021). Figure 1 illustrates the cross-cut area of the test panel coated with AC (rating 1). The results indicated that the bamboo species and type of resin had no significant effect on the adhesion strengths of AC, NC, and PU coated on plybamboo.

Pull-off adhesion properties

The pull-off tests results are in line with the classes of adhesion obtained by cross-cut, where good adhesion between coating and substrate was implied. As shown in Table 6, the highest value recorded was 4.11 N/mm^2, while the lowest was 2.14 N/mm^2 for Type 3 (PU, *G. levis*) and Type 4 (NC, *G. levis*), respectively. The average adhesion strength for all finishes coated on the plybamboo made from both bamboo species ranged from 2 to 3 N/mm^2, where more than 60% exhibited a value greater than 3 N/mm^2. In the pull-off adhesion test, two primary failure types can be identified. When less than 40% of the coating layer stays on the substrate, it signifies an adhesive failure, and the recorded strength reflects the adhesion between the coating and the substrate. In contrast, if more than 40% remains on the substrate, it is considered a cohesive failure, indicating the internal cohesion within the coating itself (Cheumani Yona *et al.* 2021). Adhesion strength values testified in the literature for wood coatings typically range from 2 to 5 MPa, though they can reach up to 10 MPa for high performance coatings (Kesik and Akyildiz 2015; Hazir and Koc 2019). After examining six polyurethane coatings, Oblak *et al*. (2006) suggested a minimum acceptable adhesion value of 2.5 MPa for wood. Type of fractures for pull off test either A/B or n/m are presented in parentheses while images of fractured occurred during pull-off test is illustrated in Fig. 2.

Table 6. Pull-off Adhesion Properties (N/mm^2) of *G. levis* and *G. scortechinii* Plybamboo Coated with Different Finishing Systems

Plybamboo	Finishing System	NC	AC	PU
G. levis	1	2.92 (B)	3.46 (B)	3.11 (BC)
	2	3.24 (B)	3.46 (B)	3.02 (n/m)
	3	2.32 (n/m)	3.73 (B)	4.11 (n/m)
	4	2.14 (n/m)	3.51 (B)	3.70 (n/m)
G. scortechinii	1	3.33 (A/B)	3.45 (A/B)	2.79 (B/C)
	2	3.4 (AB)	3.31 (AB)	2.36 (n/m)
	3	2.71 (n/m)	3.08 (AB)	3.48 (n/m)
	4	2.74 (n/m)	3.14 (AB)	3.09 (n/m)

Notes: * the value in N/mm^2

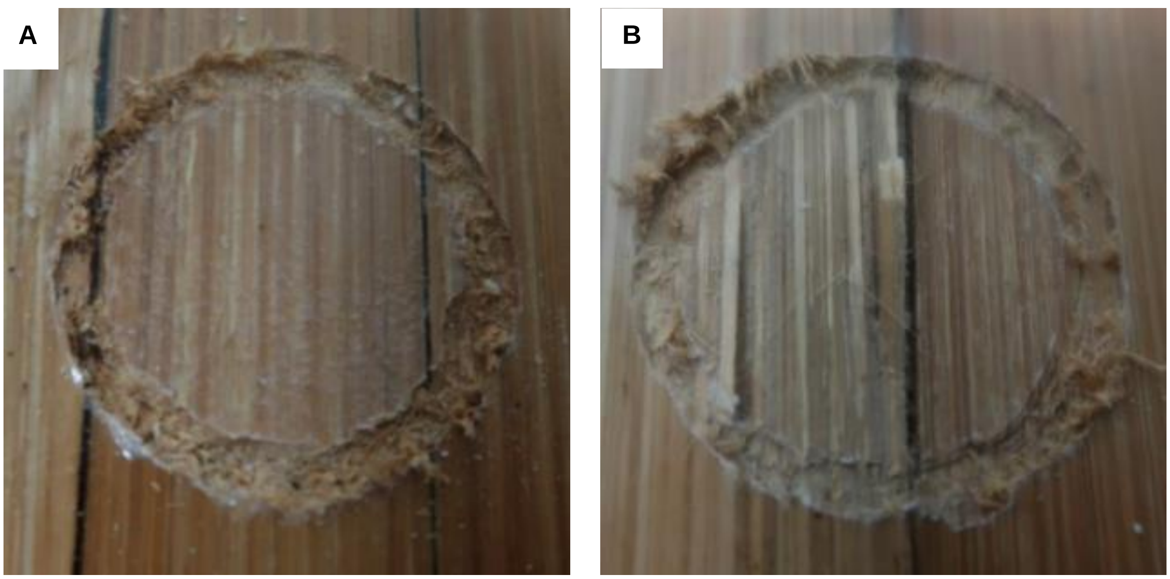

Fig. 2. Pull-off test on *G. levis* (A) and *G. scortechinii* (B) with n/m fracture

Resistance to impact properties

Table 7 shows the ratings for impact resistances of different types of finishing system and finishes. The impact marks were assessed according to the descriptive numerical evaluation code from 5 to 1. A rating of 5 was given if there were no alterations post-impact. A rating of 4 denoted a visible impact mark without any cracks in the coating film. Meanwhile, a rating of 3 indicated the presence of cracks in the coating film. Lower ratings were assigned if multiple cracks were visible (Pavlic *et al.* 2021). The impact resistance of *G. levis* and *G. scortechinii* plybamboo for all the finishing systems in this study was rated as 3 to 4, where 58% of the tested surface was rated as 3. The finishes can be classified as moderate or severe cracking at the area of the indentation while remaining samples are considered good. Among the finishing system used, Type 3 (2-layer sealer, 1-

layer topcoat) and Type 2 (1-layer sealer, 2-layer topcoat) gave a good rating for adhesion and impact test for *G. levis* and *G. scortechinii*, respectively. Generally, the coatings could withstand impact tests up to a drop height of 400 mm without being severely destroyed (Cheumani Yona *et al*. 2021). Overall, it can be stated that the finishing properties of the plybamboo can be categorized as moderate to good.

Table 7. Impact Resistance of Plybamboo Coated with Different Finishing System

Plybamboo	Finishing System	NC	AC	PU
G. levis	1	4	4	3
	2	4	4	3
	3	3	3	4
	4	3	3	3
G. scortechinii	1	4	3	3
	2	4	4	3
	3	3	3	3
	4	4	4	3

Notes: *Rating 1 to 5, where 5 is very good and 1 very poor

CONCLUSIONS

1. Three-layer-plybamboo was successfully manufactured from *Gigantochloa levis* and *G. scortechinii* bamboo species in the presence of phenol-formaldehyde (PF) resin as an adhesive.
2. The differences in the bond shear strength, physical properties, mechanical properties, and finishing properties of plybamboo showed that the properties of plybamboo are species dependent.
3. *G. levis* plybamboo exhibited higher bond shear strength, higher bending strength properties as indicated by its higher modulus of rupture (MOR) (121.10 N/mm^2) and modulus of elasticity (MOE) (16348 N/mm^2) values, as well as higher dimensional stability compared to *G. scortechinii* plybamboo.
4. In terms of finishing properties, all coatings performed well with regard to the cross-cut tape and pull-off tests, with plybamboo from both bamboo species showing excellent coating film adhesion.
5. In addition to its favorable strength, bonding, and finishing properties, it can be stated that both bamboo species are suitable alternatives for plybamboo manufacturing considering its supply volume and availability in Malaysia.

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