Research Article
doi: 10.1590/01047760202632013675
vol(32), 2026

CERNE

The effect of cellulose nanocrystals on the properties of *Erythrina poeppigiana* (Walp.) O.F. Cook plywood

Ricardo Gabriel de Almeida Mesquita[1]✤, Mara Lúcia Agostini Valle[1], Daniel Piotto[1], José Benedito Guimarães Junior[2], Lourival Marin Mendes[2]

[1]Federal University of Southern Bahia, Center for Training in Agroforestry Sciences, Brazil.
[2]Federal University of Lavras, Department of Forest Sciences, Brazil.

TECHNOLOGY OF FOREST PRODUCTS

ABSTRACT

Background: *Erythrina poeppigiana* is a fast-growing, low density tropical wood species underutilized in southern Bahia, Brazil. Its plywood exhibits limited mechanical performance due to wide parenchyma bands, low lignin content, and high porosity. Cellulose nanocrystals (NCC) have been proposed as reinforcement to enhance panel stiffness and modify adhesive behavior. This study evaluated the effects of incorporating NCC into phenol-formaldehyde adhesive (PF) on the physical and mechanical properties of *E. poeppigiana* plywood.

Results: Plywood panels were produced with NCC loadings of 0, 1, 1.5, and 2% based on the total mass of the PF adhesive. NCC addition increased the parallel modulus of elasticity from 4651 MPa in the control to 6076 MPa at 2% NCC (≈31% increase), allowing the panels to reach the minimum requirement for concrete formwork plywood. No significant effect was observed on modulus of rupture. Water absorption and 24-hour thickness swelling increased with NCC, reflecting the hydrophilic nature of NCC and the wood's anatomical structure. Shear strength decreased at higher NCC contents, particularly above 1%, likely due to increased adhesive viscosity and reduced spreading caused by NCC–polymer interactions. Other properties, including density and moisture content, remained unaffected.

Conclusion: NCC incorporation improved the stiffness of *E. poeppigiana* plywood; however, higher concentrations negatively affect bonding performance and moisture-related properties. The wood's chemical and anatomical characteristics, notably broad parenchyma bands and low density, influence the overall performance. These findings suggest that controlled NCC incorporation offers a strategy to enhance value-added applications of underutilized species.

Keywords: adhesive reinforcement; nanocellulose; tropical wood; wood anatomy; wood composites.

HIGHLIGHTS

Low-density wood anatomy strongly influenced plywood performance.
Shear strength decreased at NCC contents above 1%.
NCC increased MOE of plywood, reaching 6076 MPa at 2% content.
NCC improved stiffness but impaired bonding at high concentrations.

MESQUITA, R. G. A.; VALLE, M. L. A.; PIOTTO, D.; GUIMARÃES JUNIOR, J. B.; MENDES, L. M. . The effect of cellulose nanocrystals on the properties of *Erythrina poeppigiana* (Walp.) o.f. Cook plywood. CERNE, v. 32, e103675, 2026. DOI: 10.1590/01047760202632013675

✤Corresponding author: ricardo.mesquita@ufsb.edu.br
Scientific Editor: Paulo Ricardo Gherardi Hein

Received: December 17 2025
Accepted: April 06 2026

CERNE
ISSN 0104-7760
UNIVERSIDADE FEDERAL DE LAVRAS

INTRODUCTION

The search for alternative raw materials for wood-based panels has increased in recent years, particularly for fast-growing and underutilized tropical species with large available volumes (Lima et al., 2024; Dukarska et al., 2025; Fauziyyah et al., 2025). In southern Bahia, Brazil, one species that fits this context is *Erythrina poeppigiana*, which was introduced as a shade tree for cocoa cultivation in agroforestry systems known as cabruca (Piotto et al., 2020). Cabruca is an agroforestry system where cocoa is grown in the forest understory and plays an important role in maintaining fragments of Atlantic Forest in the region (Santos et al., 2025). Cocoa production has a major influence on the local economy, particularly because it involves many small producers. However, excessive shading can reduce cocoa productivity, leading to the need for periodic management of shade trees, including *Erythrina* (Farias et al., 2024; Figueiredo et al., 2026).

Despite its abundance, the wood of *Erythrina poeppigiana* is considered of low commercial value in the region and currently has limited industrial applications. However, its rapid growth, straight stem form, and large available volume make it a potential raw material for engineered wood products. Farias et al. (2024) evaluated plywood manufactured from *Erythrina* veneers using different adhesives and reported potential for internal and non-structural applications. Nevertheless, the panels showed relatively low mechanical performance, particularly in modulus of elasticity, mainly due to the wood's low density and anatomical characteristics, such as wide parenchyma bands. Carvalho et al. (2024) also evaluated the use of *Erythrina* wood for glued laminated timber and reported similar limitations associated with the low density of the species. In addition, Lourenço et al. (2025) investigated adhesive formulations containing tannin and nanolignin for plywood produced from *Erythrina* wood. Other studies have also explored alternative composites using this species, such as wood–cement panels (Custódio et al., 2025), reinforcing the growing interest in finding technological applications for this underutilized species.

In recent years, nanocellulose materials have attracted considerable attention due to their potential applications in several industrial sectors, including polymer nanocomposites, coatings, packaging materials, barrier films, and adhesive systems (Silva et al., 2025; Naghizadeh et al., 2024). Among these materials, cellulose nanocrystals (NCC) have been widely investigated because of their high aspect ratio, large specific surface area, and ability to interact with polymer matrices through hydrogen bonding. These characteristics allow NCC to influence adhesive rheology, curing behavior, and stress transfer within bonding lines, which may contribute to improvements in the mechanical performance of wood-based panels (Mesquita et al., 2018; Lengowski et al., 2021).

Previous studies have investigated the incorporation of cellulose nanocrystals into adhesive systems for wood-based panels. Mesquita et al. (2018) reported improvements in modulus of elasticity and strength in sugarcane bagasse particleboards bonded with urea–formaldehyde adhesive containing NCC at low reinforcement levels. Similarly, Liu et al. (2015) observed improvements in shear strength in plywood manufactured from yellow birch when NCC was incorporated into phenol–formaldehyde adhesive. These studies suggest that small amounts of NCC can enhance bonding performance and stiffness of wood-based panels by modifying the rheological and mechanical behavior of the adhesive system.

Despite the increasing interest in nanocellulose-modified adhesives, information about their application in low-density tropical woods remains limited. In highly porous species such as *Erythrina poeppigiana*, adhesive penetration and bonding behavior may differ substantially from those observed in denser temperate woods due to anatomical characteristics such as abundant parenchyma and large vessels. Understanding how NCC incorporation affects the bonding and mechanical performance of plywood produced from this wood may therefore contribute to the development of value-added applications for underutilized tropical species.

Based on these considerations, it was hypothesized that the incorporation of small amounts of cellulose nanocrystals into phenol–formaldehyde adhesive could improve the stiffness and bonding performance of plywood produced from *Erythrina poeppigiana*.

Therefore, the objective of this study was to evaluate the effect of incorporating cellulose nanocrystals into phenol–formaldehyde adhesive on the physical and mechanical properties of *Erythrina poeppigiana* plywood.

