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Partial replacement of tannin with nanolignin in adhesive formulations for bonding plywood produced with *Erythrina poeppigiana* wood

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TECHNOLOGY OF FOREST PRODUCTS

ABSTRACT

Background: Fast-growing species are crucial for the wood panel market, and *Erythrina poeppigiana* (mulungu) emerges as a promising alternative. Although its wood is not suitable for high-performance applications, using its veneers for plywood supports the diversification of raw materials in forestry. Furthermore, replacing petrochemical-based adhesives is essential due to associated health and environmental risks. Tannins from forest species provide a sustainable alternative; however, their mechanical strength and moisture resistance must be improved. Nanolignin, a nanoscale additive, enhances these properties, making it a viable option for biodegradable adhesives. This study evaluates plywood production using *E. poeppigiana* veneers bonded with a tannin–nanolignin adhesive.

Results: Adhesives were formulated with Acacia mearnsii* tannin partially replaced by nanolignin at different concentrations and tested for rheological properties. The wood, sourced from experimental plantations in Ilhéus, Bahia (Brazil), was processed into five-layer plywood panels bonded with 320 g/m^2 of natural adhesive and pressed at 150 °C and 1 MPa for 10 minutes. The resulting panels were evaluated for physical and mechanical properties, contact angle, scanning electron microscopy (SEM), acoustic insulation, and thermal conductivity. The results confirmed *E. poeppigiana* as a viable raw material for plywood production. Partial replacement of tannin with 1–2% nanolignin reduced adhesive viscosity, improving application and veneer penetration. The 2% nanolignin formulation increased hydrophobicity, reducing water absorption, while shear strength tests revealed higher cohesion and adhesion, particularly in adhesives containing 2–3% nanolignin.

Conclusions: The findings demonstrate that *E. poeppigiana* veneers bonded with tannin–nanolignin adhesives can produce plywood panels with suitable physical and mechanical performance. The incorporation of small amounts of nanolignin enhances the adhesive's rheological and bonding characteristics, contributing to improved durability and water resistance. These results support the potential use of *E. poeppigian* and nanolignin-modified tannins as sustainable materials in eco-friendly plywood manufacturing.

Keywords: Alternative raw material; Environmentally friendly production; Natural adhesives.

HIGHLIGHTS

Erythrina poeppigiana veneers are a viable and sustainable alternative for plywood production, achieving densities between 0.39 and 0.49 g/cm^3
The addition of 2% nanolignin to tannin adhesives reduced viscosity from 197.56 to 124.07 cP and increased contact angle to 74.3°, enhancing adhesive spreadability and veneer penetration
Panels bonded with 2% nanolignin adhesive showed the lowest water absorption (43% after 24 h) and the highest hydrophobicity among treatments
Shear strength increased with nanolignin addition, reaching 3.2 MPa in the 3% nanolignin treatment, surpassing the 2.3 MPa of the control.

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INTRODUCTION

Between 2020 and 2021, during and after the COVID-19 pandemic, the wood panel industry experienced a significant boost in production, with a recorded growth of 14.6% in 2021, according to the annual report from the Brazilian Tree Industry (Indústria Brasileira de Árvores – IBÁ, 2022). In this context, the increased difficulty in accessing raw materials has contributed to higher production costs, reinforcing the need not only to expand plantations of traditional forest species but also to explore alternative lignocellulosic raw materials (Faria et al., 2021).

Fast-growing species are essential to meet the growing demand for wood panels, with *Erythrina poeppigiana* (commonly known as mulungu) standing out as a promising example. This species, from the Fabaceae family, is frequently used in agroforestry systems in association with *Theobroma cacao*. However, the intense shading provided by *Erythrina poeppigiana* can negatively affect the productivity of cocoa trees, particularly disease-resistant clones (Marques and Monteiro, 2016). In response to this issue, the government of Bahia (Brazil) enacted Decree SEMA/INEMA (Instituto do Meio Ambiente e Recursos Hídricos, 2019). No. 3 on April 16, 2019, which allows the removal of non-native trees from the Atlantic Forest without prior authorization. Given its limited use for solid wood products, utilizing *E. poeppigiana veneers* for plywood production presents a sustainable solution, contributing to both forest resource diversification and waste reduction.

In parallel with the need to diversify raw materials, there is increasing interest in developing safer and more sustainable alternatives to conventional petrochemical-based adhesives currently used in wood panel manufacturing. These synthetic adhesives, such as phenol-formaldehyde (PF), urea-formaldehyde (UF), and melamine-formaldehyde (MF), pose health and environmental risks due to their formaldehyde emissions (Kumar and Leggate, 2022). Formaldehyde, classified as a human carcinogen since 2011 by the National Cancer Institute, can continue to be released for years after panel fabrication. This scenario has encouraged research into bio-based adhesives derived from renewable sources, with the global bioadhesive market projected to reach nearly 5 billion dollars by 2027 (Raj et al., 2025).

One promising option is polyphenols extracted from the bark of forest species, known as tannins (da Silva Araujo et al. 2021; Oktay et al. 2024; Zidanes et al. 2024). Found mainly in tree bark, their extraction allows sustainable use of a non-timber product and forest conservation (Tahir et al., 2019; Das et al., 2020). With a phenolic structure similar to phenol, tannins react quickly and effectively with formaldehyde, requiring less than 10% of the formaldehyde amount compared to conventional synthetic adhesives (Shirmohammadli et al., 2018).

