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RESEARCH ARTICLE

Physical Performance of Cross-Laminated Panels Made from *Nypa fruticans*

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ABSTRACT

The increasing demand for renewable and sustainable construction materials has led to the exploration of underutilised tropical biomasses for engineered wood applications. *Nypa fruticans* (nipah palm), abundant in Southeast Asian mangrove ecosystems, possesses fibrous, lignified petioles suitable for composite panel production. Despite that, the application in cross-laminated panel (CLP) manufacturing remains largely unexplored. This study addresses the knowledge gap by evaluating the physical performance of CLP fabricated from *N. fruticans*, focusing on density, moisture content, thickness swelling, and water absorption. The panels were fabricated at three target densities (400, 600, and 800 kg/m³) using long fibre strips and a bio-based epoxy resin at a 3:1 resin-to-hardener ratio. Hot-pressing was conducted at 7 MPa for 15 minutes at 100 °C. The fabricated panels were tested according to JIS A 5908:2003 standards. Results revealed that increased panel density significantly reduced moisture content, with values decreasing from 15.84% at 400 kg/m³ to 13.65% at 800 kg/m³. While only the lowest-density group exceeded the JIS moisture content limit, thickness swelling across all groups remained within the acceptable range, showing improved stability with increasing density. Water absorption demonstrated the most significant density-dependent variation, with the 800 kg/m³ panel absorbing 20% less moisture than the 400 kg/m³ counterpart. Statistical analysis via ANOVA confirmed the influence of density on all measured parameters ($p < 0.001$), and Duncan's post-hoc test highlighted significant group differences. In conclusion, *N. fruticans* is a promising sustainable raw material for CLP production, with the 800 kg/m³ configuration exhibiting optimal performance. These findings supported the viability of the *Nipah* palm in engineered panel applications and contributed to the diversification of tropical biomass resources in eco-friendly construction materials.

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1. INTRODUCTION

The global demand for sustainable, renewable, and eco-friendly materials has intensified the exploration of alternative lignocellulosic resources for structural applications in developed and developing nations. Cross-laminated timber (CLT) has gained traction as a viable material in green building technologies due to the favourable mechanical properties, dimensional stability, and reduced environmental footprint. This engineered wood panel is composed of layers of solid-sawn timber arranged perpendicularly and bonded with structural adhesives (Kurzinski et al., 2022). While softwood species such as spruce and pine have traditionally dominated CLT production, increasing deforestation, resource depletion, and transportation constraints have prompted researchers to evaluate the viability of non-conventional, fast-growing, and locally available biomass resources for panel manufacturing (Adhikari et al., 2020).

Among the underutilised natural resources in tropical regions, *Nypa fruticans*, commonly known as the nipah palm, offers considerable promise. Indigenous to mangrove ecosystems in Southeast Asia and coastal Africa, the *Nipah* palm has long been recognised for its ecological value, but its woody tissues have remained largely unexploited in engineered wood production. The stem of the *Nipah* palm, though subterranean, gives rise to erect leaf petioles with a fibrous, lignified structure (Ghani et al., 2024). Previous studies have largely focused on the palm's use in bioethanol (Irawan et al., 2016), handicrafts (Roswita et al., 2024), and material for traditional housing (Umar et al., 2017), with limited research investigating its structural potential in composite materials.

This study builds upon recent efforts to diversify the raw materials used in wood-based panel production by investigating the feasibility of employing *Nipah* palm in cross-laminated panel (CLP) configurations. Unlike conventional

CLT that relies on lumber-grade timber, the unique microstructure of *Nipah* palm, including its parenchyma-rich matrix, vascular bundles, and silica inclusions, requires tailored adhesive strategies and lamination parameters to achieve functional performance. Furthermore, the anatomical heterogeneity of the material may influence bond-line integrity, water-absorption behaviour, and dimensional stability.