MATERIAL AND METHODS

Raw material and veneer preparation

Four trees were harvested from the Jorge Amado campus of the Federal University of Southern Bahia, with approximate coordinates of 14°45′11.69″ to 14°47′6.84″ S and 39°14′17.27″ to 39°12′53.26″ W. Trees were harvested with an average diameter of 45 cm and converted into logs of four meters that were transported to the Federal University of Lavras, Minas Gerais, where they were processed using a rotary lathe. Veneers were produced and then cut to 500 x 500 x 2.43 mm (width, length and thickness) and dried in an oven to approximately 8% of moisture content.

Wood chemical, physical and anatomical characterization

The wood of *Erythrina poeppigiana* had its chemical analysis (lignin, extractives, ashes and holocellulose) and physical analysis (density) measured according to NBR 14853 (ABNT, 2002), NBR 7989 (ABNT, 2003a), NBR 13999 (ABNT, 2003b) and NBR 11941 (ABNT, 2003c), respectively. The holocellulose percentage was determined by difference. Anatomical slides were also prepared (IAWA, 1989).

Adhesive and cellulose nanocrystals

The adhesive used was phenol-formaldehyde (PF).

Freeze-dried NCC were purchased from the University of Maine (United States). The NCC were dispersed directly in the adhesive (PF). The following specifications were provided by the manufacturer: 98wt% solids; width 5-20 nm and length 150-200 nm; 1.5 g cm^{-3} (density); white and odorless (appearance); and hydrophilic (surface property). Considering a mean length of 175 nm and a mean diameter of 12.5 nm, the aspect ratio (length/diameter) was approximately 14. The NCC presented a moisture content of approximately 4%.

The morphology of the cellulose nanocrystals was analyzed by transmission electron microscopy (TEM). The analysis was performed using a Tecnai™ G2 F20 microscope operating in scanning transmission electron microscopy (STEM) mode with a dark-field detector. NCC suspensions were diluted and dispersed for 2 min in an ice bath using a Branson 450 sonicator. A drop of the diluted suspension was deposited onto a Formvar carbon microgrid (TedPella, 400 mesh), stained with a 1.5% uranyl acetate solution, and allowed to dry in a desiccator at room temperature.

Adhesive formulation and characterization

The preparation of the PF adhesive with NCC and the evaluated loadings are illustrated in Figure 1. The NCC was gradually added to the PF adhesive and mechanically mixed using a propeller mixer for 10 minutes at 600 rpm to promote dispersion within the adhesive matrix. The gradual addition during mixing was adopted to minimize particle agglomeration and facilitate a more homogeneous distribution of nanocrystals in the adhesive, a common challenge reported for nanocellulose-modified adhesives (Mesquita et al., 2018; Dorieh et al., 2022).

Four NCC loadings were evaluated: 0% (T1), 1% (T2), 1.5% (T3), and 2% (T4), based on the total mass of the PF adhesive. This concentration range was selected to evaluate the influence of low NCC contents on adhesive behavior, while avoiding excessive viscosity increase that could impair adhesive spreading. The mixture was spread in the wood veneers using a manual spatula.

The adhesive properties evaluated were contact angle, viscosity, and solids content.

The wettability of the adhesive formulations was evaluated by contact angle measurements using a goniometer (Krüss GmbH) equipped with ADVANCE software. Measurements were performed using the sessile drop method by depositing a droplet of adhesive onto the veneer surface. The droplet profile was recorded immediately after deposition and monitored for up to 1 s. The contact angle was determined as the average value obtained during the first second after droplet deposition. All measurements were performed on veneer surfaces conditioned at 22 ± 2 °C and 65 ± 5% relative humidity.

The viscosity of the PF adhesive without NCC was determined using a Ford Cup No. 4 according to ASTM D1200 (2018). However, after NCC incorporation, the adhesive formulations did not flow through the Ford Cup No. 4, preventing viscosity determination using this method. The solids content was determined as the ratio between dry mass and wet mass after four hours of oven drying, using 1 g of adhesive. Illustrative figures were developed with the assistance of artificial intelligence tools (ChatGPT, OpenAI) and subsequently refined using CorelDRAW software.

Plywood manufacturing

The plywood panels were manufactured following the experimental procedure illustrated in Figure 2. Three panels (per treatment), with five layers, were produced at a grammage of 200 g m^{-2} (single line). The veneers were arranged in a cross-laminated configuration, with alternating grain directions between adjacent layers. After the adhesive application, the wood veneers were pre-pressed for 5 minutes, to promote contact between the 5 layers, therefore assisting in the transfer and distribution of the adhesive. The wood veneers were hot-pressed in a pressing cycle of 0.78 MPa and 150°C for 10 minutes. After the hot-pressing, the panels were left to cool to room temperature and then conditioned in a chamber at 22±2 °C and 65±5% of relative humidity.

Physical and mechanical tests

The panels were squared using a circular saw for specimen preparation. The physical properties evaluated were density according to NBR 9485 (ABNT, 2011b) and moisture content according to NBR 9484 (ABNT, 2011a), using five specimens per panel. Water absorption after 2 h (WA2h) and 24 h of immersion (WA24h) was determined according to NBR 9486 (ABNT, 2011c), using four specimens per panel. Thickness swelling after 2 h (TS2h) and 24 h of immersion (TS24h) was calculated using the same specimens employed for water absorption measurements by determining the change in thickness at the central region of each specimen.

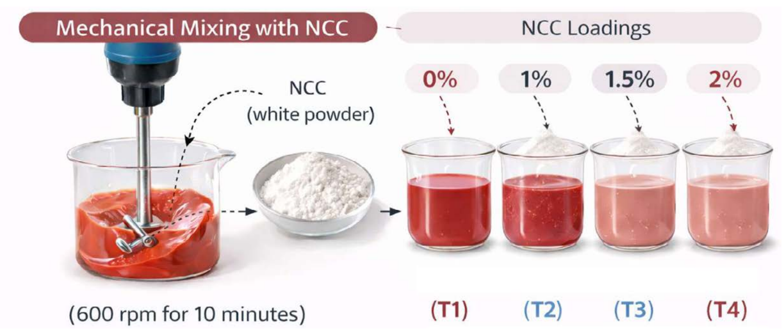

Figure 1: Mechanical mixing of PF adhesive with NCC and evaluated NCC loadings. Schematic illustration.