In comparison with synthetic adhesives, tannin adhesives have lower moisture resistance and mechanical strength and need to be modified for widespread use in wood products to be competitive in the market (Putri et al., 2024). One solution is the addition of nanoscale additives (Jeevanandam et al., 2022; Chen et al., 2019). Due to its abundance and phenolic nature, lignin is a promising additive for biodegradable adhesives (Younesi-Kordkheili, 2024; Tong et al., 2024). In recent years, there has been a growing interest in nanolignins and it has been shown in recent publications that nano-sized lignin has many interesting properties, which pave the way for a wide range of possible applications (Beisl et al., 2017).

Due to its functional groups, such as aliphatic hydroxyl, phenolic hydroxyl and carbonyl groups, nanolignin can react in the synthesis of adhesives, helping to reduce formaldehyde emissions (Wang et al., 2012). Studies such as those by Wang et al. (2012) and Younesi-Kordkheili et al. (2024) found that the addition of nanolignin to UF adhesive resulted in positive effects, such as increased gel time, increased viscosity and solids content of the adhesive, reduced curing temperature, improved mechanical strength and dimensional stability. It is therefore hoped that the addition of nanolignin to the tannin-based adhesive will improve cohesion and adhesion to help increase panel strength.

Given this, this study aims to verify the feasibility of producing plywood panels using *Erythrina poeppigiana* veneers glued with a natural tannin-based adhesive with added nanolignin. The influence of different concentrations of nanolignin, as a substitute for the tannin adhesive, on the physical, mechanical, thermal and acoustic properties of the plywood panels will also be investigated.

MATERIAL AND METHODS

Materials collection and characterization

The wood of *Erythrina poeppigiana*, approximately 5 years old, was obtained from experimental plantations located in the city of Ilhéus – Bahia (Brazil). Two logs of 4 meters in length were sectioned into billets of 58 cm in length and heated to 70 °C for 24 hours in a water tank (Iwakiri and Trianoski, 2020). After heating, the material was laminated using a rotary veneer lathe. Veneers of 2 mm thickness were obtained and then dried in ovens at 70 ± 2 °C until a moisture content of 3% (dry basis) was reached.

The wood of *Erythrina poeppigiana* was physically and chemically characterized according to the standards described in Table 1 and performed in triplicate. For these analyses, veneers were used for particle production. The particles that passed through the 12 mesh screen (1.68 mm) and were retained on the 20 mesh screen (0.84 mm) were selected. Following size classification, the material was oven dried at 70 ± 2 ºC until reaching a moisture content of 5% on a dry basis.

Production and characterization of the adhesives

Commercial tannins from the species *Acacia mearnsii*, obtained from a company in Montenegro, Rio Grande do Sul (Brazil), with a Stiasny Index (SI) value of 85.6%, were used to bond the plywood panels.

Table 1: Analyses performed for the physical and chemical characterization of *Erythrina poeppigiana* wood.

Analyses	Standards
Bulk density	NBR 11941 (ABNT, 2003)
Total Extractives (TE)	NBR 14853 (ABNT, 2010)
Lignin (L)	NBR 7989 (ABNT, 2010)
Ash Content (AC)	NBR 13999 (ABNT, 2017)
Holocellulose	100 – (*L* + *TE* + *AC*)

The commercial lignin was donated by a company in São Paulo (Brazil). For the production of nanolignin, a ratio of 10% (w/w) of lignin to water was used. The lignin was mechanically fibrillated using a Supermass Colloid Grinder MKCA6-2 (Masuko Sangyo, Japan) equipped with two stone disks MKCA6-80 (Masuko Sangyo, Japan) at 1500 rpm, with 10 cycles through the equipment.

The crosslinking agent paraformaldehyde was used to control the reactivity between tannin and formaldehyde. The adhesives produced followed a standard concentration of 60% water to 40% solids (35% tannins and 5% paraformaldehyde). The treatments were divided into tannin-formaldehyde (TF) and tannin-formaldehyde with the addition of lignin nanoparticles at concentrations of 1, 2, and 3% (TF1, TF2 and TF3, respectively). The experimental design of the study is shown in Table 2.

Table 2: Experimental design.

Treatments	Concentration		
	Tannis (%)	Nanolignin (%)	PF (%)
TF	35	-	5
TF1	34	1	5
TF2	33	2	5
TF3	32	3	5

TF: tannin-formaldehyde; TF1: tannin-formaldehyde with 1% nanolignin; TF2: tannin-formaldehyde with 2% nanolignin; TF3: tannin-formaldehyde with 3% nanolignin; PF: paraformaldehyde.

To determine the rheological properties of the adhesives, pH, solids content, gel time, and viscosity were evaluated. The pH was determined using a pH meter. The solid content was determined according to ASTM D 1490-01 (ASTM, 2013). The gel time was evaluated according to Almeida et al. (2010). Adhesive viscosities were measured at 25°C using a DV-E viscometer spindle LV 64 (AMETEK Brookfield, USA). Tests were performed in triplicate.