The fabrication of *Nipah* palm into CLP structures supports circular bioeconomy objectives and holds potential to empower rural communities through localised material sourcing and value-added processing. Looking at the materials science standpoint, characterising the physical and microstructural properties of *Nipah* palm-based CLP is essential to understand its performance metrics under standardised testing protocols. Key parameters for CLP include density, moisture content, water absorption, and thickness swelling.

Given the growing global emphasis on climate-resilient infrastructure and resource-efficient construction methods, this study addresses a significant knowledge gap by systematically evaluating the suitability of the *Nipah* palm as a raw material for engineered structural applications. These findings can support the advancement of applied and fundamental understanding of tropical biomass utilisation in the context of panel technologies.

Ultimately, this study aligns with international sustainability frameworks, such as the United Nations Sustainable Development Goals (SDG 9: Industry, Innovation, and Infrastructure; and SDG 12: Responsible Consumption and Production), by promoting innovation in bio-based construction materials. This exploration into *Nipah* palm-based CLP thus offers a pioneering step toward diversifying the material palette of engineered timber, particularly in equatorial regions where traditional wood sources are increasingly scarce.

2. LITERATURE REVIEW

The CLT has gained recognition as a structural material for sustainable construction due to superior properties such as strength, stability, and environmental performance. The application of non-traditional biomass such as *N. fruticans* presents new opportunities and challenges in engineered CLT panels. Thus, a thorough understanding of the physical properties and internal structure of this material is critical to ensure optimal utility of this material. Several studies have explored the physical and mechanical characteristics of CLT using conventional and unconventional wood species. For example, Hariz et al. (2023) examined panels composed of *Acacia mangium* and *Schima wallichii* using polyurethane adhesive and revealed that the hybrid panels achieved comparable mechanical performance to monolithic types. Similarly, de Matos et al. (2019) demonstrated that the choice of adhesive and lamella structure significantly influenced mechanical performance in panels constructed from *Schizolobium parahyba* and *Pinus oocarpa*. These studies underscored the need to customise adhesive compatibility and structural composition to match the intrinsic properties of different wood species, particularly for lesser-known palms such as *N. fruticans*.

The physical performance of CLT panels, including density, moisture absorption, and dimensional stability, is closely tied to the moisture transport mechanisms within the wood matrix. Chiniforush et al. (2022) evaluated the moisture-induced strain behaviour in spruce-based CLT panels and emphasised the differential thermal and moisture expansion coefficients between layers. Similarly, Afshari and Malek (2022) implemented finite element models to describe transient moisture behaviour in laminated composites, highlighting the impact of adhesive characteristics and wood properties on water diffusion. These findings are relevant for *Nipah* palm, which is likely to exhibit anisotropic moisture responses due to its vascular bundle-rich and fibrous structure. Furtini et al. (2021) also reported distinct water absorption behaviour in CLT from coffee wood waste, reinforcing the influence of raw material selection on panel durability under environmental exposure.

Numerical modelling has emerged as a critical tool in predicting CLT performance. Teixeira et al. (2024) validated the use of finite element modelling (FEM) for *Eucalyptus benthamii* panels that replicated physical testing outcomes for bending and shear behaviour. Subsequently, Grant et al. (2024) advanced this approach by generating a CLT virtual mesh using image-based algorithms to simulate growth ring orientation and simulate stress, strain, and moisture diffusion in a spatially realistic way. These simulation tools are valuable for non-conventional materials such as *Nipah* palm, where experimental data may be sparse and anatomical irregularities, such as varying vascular bundle density, require high-resolution modelling. Dobeš et al. (2023) also demonstrated that FEM could effectively align with laboratory bending results across multiple software platforms, further validating numerical techniques as supportive of experimental design.

Adhesive bonding quality is another fundamental parameter in CLT studies. Cristescu et al. (2015) demonstrated that pressing conditions, particularly temperature, significantly impacted the bond strength, water resistance, and dimensional behaviour of self-bonded laminated beech panels. This finding indicated that higher pressing temperatures increased density and improved performance metrics, which have direct implications for species such as Nipah palm that may require unconventional bonding conditions due to high silica content or cellular irregularity. Likewise, (Hariz et al., 2023) emphasised that bonding effectiveness with polyurethane adhesives could vary significantly across wood types, affecting wettability and modulus values. This concern is echoed by de Matos et al. (2019), who observed variations in glue line shear strength due to adhesive interaction with different anatomical structures, reinforcing the need to optimise glue line design in Nipah-based CLT applications.