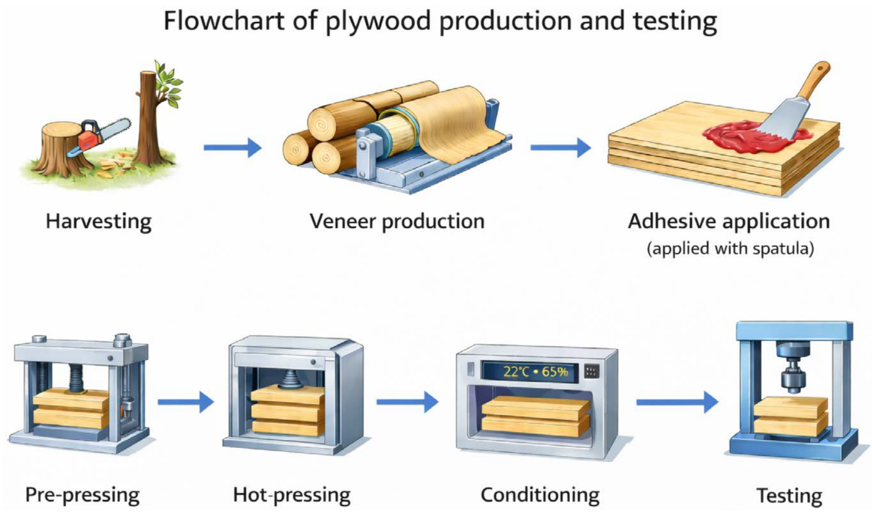

Figure 2: Experimental flowchart of plywood manufacturing and characterization procedures. Schematic illustration.

For mechanical properties, static bending tests were conducted to determine modulus of elasticity (MOE) and modulus of rupture (MOR) according to EN 310 (1993), using two specimens per panel. Shear strength tests were also performed according to EN 314-2 (1993), using six specimens per panel.

Statistical analysis

Three panels were produced for each treatment, and each panel was considered the experimental unit. Multiple test specimens were obtained from each panel for physical and mechanical characterization; however, the mean value per panel was used in the statistical analysis in order to avoid pseudo-replication. Results of the physical and mechanical properties were subjected to statistical analysis using the Shapiro-Wilk test to verify normality and the Levene test for homoscedasticity, followed by ANOVA. When significant, means were compared using Tukey's test ($p < 0.05$). Statistical analyses were performed using R software (R Core Team).

RESULTS

Wood chemical and anatomical characterization

Erythrina wood had the following chemical composition: lignin (18.91±1.03%); ash (3.12±0.07%); extractives (9.54±1.37%); and holocellulose (68.43±0.83%).

The basic wood density was 0.268 ± 0.013 g cm^{-3}, therefore the wood can be classified as low-density (IAWA, 1989).

Regarding the anatomical characteristics of the wood, the heartwood and sapwood were indistinct as well as growth rings. Rays, parenchyma, and vessels were clearly visible to the naked eye (Figure 3). The paratracheal parenchyma was banded and abundant (Figure 4). The parenchymal bands were wider than the fiber bands (Figure 5) and exhibited a storied arrangement (Figure 6). The porosity was diffuse, the vessels were mostly solitary and in multiples of 2-3 (Figure 4) with large diameter and conspicuous. Rays were wide and moderately abundant, multiseriate and unisseriate (Figure 5), heterogeneous and non-storied (Figure 6). Septate fibers and a thick horizontal band running through the fibers were also observed (Figure 5).

Figure 3: Sanded surface of *Erythrina poeppigiana* wood. Scale in mm.

NCC morphology and adhesive characterization

Figure 7 shows the morphology of the cellulose nanocrystals obtained by transmission electron microscopy (TEM). The TEM images confirmed the rod-like morphology typical of cellulose nanocrystals. The nanocrystals presented nanoscale dimensions consistent with the specifications provided by the supplier. These dimensions result in a high aspect ratio.

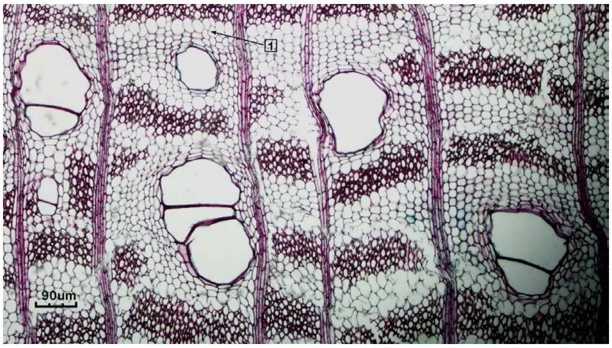

Figure 4: Banded and abundant paratracheal parenchyma of *E. poeppigiana* from southern Bahia. Transverse plane. Magnification 4×. Bar = 90 µm. Arrow 1 indicates axial parenchyma in bands.

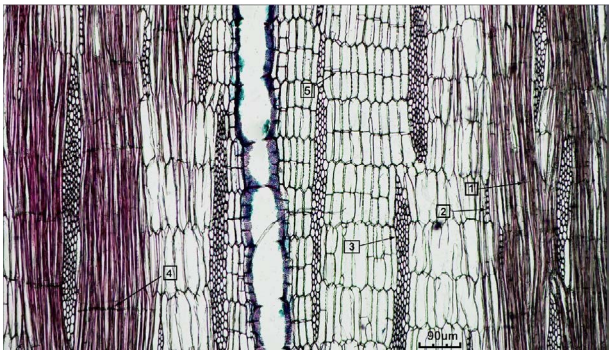

Figure 5: Tangential plane showing that parenchymal bands are wider than fiber bands in trees of *E. poeppigiana* in southern Bahia. Magnification 4×. Bar = 90 µm. Arrows indicating: 1, septate fibers; 2, uniseriate rays; 3, multiseriate rays; 4, thick horizontal band traversing the fibers; 5, storied axial parenchyma.

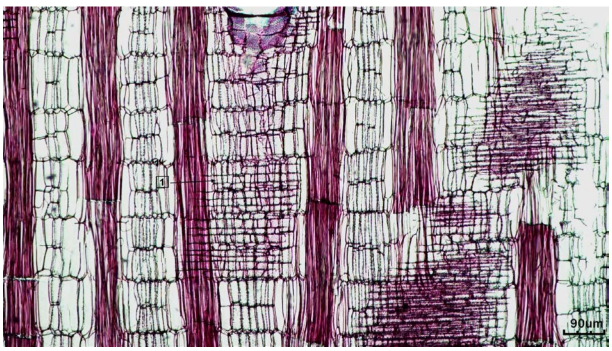

Figure 6: Septate fibers of *E. poeppigiana* wood from southern Bahia, Brazil. Radial plane. Magnification 4×. Bar = 90 µm. Arrow 1 indicates heterogeneous rays.

The PF adhesive without NCC showed a solids content of 44.65% and a viscosity of 643.4 cP. After NCC incorporation, viscosity measurements could not be performed because the adhesive formulations did not flow through the Ford Cup No. 4, preventing viscosity measurement. The solids content was slightly below the recommended range of 48–51%, and the viscosity was within the reference values of 400 to 800 cP (Fitrianum et al., 2023).