Contact Angle

Contact angle measurements on the longitudinal surface of the *Erythrina poeppigiana* veneers were performed using the sessile drop method with the DSA25 instrument and DSA3 *software* (Krüss GmbH, Germany).

In this test, all produced adhesives were tested (Table 2). The adhesives were applied to the surface of the veneers to calculate the average contact angle between the adhesive drop and the veneer surface after 5 seconds. For each treatment, 25 contact angle measurements were taken, with a total of 100 measurements.

Plywood Production

Five *Erythrina poeppigiana* veneers were used to produce the panel. Ten plywood panels with dimensions of 30x30 cm were produced, with an adhesive application rate of 320 g/m^2 per glue line and a pressing cycle of 1.0 MPa for 10 min at 150°C using a hydraulic press. After pressing, the panels were acclimated at 20 ± 2 °C and 65 ± 5% relative humidity for 7 days until the test specimens were removed.

Tests were performed for apparent density; moisture content on a dry basis; water absorption after 2 and 24 hours of immersion in water according to NBR 9486 (ABNT 2011); dry shear strength EN-314 (European Committee for standardization, 1993b); and Flexural strength including determination of modulus of elasticity and modulus of rupture (MOE and MOR) EN-310 (European Committee for standardization, 1993a). All these tests were conducted with 10 specimens and 5 values were used for statistical analyses.

Scanning Electron Microscopy (SEM)

After the shear test, the specimens were reduced to 6 mm in diameter and 3 mm in thickness and analyzed by scanning electron microscopy (SEM). The samples were coated with a thin layer of gold in an evaporator and analyzed using a CLARA model scanning electron microscope (TESCAN, Czech Republic) operated at 20 kV.

Acoustic Insulation

To evaluate acoustic insulation, the methodology described by Arantes et al. (2023) was used and performed in triplicate. A microcomputer, two speakers (50 W RMS with a frequency response of 22 Hz to 30,000 Hz), and a sound level meter were employed. The speaker was connected to the audio output of the microcomputer and placed inside the wooden panel box, allowing the sound to be transmitted either through the composite material (test condition) or through an open space without the material (control condition). All transmitted noise was measured by the sound level meter, following the recommendations of NBR 12179 (ABNT, 1992) and ISO 10534-2:1998 (ISO, 2010).

Thermal Conductivity

To evaluate the thermal insulation of the panels, the method proposed by Mendes et al. (2021) was followed. A thermal actuator was positioned at the bottom of the panel, maintaining a constant temperature of approximately 60 ºC. Sensors recorded the temperatures throughout the test.

The heating rate was set at 1 ºC/min, with a 1-hour cycle. The data were collected using a data collector, model IM DC 100-01E (manufacturer not specified). The thermal insulation results of the material were determined by the temperature difference between the thermocouples positioned at the base and the top of the panel. The thermal conductivity values were obtained according to NBR 15220 (ABNT, 2005) and performed in triplicate.

Statistical Analyses

Experimental data for the adhesive's properties, the contact angle of the adhesives, as well as the physical, mechanical, and thermal properties of plywood panels, were subjected to statistical analyses. The normality of the data was verified using the Shapiro-Wilk test. Once normal distribution was confirmed, analyses of variance (ANOVA) were performed to determine the significance of differences among treatments. When significant effects were identified ($p \leq 0.05$), means were compared using the Tukey test at a 5% probability level. These analyses were conducted using R Studio software (Posit PBC, United States).

RESULTS AND DISCUSSIONS

Chemical composition of wood

The chemical analysis values of *Erythrina poeppigiana* wood are presented in Table 3. The percentage of total extractives was higher than reported by Furtini et al. (2022), who obtained an average content of 6.18% for *Pinus oocarpa* wood, the species widely used for panel production worldwide (Herrera-Builes et al., 2021). Brito et al. (2021) investigated the same species and obtained an average content of 6.34%. Although values above 10% are generally considered detrimental to adhesive bonding due to surface interference and potential panel delamination during hot pressing (Iwakiri and Trianoski, 2020; Gorski, 2014), the extractives content observed in *Erythrina poeppigiana* wood remains within an acceptable range for industrial applications.

Table 3: Chemical components *Erythrina poeppigiana* wood.

	Percentage (%)	Coefficient of variation (%)
Total extractives	8.49 ± 0.76	8.96
Lignin	26.92 ± 1.78	6.62
Hollocelulose	63.61 ± 2.39	3.76
Ash	0.98 ± 0.10	10.01

The lignin content was 26.92%, significantly lower than that of Pinus oocarpa wood, which typically contains around 29.20 and 29.28% (Furtini et al., 2021; Villarruel et al., 2023). Although lignin contributes to panel cohesion due to its hydrophobic and adhesive-enhancing properties (Ang et al., 2019), this moderately lower value does not necessarily compromise adhesive interaction.

The average ash content was higher than in the study by Matos et al. (2019), which found a content of 0.15% for *Pinus sp*. wood, and lower than in the study by Miranda et al. (2023), which found an average content of 1.20% for *Pinus sp*. wood. High concentrations of ash can block reactive adhesion sites, affecting the quality of the bond and the mechanical performance of the panel (Ndazi et al., 2007).