Other studies have explored hybrid or waste-wood CLT designs as part of sustainability-driven innovation. Furtini et al. (2021) evaluated CLT panels composed of *Pinus oocarpa* and *Coffea arabica* residues. They found no delamination, suggesting successful adhesive penetration and bond integrity despite the heterogeneous origin of the materials. These panels demonstrated high modulus of elasticity and acoustic and thermal performance consistent with building standards. Such findings encourage exploration into species such as the Nipah palm, particularly when sustainably sourced and potentially combined with other local materials. These approaches align with circular economy principles and extend the usable raw material pool for structural applications.

3. MATERIALS AND METHODS

3.1. Study Area

The CLP in this study was fabricated using two primary components: *Nipah* palm as the main raw material and bio-epoxy resin as the adhesive. The *Nipah* palm was sourced from Maludam, Sarawak. The epoxy resin, procured from a local supplier, was utilised in the as-received condition without any purification or modification.

3.2. CLP Fabrication

The fabrication process involved layering *Nipah* palm long fibres (80 wt%) with an aqueous epoxy resin solution (20 wt%). The resin-to-hardener ratio was maintained at 3:1 by weight to facilitate optimal curing kinetics (see Figure 1). The target density for the composite board was designed at three different densities (400, 600, and 800 g/m^3) for performance comparisons. The prepared mixture was evenly distributed into a steel mould with internal dimensions of 320 x 320 x 25 mm. Subsequently, a releasing agent and baking paper were placed within the mould to aid in demoulding and prevent surface defects. Hot pressing was carried out at a pressure of 7 MPa for 15 minutes at 100 ºC to achieve effective consolidation and curing of the material. Figure 2 illustrates the fabricated CLP manufacturers in this study.

Following the hot-pressing process, the composite boards were demoulded and subsequently cut into standardised test specimens in accordance with the Japanese Industrial Standards (JIS) and American Society for Testing and Materials (ASTM).

Figure 1: Adhesive coating process on the Nipah palm long fibres

Figure 2: The CLP fabricated from Nipah Palm

3.3. Physical Test

The physical performance of the fabricated CLP was evaluated through a series of standardised tests. First, density testing was carried out according to the JIS A 5908: 2003 (JIS, 2003). The specimens were cut into small cubes (5 cm x 5 cm x 0.48 cm) and placed in an oven at 105 °C ± 2 for 24 hours or until the weight became constant. Subsequently, the specimens were placed in a desiccator for 15 minutes and weighed. These steps were repeated until a constant weight was obtained. The density was calculated as follows:

$$Density\ (g/cm^3 = \frac{Ovendry\ weight\ of\ specimen\ (g)}{Volume\ of\ the\ sample\ (cm^3)}$$

Moisture content testing was conducted in accordance with JIS A 5908:2003 (JIS, 2003). The weight of each test piece was measured after drying at 103 ± 2 °C until a consistent weight was achieved. Weight loss was then calculated as a percentage of the initial weight of the test pieces. The moisture content (MC) was calculated using the following equation.

$$Moisture\ content\ (\%) = \frac{Initial\ weight\ of\ sample\ (g)\ -\ Oven - dry\ weight\ of\ sample\ (g)}{Oven - dry\ weight\ of\ sample\ (g)}$$

Thickness swelling tests were performed according to the JIS A 5908: 2003 (JIS, 2003). The thickness of the samples (Dimensions: 50 mm x 50 mm x 10 mm) was measured using a digital micrometer (Mitutoyo). Subsequently, the samples were immersed in water horizontally, approximately 3 cm below the water surface, for 24 hours before being remeasured with modification. The thickness swelling was calculated as follows:

$$Thickness\ swelling\ (\%) = \frac{Final\ weight\ of\ sample\ (g)\ -\ Initial\ weight\ \ of\ sample\ (g)}{Initial\ weight\ of\ sample\ (g)}$$