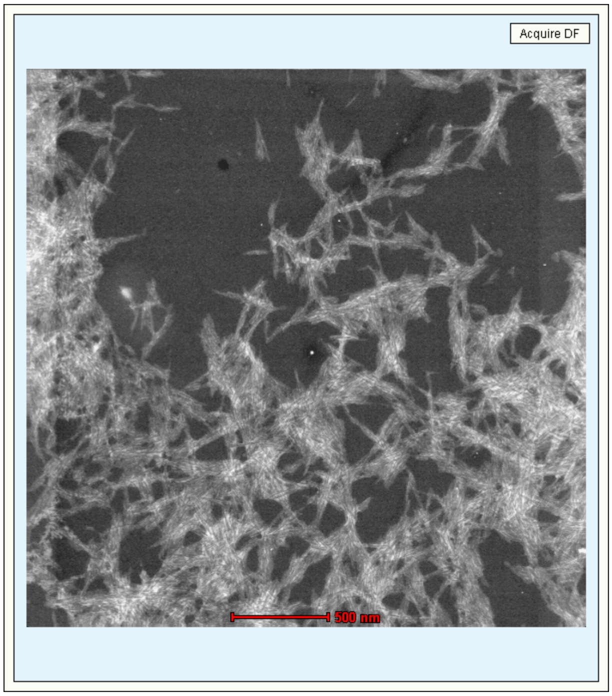

Figure 7: Transmission electron microscopy (TEM) image of the cellulose nanocrystals used in the adhesive formulations. Scale bars = 500 nm.

The contact angle increased from 121.9° in the control adhesive to 130.4° at 2% NCC, indicating a progressive reduction in adhesive wettability. Figure 8 illustrates the sessile drop geometry used for contact angle determination and conceptually summarizes how changes in wettability may influence adhesive penetration and bonding performance in plywood panels.

Physical properties of plywood

No significant difference was observed for the density and moisture content of the plywood (Figure 9). Means are presented in the figures, and error bars represent 95% confidence intervals for all evaluated properties.

NCC incorporation significantly affected water absorption after 2 and 24 h of immersion (Figure 10). For WA2h, a significant difference was detected only between the 1% and 2% NCC treatments, while the other treatments showed intermediate values. For WA24h, the 1.5% and 2% NCC treatments presented higher values than the control and 1% NCC treatments.

NCC incorporation did not significantly affect thickness swelling according to Tukey's test (Figure 11).

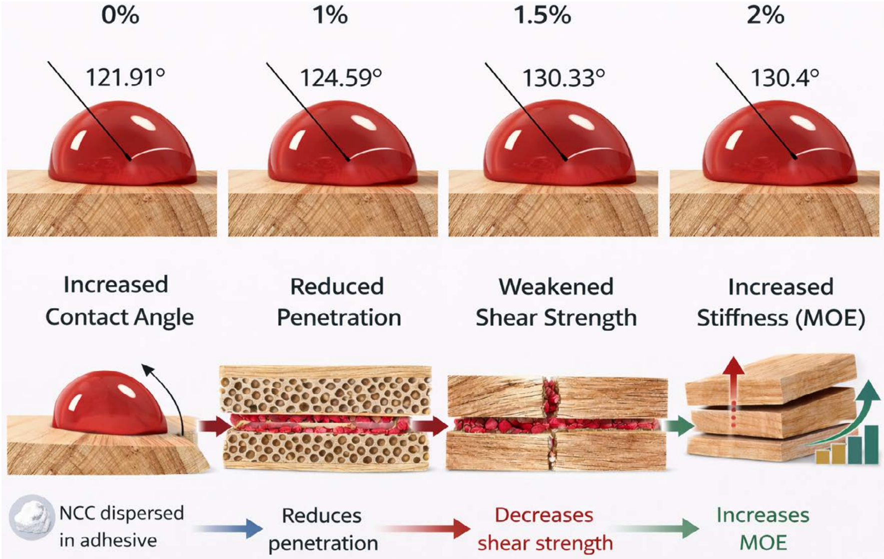

Figure 8: Conceptual schematic illustrating the influence of NCC incorporation on adhesive. Schematic illustration.

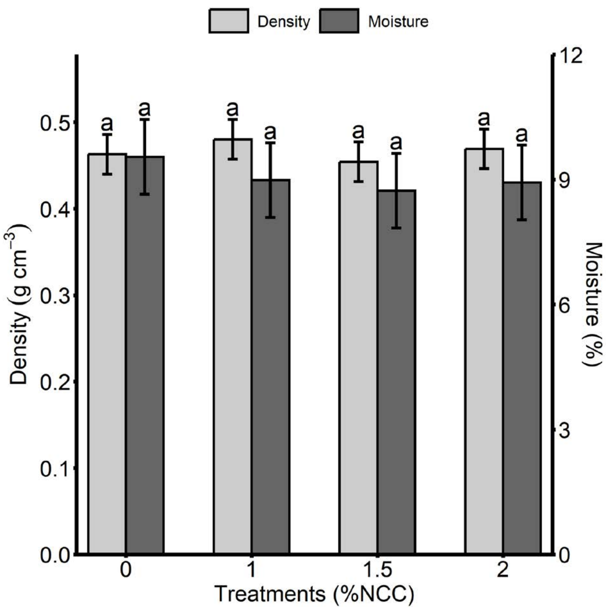

Figure 9: Left-hand y-axis (light gray bars) density. Right-hand y-axis (dark gray bars) moisture content. Mean values followed by the same letters do not differ by Tukey's test (α = 0.05). Error bars represent 95% confidence intervals.

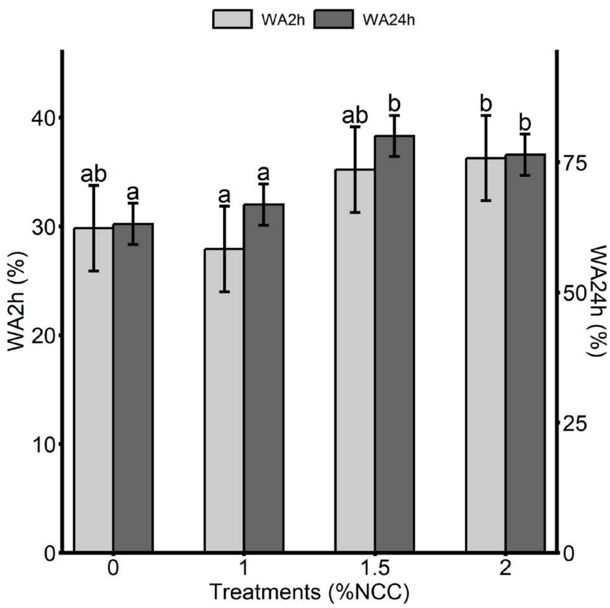

Figure 10: Left-hand y-axis (light gray bars) water absorption after two hours (WA2h). Right-hand y-axis (dark gray bars) water absorption after twenty-four hours (WA24h). Mean values followed by the same letters do not differ by Tukey's test (α = 0.05). Error bars represent 95% confidence intervals.

Mechanical properties of plywood

The effects of NCC incorporation differed for parallel and perpendicular modulus of elasticity (Figure 12). For MOE0, the 2% NCC treatment showed higher values than the control, whereas the intermediate NCC levels did not differ significantly from either group. For MOE90, the highest mean was observed at 2% NCC, and Tukey's test indicated a significant difference only between the 1.5% and 2% treatments.

There was no statistical difference between the treatments for parallel and perpendicular modulus of rupture (Figure 13).

NCC incorporation significantly affected both dry and wet shear strength (Figure 14). For both properties, the control treatment showed higher values than the 2% NCC treatment, while the 1% and 1.5% NCC treatments presented intermediate values and did not differ significantly from either group.