Regarding holocellulose, the value in the present study was relatively the same as Santos et al. (2022), who obtained a content of 63.29% for *Pinus sp*. wood. These values may increase the water affinity or block reactive adhesion sites, affecting the quality of the bond and the mechanical performance of the panel (Soares et al., 2017).

Characterization of adhesives

The solid content levels (Table 4) reached the levels required by the industry for panel production, which requires a solid content of adhesives equal to or greater than 40%, considered sufficient to ensure the quality of the adhesive (Pizzi and Mittal, 1994). The maintenance of the solid content levels even after the substitution of tannin with nanolignin is crucial for the application of the nanostructure in tannic adhesives, demonstrating its ability to maintain the solid content compared to the control adhesive (Zidanes et al., 2024).

The addition of nanolignin reduced the gel time of the adhesives (Table 4), which can be explained by the reduced reaction rate between tannin and formaldehyde. Superior results were found for tannic adhesives from *Stryphnodendron adstringens* reinforced with cellulose nanofibrils (Zidanes et al., 2024) and inferior results for the unreinforced amazonian species *Myrcia eximia* (Araújo et al., 2021). Gel time is a fundamental parameter in the adhesive industry, as it indicates the time required for the adhesive to complete the curing process (Kumar and Leggate, 2022). Therefore, an ideal adhesive for production should have a cure time that is fast enough to optimize efficiency but not so fast as to interfere with the application of the adhesive to the wood piece (Pizzi and Mittal, 1994).

Table 4: Adhesives properties.

Adhesives	SC* (%)	Viscosity (cP)	Gel time (s)	pH
TF	44.02A ± 1.22	197.56A ± 8.68	64A ± 1.67	4.59A ± 0.08
TF1	42.03AB ± 0.55	120.08B ± 1.83	100B ± 1.33	4.70AB ± 0.09
TF2	40.17B ± 0.70	124.07B ± 1.42	87C ± 1.19	5.00C ± 0.10
TF3	41.74AB ± 0.42	272.63C ± 1.84	84C ±1.03	4.97 BC ± 0.09

*SC: solid content. Means followed by the same letter in the column do not differ at 5% probability.

It was observed that the viscosity values (Table 4) were low for all treatments, possibly due to the lower molecular weight of nanolignin compared to the tannin (Huang et al., 2022). In comparison, commonly used synthetic adhesives have viscosity values of 400-1000 cP for UF and 300-600 cP for FF, values that exceed those recorded in this research for tannic adhesives. A factor limiting the use of tannin extract as an adhesive is its high viscosity, mainly due to the presence of the ether ring in the flavonoid structure, which imparts hydrophobicity, and the presence of high molecular weight hydrocolloid gums (Pizzi and Mittal, 1994). Viscosity values are essential in determining the quality of an adhesive. Highly viscous adhesives hinder penetration and workability in wood and tend to form a weak glue line. On the other hand, low-viscosity adhesives tend to penetrate the wood structure quickly, forming what can be called a "starved glue line".

Contact Angle

The highest contact angles were observed for adhesives with nanolignin additives (Table 5). Tannic adhesives contain water (60% water and 40% solids), which has a high-affinity hydrophilic surface such as wood veneers, resulting in lower contact angle values, as observed with the TF treatment. Lignin is an apolar macromolecule, and its addition may have decreased the polarity of the water present in the tannic adhesives, resulting in an increase in contact angle values due to reduced affinity with the wood veneers.

Table 5: Contact angle of adhesives with and without added nanolignin on *Erythrina poeppigiana* veneers.

Adhesives	Contact Angle (º)
TF	82.92A ± 4.27
TF1	95.53AB ± 4.15
TF2	116.32C ± 4.46
TF3	105.00BC ± 7.53

Means followed by the same letter in the column do not differ at 5% probability.

The contact angle is a key parameter to understanding wettability and adhesion to wood surfaces. When the contact angle is less than 90°, it indicates a good spread of the adhesive over the wood surface, which indicates effective adhesion. On the other hand, when the contact angle is greater than 90°, the liquid tends to form droplets, and its spreading is reduced, resulting in significantly weaker adhesion (Erbil, 2014; Schuster et al., 2018). Bianche et al. (2022) evaluated the contact angle of synthetic resorcinol-formaldehyde adhesives, which ranged from 76.40 to 64.90º for 10 to 120 seconds, respectively.

The contact angle is directly related to the viscosity of the adhesive. Low-viscosity liquids tend to spread more easily, resulting in a lower contact angle, while more viscous liquids can spread more slowly, leading to a higher contact angle (Albino et al., 2010; Bianche et al., 2022).

Physical characterization of plywood panels

The bulk density values exhibited a range of 0.39 to 0.49 g/cm³ across the treatments, with plywood containing 3% nanolignin having the lowest apparent density of all the treatments (Table 6). According to the NBR 9531 (2008), this range of density can be classified as low density compared to typical structural panels. The low density of *Erythrina* wood is advantageous, as it improves the conformability and workability of the panel (Iwakiri and Trianoski, 2020).

Table 6: Physical characteristics of plywood panels produced with *Erythrina poeppigiana* veneers and natural adhesives.