A water absorption test was carried out to determine the CLP dimensional stability. The test was carried out according to the JIS A 5908:2003 (JIS, 2003). Water absorption of the board was measured using the following equation:

$$Water\ absorption\ (\%) = \frac{Final\ thickness\ of\ sample\ (mm)\ -\ Initial\ \ thickness\ of\ sample\ (mm)}{Initial\ thickness\ of\ sample\ (g)}$$

4. RESULTS AND DISCUSSION

4.1. Moisture Content

The moisture content of *Nipah* palm CLP is presented in Table 1 and Figure 3. The analysis highlights the influence of density (400, 600, and 800 kg/m^3) on the moisture content of the samples. The moisture content of *N. fruticans* CLPs was evaluated across three target densities, which are 400, 600, and 800 kg/m^3. The results indicated a clear inverse relationship between panel density and moisture content (see Table 1). As the density increased, the average moisture content decreased.

At a density of 400 kg/m^3, the panel exhibited the highest moisture content at 15.84% with a very low standard deviation (±0.08%), indicating consistent moisture distribution across specimens. Nevertheless, this value exceeded the maximum allowable limit of 13% specified in JIS A 5908:2003, suggesting non-compliance with industry standards. In contrast, panels fabricated at 600 kg/m^3 and 800 kg/m^3 recorded average moisture contents of 13.80 ± 1.36% and 13.65 ± 0.44%, respectively. Despite the improvements, these values exceeded the threshold set by the JIS standard.

The reduction in moisture content with increasing density may be attributed to enhanced compaction of the lignocellulosic matrix during the hot-pressing process (Oliaei et al., 2021). Higher-density panels typically contain fewer voids and less interstitial space, limiting moisture retention capacity (Mehrvan et al., 2024). Furthermore, increased densification may lead to more uniform adhesive distribution, improving the sealing effect and reducing the ability of the material to absorb ambient humidity (Yu et al., 2020).

Table 1: Moisture Content of CLP based on density

Density (kg/m^3)	Moisture content (%)	Standard deviation
400	15.84	0.08
600	13.80	1.36
800	13.65	0.44

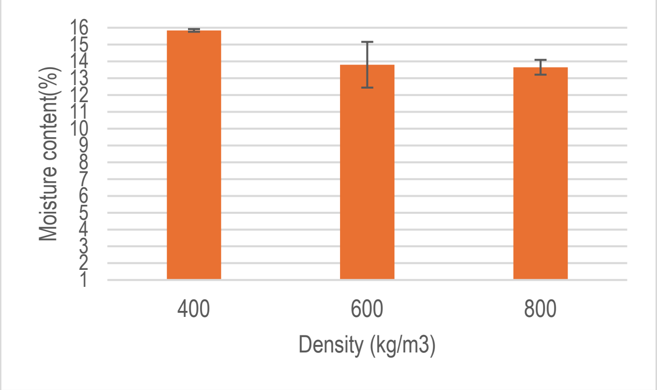

Figure 3: Moisture content of CLP according to density

Despite the improvements at higher densities, none of the tested specimens met the JIS A 5908:2003 requirement. The slightly exceeded values in moisture content at 600 and 800 kg/m^3 densities may be addressed by optimising drying conditions before pressing or modifying pressing parameters such as temperature, duration, or pressure. The low standard deviation at 800 kg/m^3 suggested better process control and more consistent material performance at this density level, indicating the potential for industrial application with minor process refinement.

4.2 Thickness Swelling

The thickness swelling of CLP produced from *Nipah* palm is presented in Table 2 and Figure 4. The analysis highlighted the influence of density (400, 600, and 800 kg/m^3) on the thickness swelling of the samples.