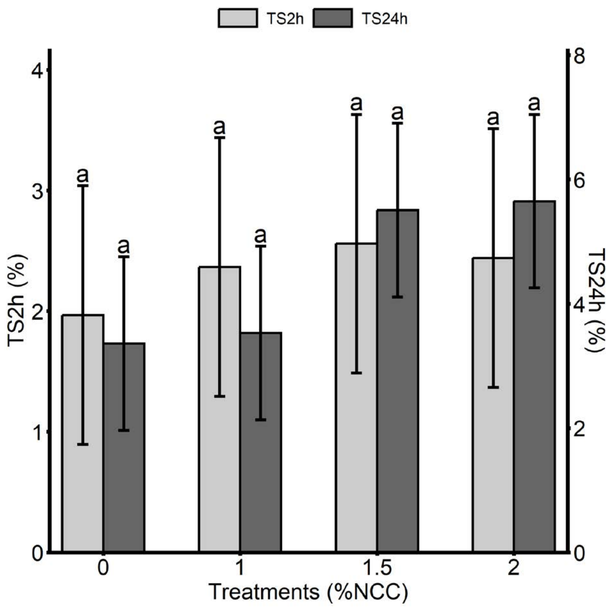

Figure 11: Left-hand y-axis (light gray bars) thickness swelling after two hours (TS2h). Right-hand y-axis (dark gray bars) thickness swelling after twenty-four hours (TS24h). Mean values followed by the same letters do not differ by Tukey's test (α = 0.05). Error bars represent 95% confidence intervals.

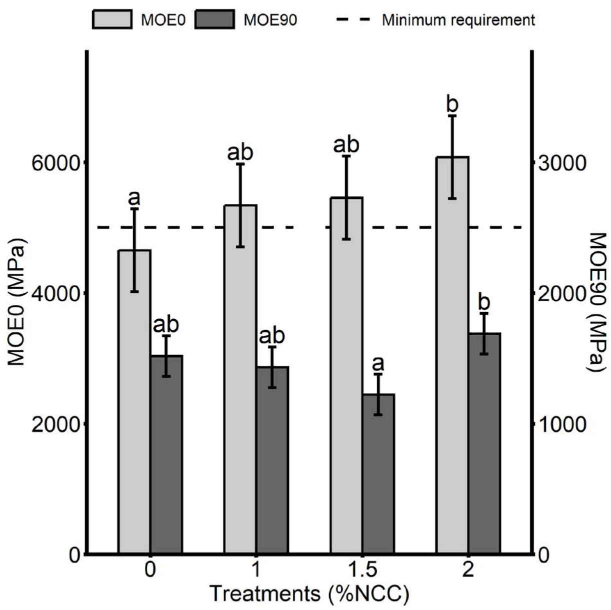

Figure 12: Left-hand y-axis (light gray bars) parallel modulus of elasticity (MOE0). Right-hand y-axis (dark gray bars) perpendicular modulus of elasticity (MOE90). Mean values followed by the same letters do not differ by Tukey's test (α = 0.05). Error bars represent 95% confidence intervals.

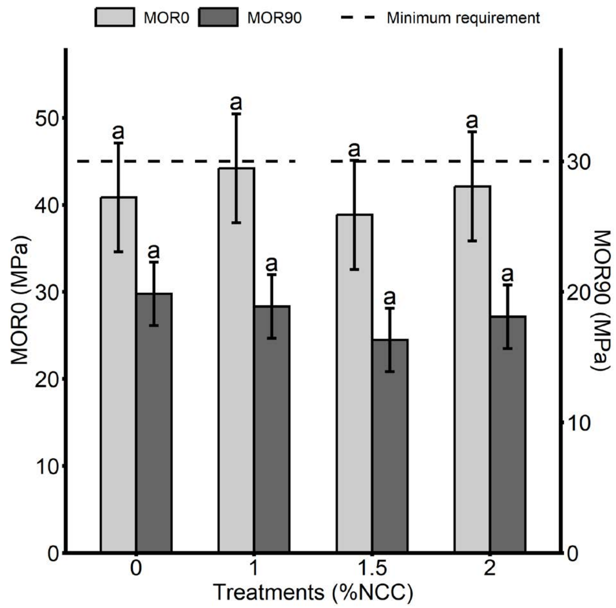

Figure 13: Left-hand y-axis (light gray bars) parallel modulus of rupture (MOR0). Right-hand y-axis (dark gray bars) perpendicular modulus of rupture (MOR90). Mean values followed by the same letters do not differ by Tukey's test (α = 0.05). Error bars represent 95% confidence intervals.

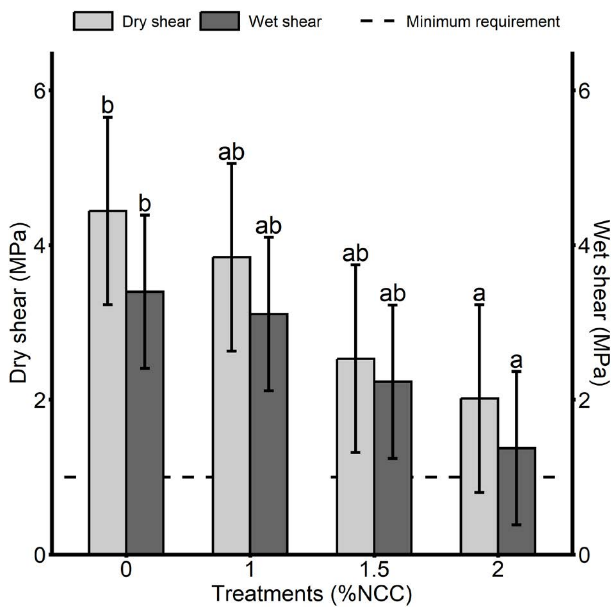

Figure 14: Left-hand y-axis (light gray bars) dry shear. Right-hand y-axis (dark gray bars) wet shear. Mean values followed by the same letters do not differ by Tukey's test (α = 0.05). Error bars represent 95% confidence intervals.

DISCUSSION

Wood characteristics and implications for bonding

The chemical composition is within the range reported in the literature; however, lignin values were close to the lower end of the reported range, while extractives content was close to the higher end (Eloy et al., 2024). Lignin is associated with wood stiffness, and lower lignin contents may negatively influence elastic modulus values. Alkaline adhesives (such as phenol-formaldehyde) are more tolerant to surfaces contaminated by extractives, generating fewer surface inactivation problems in species with high extractives content (Longui et al., 2025; Mangini et al., 2025).

Wood density is inversely related to porosity and adhesive penetration. In low-density woods, adhesive may penetrate excessively into the porous structure, which can result in a starved glue line and reduced bonding performance (Apsari and Tanaka, 2023). The anatomical characteristics observed for *Erythrina poeppigiana*, particularly the presence of wide parenchymal bands and large vessels, may intensify this effect by facilitating deeper adhesive penetration into the wood structure.

Similar densities were reported by Farias et al. (2024) for plywood manufactured from *Erythrina* wood using phenol-formaldehyde adhesive.