Treatments	Bulk density (g/cm³)	Moisture (%)
TF	0.49A	7.20AB
TF1	0.42AB	6.00A
TF2	0.41AB	7.55B
TF3	0.39B	6.7AB

Means followed by the same letter in the column do not differ at 5% probability.

In a recent study conducted by Farias et al. (2024), the sustainable use of *Erythrina poeppigiana* in the production of plywood bonded with phenol-formaldehyde (FF), urea-formaldehyde (UF), and castor oil-based polyurethane (PU) adhesives were evaluated. The panels exhibited densities between 0.42 and 0.45 g/cm³, which is comparable to the values observed in the present study.

The moisture content on a dry basis exhibited average values ranging from 6% to 7.55%, with statistically significant differences between treatments (Table 6). All treatments complied with the requirements of NBR 7190 (2022), maintaining moisture content below 12%. In a previous study, Ferreira et al. (2022) reported an average moisture content on a dry basis of 12.56% for *Pinus* sp. plywood panels.

It was observed that the panels produced with the TF3 adhesive exhibited greater water absorption after 2 and 24 hours of immersion compared to the other treatments (Figure 1), which is explained by the lower apparent density found for this treatment (Table 6). The TF2 treatment showed the lowest water absorption after 2 and 24 hours of immersion (Figure 1). With 2% nanolignin there was an increase in the adhesive's hydrophobicity (Table 5), which explains the lower water absorption for this treatment.

The water absorption results obtained in this study after a two-hour immersion period were lower than those reported by Macedo et al. (2019) and Campos et al. (2009). The former study reported a water absorption value of 65%, while the latter reported a value of 68%. In these studies, castor oil-based bicomponent polyurethane resin was employed for the fabrication of *Pinus* sp. plywood panels.

Mode et al. (2023) observed 24-hour water absorption values for plywood panels produced with *Pinus taeda* of 59.81%, *C. lusitanica* of 64.12%, and when mixing the two species (*P. taeda* x *C. lusitanica*) of 62.81%. These values were lower than those observed in the present study. In a similar study, Pinati et al. (2018) investigated the water absorption properties of plywood produced from the residues of *Pinus oocarpa*, *Castilla ulei*, and *Acrocarpus fraxinifolius* woods. They observed water absorption values of 67.77, 46.88, and 56.98%, respectively, which are comparable to the values observed in this study when analyzed at two hours.

Mechanical Properties

The average values obtained for the modulus of rupture (MOR) and modulus of elasticity (MOE) for the plywood panels are presented in Figure 2.

The data indicated that the inclusion of lignin nanoparticles did not result in a statistically significant difference in the mechanical properties of the plywood panels, as evidenced by the similarity in the mean values of the modulus of rupture (MOR) and the modulus of elasticity (MOE) in Figures 2a and 2b, respectively. Following NBR 31:000.05-001/2 (ABNT, 2001), the minimum requisite values for parallel and perpendicular MOR are 30.90 and 14.00 MPa, respectively. Therefore, all treatments satisfy the minimum requirements set forth by the standard.

Concerning MOE, the standard stipulates a minimum of 5223 MPa for the parallel direction and 1485 MPa for the perpendicular direction. Only the TF2 treatment meets the standard for parallel MOE, while all treatments meet the minimum requirements for perpendicular MOE.

In a study conducted by Magalhães et al. (2019), plywood panels made with Pinus spp. wood and a lignin-phenol-formaldehyde adhesive exhibited parallel MOR of 10.29 MPa, perpendicular MOR of 38.42 MPa, parallel MOE of 232.42 MPa, and perpendicular MOE of 1804.41 MPa. These values are lower than those reported in the present study.

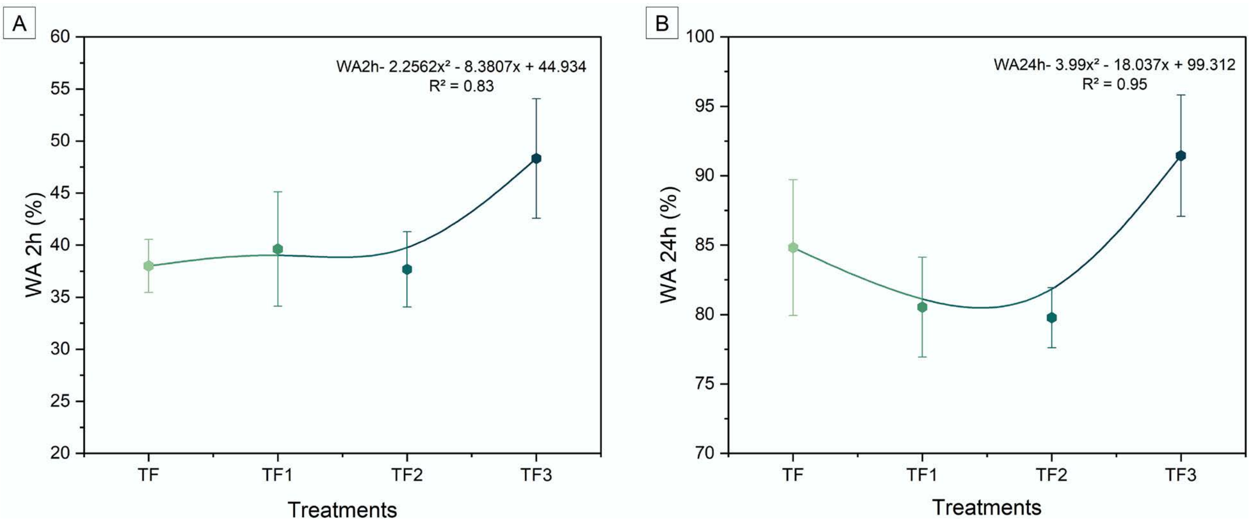

Figure 1: Water absorption after 2 and 24 hours immersion of plywood panels produced with *Erythrina poeppigiana* veneers and natural adhesives.