Table 2: Thickness Swelling of CLP based on density

Density (kg/m^3)	Thickness swelling (%)	Standard deviation
400	10.00	0.73
600	8.34	0.37
800	8.00	0.36

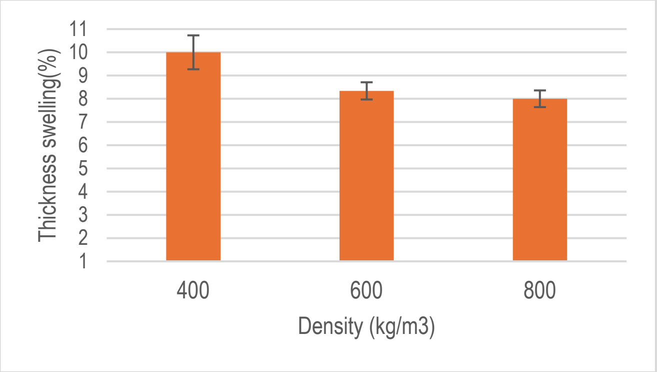

Figure 4: Thickness swelling of CLP according to density

Table 2 demonstrates a clear trend of decreasing thickness swelling with increasing panel density. At the lowest density (400 kg/m³), the average thickness swelling was 10.00 ± 0.73%. While being the highest among the three density levels, the value fell within the acceptable limit of 12% as prescribed by JIS A 5908:2003. Panels with higher densities exhibited superior performance, with the 600 kg/m³ and 800 kg/m³ groups demonstrating reduced swelling of 8.34% ± 0.37% and 8.00 ± 0.36%, respectively. These findings confirmed that all panels across the tested density range complied with the standard, indicating satisfactory dimensional stability under moisture exposure.

The inverse correlation between density and thickness swelling may be attributed to the enhanced compaction and reduced void volume in higher-density panels, which limits water penetration and fibre expansion (Lube, 2016). Increased densification likely improves the integrity of the adhesive bonding and minimizes interfacial gaps, thereby reducing water absorption pathways. Furthermore, the lower standard deviations observed at higher densities suggested more uniform material performance, indicating better process control and structural consistency.

4.3 Water Absorption

The water absorption of *Nipah* palm CLP is detailed in Table 2 and Figure 5. The analysis highlighted the influence of density (400, 600, and 800 kg/m³) on the water absorption of the samples.

Table 3: Water absorption of CLP based on density

Density (kg/m³)	Water absorption (%)	Standard deviation
400	70.42	3.17
600	67.49	1.42
800	56.02	1.07

Table 3 demonstrates a clear decreasing trend in water absorption with increasing panel density, indicating that densification is crucial for moisture resistance in laminated bio-based composites. At a density of 400 kg/m³, the CLP exhibited the highest average water absorption, measuring 70.42 ± 3.17%. As the density increased to 600 kg/m³, water absorption decreased to 67.49 ± 1.42% and further declined to 56.02 ±1.07% at 800 kg/m³. These results suggested that higher-density panels exhibited improved dimensional stability when exposed to moisture, which can be attributed to enhanced fibre compaction, reduced porosity, and better adhesive bonding that collectively restricted capillary pathways for water ingress (Mohammed, 2022).

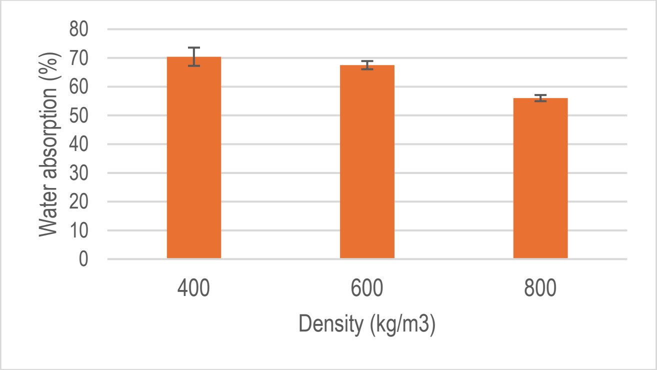

Figure 5: Water absorption of CLP according to density

The JIS A 5908:2003 standard does not specify explicit limits for water absorption. Nonetheless, water absorption is a critical indicator of panel durability, particularly in humid or wet conditions, which may compromise structural integrity. The relatively high absorption values across all densities reflected the inherently hygroscopic nature of *N. fruticans*, which possesses vascular bundles and parenchymatous tissue that tend to facilitate water uptake, as other palm-based lignocellulosic materials (Chand & Fahim, 2020).