Adhesive behavior and wettability

The contact angle in wood is typically close to 90°, resulting in incomplete wetting. In highly porous woods such as *E. poeppigiana*, adhesive wetting and penetration play a critical role in bond formation. Changes in adhesive rheology or surface wetting behavior may therefore strongly influence bonding performance in plywood manufactured from low-density tropical species (Amin et al., 2024). As illustrated in Figure 8, higher contact angles tend to limit adhesive spreading on the wood surface and are detrimental to bonding. The lower the angle, the better the wetting and the greater the adhesive–wood compatibility. Low-density and highly porous woods generally exhibit improved wettability; however, the presence of excessive extractives can cause adverse effects (Amin et al., 2024). Nanoproducts can also modify wettability. Lima et al. (2024) observed that silicon-based nanoproducts reduced the wettability of tropical woods by changing the contact angle. Figure 15 conceptually illustrates the interaction between phenol–formaldehyde adhesive, cellulose nanocrystals (NCC), and the wood cell wall, highlighting hydrogen bonding interactions and their potential effects on adhesive spreading and bonding performance.

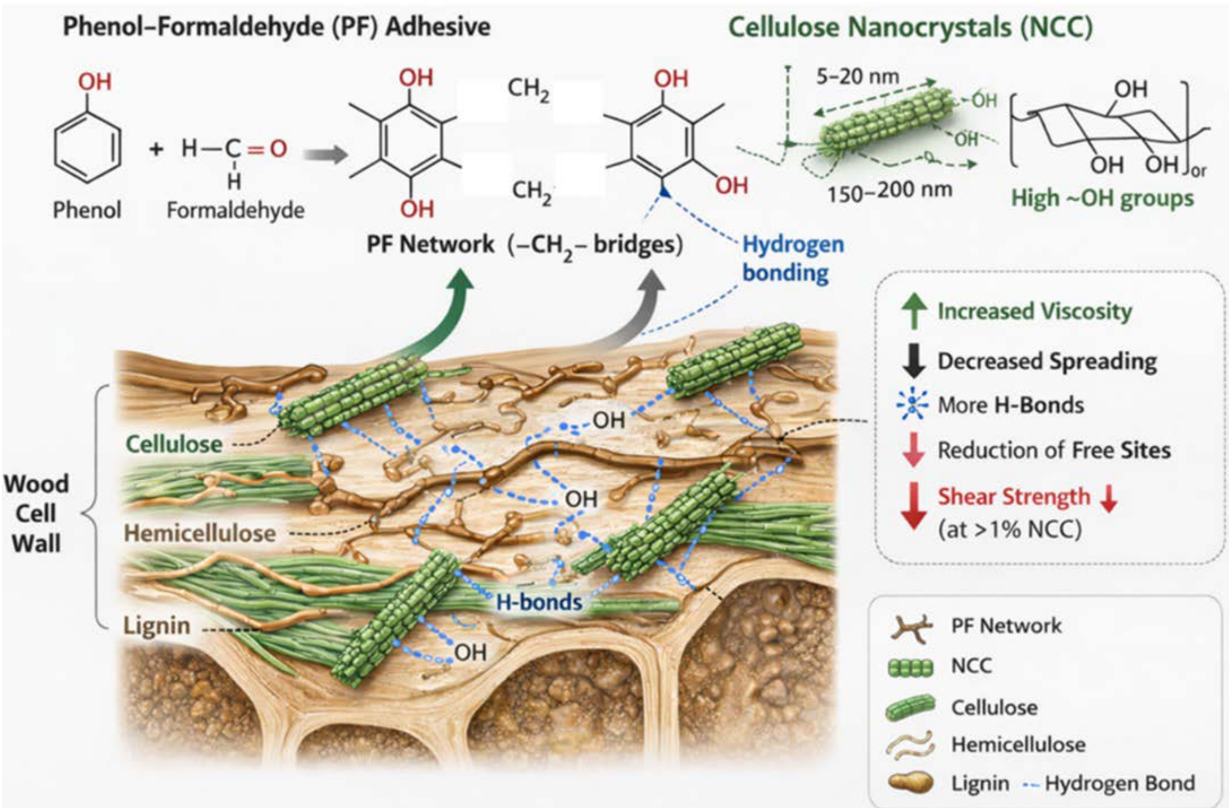

Figure 15: Proposed mechanism of interaction between phenol–formaldehyde adhesive, cellulose nanocrystals (NCC), and the wood cell wall of *Erythrina poeppigiana*. Adapted from Dorieh et al. (2022) and Naghizadeh et al. (2024). Schematic illustration.

The inability of the NCC-modified formulations to flow through the Ford Cup No. 4 indicates a substantial increase in adhesive viscosity after nanocrystal incorporation. This result aligns with previous observations reported for nanocellulose-modified adhesives. Mesquita et al. (2018) reported a progressive increase in adhesive viscosity with the incorporation of cellulose nanocrystals obtained from the same source used in the present study. In that work, the viscosity of a urea–formaldehyde adhesive, measured using a Brookfield viscometer, increased from approximately 127 cP in the control formulation to about 300 cP with the addition of 2% NCC, representing an increase of roughly 136%. This behavior was attributed to the high surface area of nanocrystals and their ability to establish hydrogen-bonding interactions within the adhesive matrix. Although a different adhesive system was used in the present study (phenol–formaldehyde), a similar mechanism may explain the increase in contact angle observed after NCC incorporation, since higher viscosity can reduce adhesive spreading over the wood surface.

Physical performance of plywood panels

The effect of inclusion of NCC caused an increase in water absorption and was more pronounced with 1.5 and 2% inclusions. This behavior is consistent with the chemical composition of NCC, which contains abundant hydroxyl groups capable of interacting with water. A similar trend was observed by Mesquita et al. (2018) with the inclusion of 2 and 3% of NCC in particleboards of sugar cane bagasse using urea-formaldehyde.

According to Dorieh et al. (2022) one of the main challenges in using cellulose-based nanomaterials in PF adhesives is the intrinsic hydrophilicity of NCC. The authors discussed that surface modification or partial esterification of NCC can mitigate these effects, suggesting potential strategies for new studies.

The presence of more OHs favors water absorption and swelling. Mesquita et al. (2018) observed increased swelling after both 2 and 24 hours for most NCC additions tested in particleboards of sugar cane bagasse using urea-formaldehyde.

The presence of wide parenchyma bands also favors water absorption and thickness swelling. Parenchyma cells have only primary, non-lignified walls. Lignin is considered a more hydrophobic component in wood (Farias et al., 2024; Szlek et al., 2022).

Mechanical performance of plywood panels

For parallel modulus, the minimum requirement is 5000 MPa for concrete forms (DIN 68792, 1979), while for perpendicular modulus the minimum is 2500 MPa. None of the treatments reached the minimum value for MOE90. For MOE0, only the treatment with 2% NCC clearly exceeded the minimum requirement, while the other treatments showed lower or intermediate values.