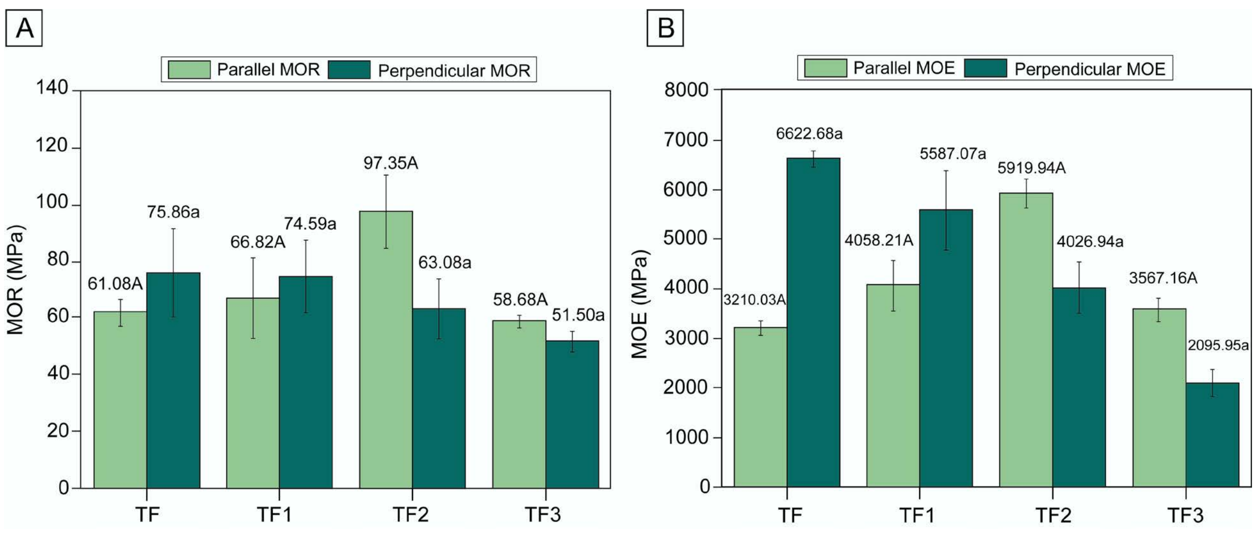

Figure 2: Modulus of rupture (a) and Modulus of elasticity (b) of *Erythrina poeppigiana* plywood glued with nanomodified tannin-formaldehyde adhesives. Means followed by the same letter in the column do not differ at 5% probability.

Krefta et al. (2022) reported average values for commercial plywood panels with *Pinus* spp. wood and phenol-formaldehyde adhesive. These included parallel MOR of 50.06 MPa, perpendicular MOR of 55.28 MPa, parallel MOE of 6856 MPa, and perpendicular MOE of 4838 MPa. It is observed that the MOR values (Figure 2a) of the present study were higher, while the parallel MOE was lower and the perpendicular MOE showed similar values, except for TF3 (Figure 2b). The MOE and MOR values for bending found in this study are promising, since the literature reports that panels made with tannin-based adhesives have low mechanical strength.

The shear strength of the panels glued with *Acacia mearnsii* tannin-based adhesives was found to be influenced by the addition of nanolignin (Figure 3). The treatment with 2% nanolignin (TF2) did not exhibit a statistically significant difference compared to the other treatments. However, the TF3 treatment demonstrated a statistically significant difference from both the control and the TF1 treatment. All panels in this study demonstrated compliance with the criteria for external utilization, as outlined in the EM-310 standard (European Committee for standardization, 1993). This standard specifies a minimum value of 1 MPa for wood failure tests under dry conditions for plywood panels.

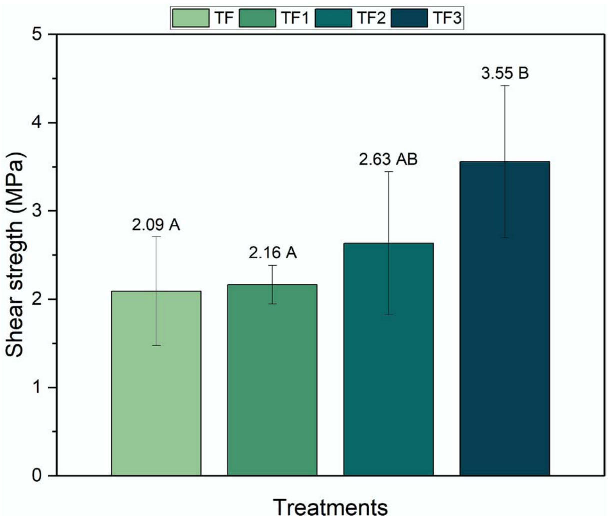

Figure 3: Dry shear strength of *Erythrina poeppigiana* plywood glued with nanomodified tannin-formaldehyde adhesives. Means followed by the same letter in the column do not differ at 5% probability.