4.4 Statistical Analysis

4.4.1 Moisture Content

Table 4 presents the analysis of variance (ANOVA) performed on the moisture content of the *Nipah* palm CLP at different densities.

Table 4: ANOVA of the moisture content in *Nipah* palm CLP with different densities

		Sum of square	df	Mean square	F	Sig.
Moisture content	Between groups	17.960	2	8.980	13.055	< 0.001
	Within groups	10.318	15	.688		
	Total	28.278	17			

Based on Table 4, there was a statistically significant effect in the moisture content (F = 13.055, p < 0.001) between different CLP densities. This finding indicated that variations in density contributed substantially to differences in moisture content of the panels, which supported earlier observations that higher-density panels exhibit lower moisture content. This outcome can be attributed to the improved compaction and reduced internal voids, which limit the hygroscopic response of the material.

Table 5 demonstrates the Duncan-post hoc for moisture content. The results indicated that the 800 kg/m³ and 600 kg/m³ groups were not statistically different (Sig. = 0.758), with mean values of 13.65% and 13.80%, respectively. Thus, these groups belong to the same homogeneous subset (Subset 1). Increased density did not result in a statistically meaningful change in moisture content. In contrast, the 400 kg/m³ group formed a separate subset (Subset 2) with a significantly higher mean moisture content (15.84%). This outcome suggested that lower-density panels exhibit greater moisture retention.

Table 5: Duncan post hoc test for the moisture content

Density	N	Subset for alpha = 0.05	
		1	2
800.00	6	13.6450	
600.00	6	13.7950	
400.00	6		15.8350
Sig.		.758	1.000

Means for groups in homogeneous subsets are displayed a. Uses harmonic mean sample size = 6.000.

4.4.2 Thickness Swelling

Table 6 demonstrates the ANOVA results on the effect of different densities on the thickness swelling of *Nipah* palm CLP. Moisture content demonstrated a similar trend with thickness swelling, where the influence of density was found to be highly significant (F = 25.687, $p < 0.001$). The mean square value between groups (6.884) was markedly higher than the within-group mean square (0.268), indicating that changes in density significantly impacted the CLP dimensional stability when exposed to moisture. The results suggested that higher-density panels were more resistant to thickness swelling, potentially due to stronger inter-fibre bonding and reduced absorption and water retention of the laminated structure.

Table 6: ANOVA of the thickness swelling in *Nipah* palm CLP with different densities

		Sum of square	df	Mean square	F	Sig.
Thickness swelling	Between groups	13.769	2	6.884	25.687	< 0.001
	Within groups	4.020	15	.268		
	Total	17.789	17			

Table 7 details the Duncan post hoc test thickness swelling. The CLPs with higher densities (800 kg/m³ and 600 kg/m³) were not significantly different (Sig. = 0.280) in thickness swelling, thus grouped within Subset 1 with mean swelling values of 8.00% and 8.34%, respectively. Meanwhile, the 400 kg/m³ CLP was assigned to a separate subset (Subset 2), with a higher swelling mean of 10.00%. The contrast between 400 kg/m³ and the other groups indicated that higher-density panels provide better resistance to dimensional deformation upon moisture exposure. This outcome supported that densification enhances the structural rigidity and stability of the *N. fruticans*-based CLP, which may be attributed to the reduced internal voids and stronger adhesive bonding.