Low elastic modulus values reflect *Erythrina's* chemical and anatomical composition. The presence of parenchyma bands wider than fiber negatively influences the elastic modulus. Parenchyma cells lack a secondary cell wall and lignification. Elastic modulus is an indicator of rigidity, closely associated with lignin and the wall fraction (Farias et al., 2024; Mesquita et al., 2018).

Lengowski et al. (2021) when evaluating the inclusion of nanocellulose (NFC) in pine plywood, observed a decrease in the values of parallel modulus of elasticity as the amount of NFC increased, but no difference was observed for perpendicular modulus of rupture.

Dorieh et al. (2022) highlight that nanocellulose can influence the cross-linking behavior of PF adhesive through physical entanglement and hydrogen bonding with phenolic hydroxyl groups. This can locally restrict chain mobility, leading to an increase in stiffness but also to stress concentrations that reduce strength when excess NCC is added. This is similar to the behavior observed in the present study.

The different response observed between stiffness (MOE) and strength (MOR) may be related to the reinforcing mechanism of nanocellulose. Low concentrations of NCC may restrict polymer chain mobility and increase matrix stiffness without necessarily improving stress transfer across the glue line. As a result, stiffness may increase while strength remains unchanged or even decreases when nanocrystal aggregation occurs (Dorieh et al., 2022; Rana et al., 2023; Naghizadeh et al., 2024; Antony Jose et al., 2025), which is consistent with the present results. Particularly considering the reduction observed in shear strength at higher NCC contents.

As observed in the TEM images (Figure 7), the relatively high aspect ratio of cellulose nanocrystals may contribute to their reinforcing potential in polymeric matrices. Nanocrystals with elongated morphology can restrict polymer chain mobility and improve stress transfer within the adhesive network (Naghizadeh et al., 2024; Hariry et al., 2025), which may partially explain the increase observed in the modulus of elasticity, particularly at higher NCC contents, although this effect did not translate into improved bonding performance.

For parallel modulus (MOR0) the minimum required value is 45 MPa for use in concrete forms (DIN 68792, 1979). For perpendicular modulus (MOR90) the minimum is 30 MPa. None of the treatments met the minimum values for either MOR0 or MOR90.

Lengowski et al. (2021), testing the inclusion of nanocellulose (NFC) in pine plywood, observed an increase in strength values (dry and moisture) as the amount of NFC increased. However, in the present study, no significant differences were observed for MOR, indicating that NCC incorporation did not affect bending strength.

The minimum requirement for both dry and wet shear strength is 1 MPa (EN 314-2, 1993), and all treatments met this requirement.

In the present study, a clear reduction in both dry and wet shear strength was observed at higher NCC contents, particularly at 2%, while the intermediate concentrations showed intermediate values. This behavior is consistent with the trend reported by Liu et al. (2015), where excessive NCC content led to a decrease in bonding performance. Some mechanical properties are observed to increase with the inclusion of low proportion of reinforcement, followed by a subsequent decrease in average values. In many cases, this behavior is attributed to dispersion limitations or nanoparticle aggregation (Silva et al., 2025). If NCC aggregates are present, this will reduce the bonding strength (Liu et al., 2015), which is consistent with the reduction observed at higher NCC contents in this study. Increased contact angle values also harm bonding by impairing adhesive dispersion (Cordeiro et al., 2023). In the present study, the combined effects of wood anatomy, increased contact angle, and potential changes in adhesive rheology caused by NCC incorporation may have contributed to the reductions observed in shear strength at higher NCC contents.

Recent reviews note that while low concentrations of nanocellulose may enhance interfacial adhesion and stiffness, higher contents tend to increase viscosity, reduce mobility during curing, and even impair bonding, behavior consistent with the trends observed in the present study, particularly for the 2% NCC treatment (Dorieh et al., 2022; Naghizadeh et al., 2024).

These results highlight that the performance of nanocellulose-modified adhesives may strongly depend on the anatomical characteristics of the wood species. For highly porous tropical woods such as *Erythrina poeppigiana*, further optimization of adhesive formulation and application parameters may be required to fully exploit the reinforcing potential of nanocellulose while minimizing its negative effects on bonding performance.

CONCLUSION

The inclusion of NCC improved the parallel modulus of elasticity of *Erythrina poeppigiana* plywood, allowing panels to reach the minimum requirement for concrete formwork at 2% NCC. However, NCC incorporation increased water absorption and thickness swelling and reduced shear strength at contents above 1%. These responses are associated with the hydrophilic nature of NCC and with the anatomical characteristics of the wood, particularly the presence of broad parenchyma bands and low density, which favor adhesive penetration and moisture interaction. The increase in stiffness is particularly relevant for applications such as concrete formwork plywood, where elastic modulus is a key performance parameter. These findings also highlight how wood anatomical structure can influence the performance of nanocellulose-modified adhesives in low-density tropical species. Future studies should investigate strategies to optimize the adhesive formulation and improve NCC dispersion in phenol–formaldehyde systems to enhance bonding performance.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the financial support provided by the National Council for Scientific and Technological Development (CNPq, Brazil), the Coordination for the Improvement of Higher Education Personnel (CAPES, Brazil), and the Research Support Foundation of the State of Minas Gerais (FAPEMIG, Brazil). The authors also thank the UEPAM and LASV laboratories of the Federal University of Lavras (UFLA) and the Central Laboratory of Forest Products Technologies (LCTPF) of the Federal University of Southern Bahia (UFSB) for the infrastructure and technical support.

AUTHORSHIP CONTRIBUTION

Project Idea: RGAM

Funding: RGAM; JBGJ; LMM

Database: RGAM

Processing: RGAM

Analysis: RGAM

Writing: RGAM; MLAV; DP; JBGJ; LMM

Review: RGAM; MLAV; DP; JBGJ; LMM

DATA AVAILABILITY

The datasets analyzed during the current study are available from the corresponding author upon reasonable request.

REFERENCES

AMIN, Y.; NUGROHO, N.; BAHTIAR, E. T.; et al. Surface roughness, dynamic wettability, and interphase of modified melamine formaldehyde-based adhesives on jabon wood. Polymers, v. 16, n. 8, p. 1084, 2024.

ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS. NBR 11941: madeira – determinação da densidade básica. Rio de Janeiro, 2003c.

ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS. NBR 13999: papel, cartão, pasta celulósica e madeira – determinação do resíduo (cinza) após incineração a 525 °C. Rio de Janeiro, 2003b.

ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS. NBR 14853: madeira – determinação do material solúvel em etanol-tolueno e em diclorometano. Rio de Janeiro, 2002.

ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS. NBR 7989: pasta celulósica e madeira – determinação de lignina insolúvel em ácido. Rio de Janeiro, 2003a.

ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS. NBR 9484: compensado – determinação do teor de umidade. Rio de Janeiro, 2011a.

ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS. NBR 9485: compensado – determinação da massa específica aparente. Rio de Janeiro, 2011b.

ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS. NBR 9486: painéis de madeira compensada – determinação da absorção de água. Rio de Janeiro, 2011c.

AMERICAN SOCIETY FOR TESTING AND MATERIALS. ASTM D1200: standard test method for viscosity by Ford viscosity cup. West Conshohocken, 2018.