In contrast to the findings of the present study, Zidanes et al. (2023) investigated the influence of incorporating cellulose nanofibrils derived from Eucalyptus sp. and Pinus sp. into tannin adhesives derived from *Stryphnodendron adstringens* (Mart.) Coville and *Myrcia eximia* DC for wood bonding. Their results demonstrated shear strength values that were lower than those observed in this research, reaching a maximum of 2.20 MPa. Lourenço et al. (2024) investigated the inclusion of talc nanostructures in synthetic adhesives used in bonding *Pinus* sp. plywood panels and found that all shear values obtained were lower than those observed in this research.

The highest average shear strength value observed in the TF3 treatment can be attributed to the introduction of nanoscale materials, which often exhibit a higher proportion of atoms on their surface. Consequently, surface properties can exceed those of the material at its normal scale, resulting in an enhanced mechanical property of adhesives (Fechine, 2020).

The high shear strength values observed in plywood panels are strongly correlated with the quality and thickness of the glue line used. A strong and well-distributed glue line significantly contributes to the cohesion between the wood veneers, thereby facilitating the uniform distribution of shear stresses across the panel surface (Segundinho et al., 2018; Iwakiri and Trianoski, 2020). The glue lines of the respective treatments are illustrated in Figure 4.

A uniform glue line can be observed along the entire length across all treatments (Figure 4). This not only increases the adhesive contact area but also enhances the panel's ability to withstand external forces without interlaminar failures, resulting in higher shear strength values. Thus, the quality of the glue line is a critical determinant of the mechanical performance of plywood panels. This justifies the observation of high shear values for treatments TF2 and TF3 (see Figure 3).

Acoustic Insulation

The acoustic insulation test results are shown in Figure 5. Compared to the reference sample, the plywood panels exhibited a reduction in sound intensity across all analyzed frequencies.

The efficacy of the wood panel bonding process plays a crucial role in the acoustic insulation properties of the material. A strong bonding process is essential to ensure the structural integrity of the product, preventing the occurrence of delamination or failures that can create voids or gaps, thereby allowing sound to pass through and reducing the effectiveness of acoustic insulation (Salvalaggio et al., 2024).

The most significant differences between treatments are observed at frequencies of 1000 Hz and 2000 Hz. At these frequencies, the TF1 treatment exhibited the most favorable performance, with sound intensity measurements of 55.75 dB and 74.75 dB, respectively. In contrast, the control exhibited 59.60 dB for 1000 Hz and 81.20 dB for 2000 Hz. Lower results were observed in particleboard panels of *Eucalyptus* bonded with lignin, with values of 69.98 dB (Vieira et al., 2024).

According to the specifications of NBR 10152 (ABNT, 2020), at a frequency of 1000 Hz, all evaluated panels were considered suitable for sound comfort in the range of 50 to 60 dB, ideal for offices with typing rooms, and in the range of 45 to 50 dB, suitable for enclosed pavilions intended for shows and sports activities. The other frequencies did not achieve the sound comfort levels established by the standard.