Table 7: Duncan post hoc test for the thickness swelling

Density	N	Subset for alpha = 0.05	
		1	2
800.00	6	8.0000	
600.00	6	8.3350	
400.00	6		10.0000
Sig.		.280	1.000

Means for groups in homogeneous subsets are displayed a. Uses harmonic mean sample size = 6.000.

4.4.3 Water Absorption

Table 8 presents the ANOVA on the effect of different densities on the water absorption of *Nipah* palm CLP. The most pronounced statistical difference among the three parameters was observed in water absorption, with an F-value of 78.788 and a p-value below 0.001. The between-group variation (sum of squares = 694.494) accounted for most of the total variance (760.605), confirming that density significantly influenced water absorption behaviour. Lower water absorption in higher-density panels may be attributed to reduced porosity, greater adhesive coverage, and increased resistance to capillary transport. This outcome aligns with previously discussed findings, indicating superior water resistance at a density of 800 kg/m³.

Table 8: ANOVA of water absorption in Nipah Palm CLP with different densities

		Sum of square	df	Mean square	F	Sig.
Moisture content	Between groups	694.494	2	8.980	78.788	<.001
	Within groups	66.111	15	4.407		
	Total	760.605	17			

Table 8 demonstrates the Duncan post hoc test for water absorption of *Nipah* palm CLP at different densities. The results exhibited the most distinct stratification among density levels. Each density fell into a separate homogeneous subset (Subsets 1, 2, and 3, respectively), with no statistical overlap. The mean water absorption values were 56.02% for 800 kg/m³, 67.49% for 600 kg/m³, and 70.42% for 400 kg/m³. The statistically significant differences between all groups (Sig. = 1.000 for each subset) confirmed that water absorption behaviour is highly sensitive to changes in panel density. The substantial reduction in water uptake at higher densities reinforces the effectiveness of densification in limiting fluid ingress, potentially due to enhanced fibre compaction and adhesive coverage that reduce capillary pathways.

Table 8: ANOVA of water absorption in *Nipah* palm CLP with different densities

Density	N	Subset for alpha = 0.05		
		1	2	3
800.00	6	56.0200		
600.00	6		67.4850	
400.00	6			70.4150
Sig.		1.000	1.000	1.000

Means for groups in homogeneous subsets are displayed a. Uses harmonic mean sample size = 6.000

5. CONCLUSION

This study investigated the feasibility and performance of *N. fruticans* CLP, focusing on the physical properties and microstructural characteristics across three different density levels: 400, 600, and 800 kg/m³. The analysis revealed that panel density had a statistically significant effect on all evaluated physical parameters, including moisture content, thickness swelling, and water absorption.

Moisture content decreased with increasing panel density, with the 800 kg/m³ CLP exhibiting the lowest average value. Nonetheless, all panels slightly exceeded the 13% limit prescribed by JIS A 5908:2003, indicating the need for further optimisation of pre-processing or drying techniques. Thickness swelling followed a similar pattern, with higher-density panels demonstrating improved dimensional stability under moisture exposure. All values remained within the JIS threshold of 12%, affirming the suitability of these CLPs for structural applications. Meanwhile, water absorption exhibited the most distinct stratification among densities, with the 800 kg/m³ group achieving the most favourable performance. This outcome is likely due to improved compaction and reduced porosity that limited moisture ingress. Duncan's post-hoc tests confirmed that the 800 kg/m³ panels consistently outperformed those at lower densities, with significant differences particularly evident in water absorption.

In conclusion, the findings demonstrated that *N. fruticans* possesses viable potential as a raw material for engineered CLP products. Panels fabricated at 800 kg/m³ demonstrated the most promising results in physical performance and structural consistency, suggesting that high-density configurations are preferable for applications requiring enhanced moisture resistance and dimensional stability. These results contribute to the growing body of knowledge on sustainable tropical biomaterials and highlight the importance of density optimisation in the development of non-traditional lignocellulosic composite panels. Further research may explore mechanical properties and durability performance under accelerated ageing to fully validate the structural application potential of *N. fruticans*-based CLP.

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