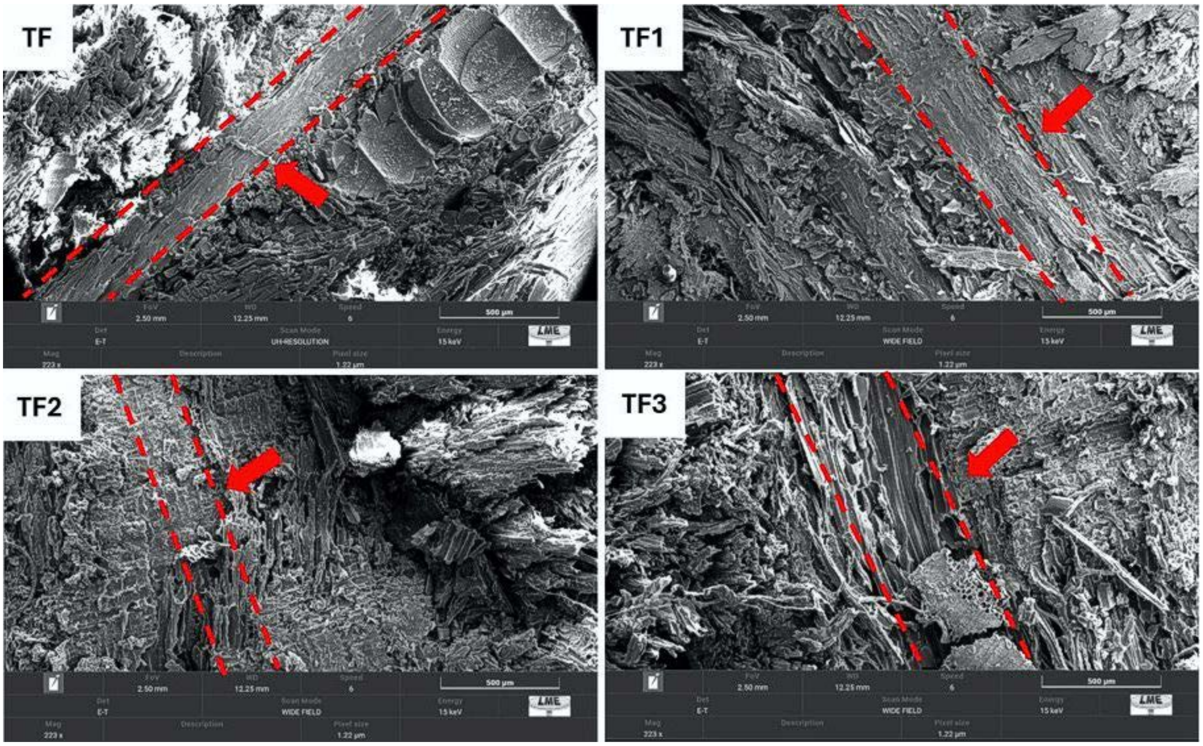

Figure 4: Micrographs of plywood panels: (TF) Tannin-formaldehyde; (TF1) Tannin-formaldehyde-1% nanolignin; (TF2) Tannin-formaldehyde-2% nanolignin; (TF3) Tannin-formaldehyde-3% nanolignin.

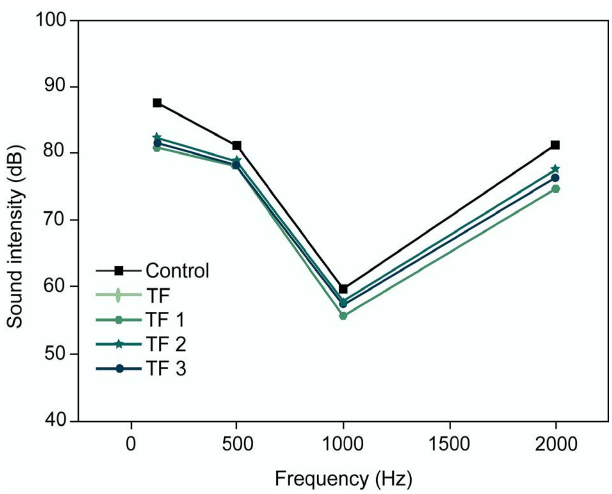

Figure 5: Acoustic insulation of *Erythrina poeppigiana* plywood panels.

Thermal Conductivity

The data in Table 7 indicate that the addition of lignin nanoparticles to the adhesive had no significant impact on its thermal conductivity. In a similar study conducted by Magalhães et al. (2024), the addition of 2% lignin nanoparticles to a cardanol-formaldehyde adhesive resulted in thermal conductivity values between 0.04 and 0.05 W/m.K, which are lower than those observed in the present study. According to Cravo (2013), a material must exhibit a thermal conductivity value below 0.25 W/m.K to be classified as a thermal insulator. Therefore, the panels produced with *Erythrina poeppigiana* wood using commercial *Acacia mearnsii* tannin adhesive with or without lignin nanoparticles can be applied as thermal insulation materials in indoor building environments.

Table 7: Thermal conductivity of *Erythrina poeppigiana* plywood panels produced with *Acacia mearnsii* commercial adhesive with or without lignin nanoparticles.

Adhesives (%)	λ (W/m.K)
TF	0.13A ± 0.01
TF1	0.14A ± 0.01
TF2	0.12A ± 0.01
TF3	0.14A ± 0.01

Following NBR 15220 (ABNT, 2005), panels are classified as thermal insulating materials when their thermal conductivity values are below 2 W/m.K. Consequently, all panels comply with the stipulated criteria.

CONCLUSIONS

The incorporation of nanolignin as a partial substitute for tannin in adhesive formulations significantly influenced the performance of plywood panels produced with *Erythrina poeppigiana* veneers. Among the tested concentrations, the 2% nanolignin treatment (TF2) delivered the most balanced results across multiple parameters. This formulation reduced adhesive viscosity and enhanced spreadability, as evidenced by lower viscosity and increased contact angle values. These modifications facilitated deeper veneer penetration and contributed to improved adhesive cohesion.

TF2 panels exhibited superior water resistance, with the lowest water absorption after 24 hours, and achieved hydrophobicity levels superior to the control. Moreover, the shear strength of panels bonded with 2 and 3% nanolignin adhesives surpassed that of the control, indicating enhanced mechanical performance due to improved interfacial adhesion.

While the MOE and MOR did not differ significantly among treatments, the TF2 adhesive was the only one to meet the standard for parallel MOE, reinforcing its optimized balance between flexibility and strength. In terms of additional functionalities, all panels met the criteria for thermal insulation ($\lambda < 0.14$ W/m.K) and showed promising acoustic insulation at key frequencies, particularly the TF1 and TF2 treatments.

Nanolignin proved to be a viable and sustainable additive for enhancing the performance of tannin-based adhesives. The 2% concentration emerged as the optimal formulation, offering favorable properties. These findings highlight the potential of nanolignin to improve the performance of natural adhesives in wood-based panel production.

AUTHORS' CONTRIBUTION

Project Idea: YBCL; JBGJ

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DATA AVAILABILITY

The datasets supporting the conclusions are included in the article.

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