ANTONY JOSE, S.; COWAN, N.; DAVIDSON, M.; et al. A comprehensive review on cellulose nanofibers, nanomaterials, and composites: manufacturing, properties, and applications. Nanomaterials, v. 15, p. 356, 2025.

APSARI, A. N.; TANAKA, T. Effects of glue spreading rate and veneer density on sugi (Cryptomeria japonica) plywood adhesive penetration. Maderas Ciencia y Tecnología, v. 25, n. 8, p. 1–10, 2023.

CARVALHO, J. V.; LOURENÇO, Y. B. C.; BORGES, I. O.; et al. Valorização da madeira de Erythrina poeppigiana na produção de madeira laminada colada com adesivo de poliuretano vegetal. In: RODRIGUES, J. C. Engenharia de materiais e meio ambiente: reciclagem, sustentabilidade, novos processos e desafios. Ponta Grossa: Aya, 2024. p. 12–21.

CORDEIRO, L. A.; MIRANDA, B.; CARNEIRO, M. E.; et al. The effect of sanding on the wettability and surface quality of Imbuia, Red oak, and Pine wood veneers. Maderas Ciencia y Tecnología, v. 25, p. 21, 2023.

CUSTÓDIO, A. P.; BORGES, I. O.; ARANTES, L. S.; et al. Effect of accelerated carbonation on the properties of wood-cement panels from the species Erythrina poeppigiana. Ambiente Construído, v. 25, p. 1–14, 2025.

DEUTSCHES INSTITUT FÜR NORMUNG. DIN 68792: plywood for concrete formwork – requirements and testing. Berlin, 1979.

DORIEH, A.; AYRILMIS, N.; POUR, M. F.; et al. Phenol-formaldehyde resin modified by cellulose and lignin nanomaterials: review and recent progress. International Journal of Biological Macromolecules, v. 222, p. 1888–1907, 2022.

DUKARSKA, D.; KAWALERCZYK, J.; SEDLIAČIK, J.; et al. Alternative wood raw material sources in particleboard and OSB production: challenges and perspectives. Polymers, v. 17, p. 1760, 2025.

ELOY, E.; PEDRAZZI, C.; COLDEBELLA, R.; et al. Effect of chemical constituents on the energetic and physical properties of wood from forestry species. Ciência Rural, v. 54, e20230290, 2024.

EUROPEAN COMMITTEE FOR STANDARDIZATION. EN 310: wood-based panels – determination of modulus of elasticity in bending and of bending strength. Brussels, 1993.

EUROPEAN COMMITTEE FOR STANDARDIZATION. EN 314-2: plywood – bonding quality – part 2: requirements. Brussels, 1993.

FARIAS, L. S.; ALMEIDA NETO, J. A.; MESQUITA, R. G. A.; et al. Sustainable use of Erythrina poeppigiana in formaldehyde-free plywood: environmental and energy analysis. Ambiente Construído, v. 24, e132136, 2024.

FAUZIYYAH, S.; PIPÍŠKA, T.; STOJIC, S.; et al. Wood-based panels derived from fast-growing tropical lightwood species: panel properties and environmental impact assessment. Wood Material Science & Engineering, p. 1–15, 2025.

FIGUEIREDO, M. G.; ROCHA-SANTOS, L.; MARIANO-NETO, E.; et al. High-yield potential of carbon and biodiversity-rich cocoa agroforests in Bahia, Brazil. Agroforestry Systems, v. 100, p. 9, 2026.

FITRIANUM, F.; LUBIS, M. A. R.; HADI, Y. S.; et al. Adhesion and cohesion strength of phenol-formaldehyde resin mixed with different types and levels of catalyst for wood composites. Journal of Composites Science, v. 7, p. 348, 2023.

HARIRY, A.; MARDAWATI, E.; ISWANTO, A. H.; et al. Nanocellulose-based adhesives for sustainable wood-polymer composites: recent advancement and future perspective. Journal of Renewable Materials, v. 13, n. 4, p. 773–798, 2025.

IAWA COMMITTEE. IAWA list of microscopic features for hardwood identification, with an appendix on non-anatomical information. IAWA Bulletin, v. 10, p. 219–332, 1989.

LENGOWSKI, E. C.; BONFATTI JÚNIOR, E. A.; DALLO, R.; et al. Nanocellulose-reinforced phenol-formaldehyde resin for plywood panel production. Maderas Ciencia y Tecnología, v. 23, p. 405, 2021.

LIMA, N. O.; RAABE, J.; LIMA, M. D. R.; et al. Does a silicon-based nanoproduct improve the surface characteristics of Amazonian woods? Cerne, v. 30, e103360, 2024.

LIU, Z.; ZHANG, Y.; RODRIGUE, D. Reinforcement of lignin-based phenol-formaldehyde adhesives with nano-crystalline cellulose. Materials Sciences and Applications, v. 6, p. 567–575, 2015.

LONGUI, E. L.; CAVALHEIRO, C. C.; SANTOS, R. S. M.; et al. Chemical characterization of eleven Latin American woods. Research, Society and Development, v. 14, n. 10, e103141049714, 2025.

LOURENÇO, Y. B. C.; SANTOS, C. A.; FURTINI, A. C. C.; et al. Partial replacement of tannin with nanolignin in adhesive formulations for bonding plywood. Cerne, v. 31, e103546, 2025.

MANGINI, T. S.; CANDATEN, L.; NARDINI, C.; et al. Biological resistance and chemical properties of wood from an agroforestry system. Holzforschung, v. 79, n. 10, p. 489–496, 2025.

MESQUITA, R. G. A.; MENDES, L. M.; SANADI, A. R.; et al. Urea formaldehyde and cellulose nanocrystals adhesive applied to sugarcane bagasse particleboards. Journal of Polymers and the Environment, v. 26, p. 3040–3050, 2018.

NAGHIZADEH, Z.; AYRILMIS, N.; DORIEH, A.; et al. Nanocellulose-phenol formaldehyde adhesive system for engineered wood products: review. Forest Products Journal, v. 74, p. 1–10, 2024.

PIOTTO, D.; MARQUES, J. R. B.; NUNES, A. C. P. Desempenho de espécies madeireiras em sistema agroflorestal de cacaueiro e seringueira no sul da Bahia, Brasil. Agrotrópica, v. 32, n. 2, p. 97–104, 2020.

RANA, S.; SAMANTA, S.; MITRA, B. C.; et al. The impact of physico-chemical properties of nanocellulose on the mechanical performance of polymer nanocomposites. Journal of Reinforced Plastics and Composites, v. 42, n. 11–12, p. 525–543, 2023.

SANTOS, A. S.; LEAL, J. B.; CORRÊA, R. X.; et al. The role of cacao agroforests in the genetic conservation of Cariniana legalis. BMC Ecology and Evolution, v. 25, p. 89, 2025.

SILVA, L. C. L.; LIMA, F. O.; MONTEIRO, S. N.; et al. The use of nano-structured cellulose to improve plywood: a review. Journal of Materials Research and Technology, v. 35, p. 392–401, 2025.

SZLEK, D. B.; REYNOLDS, A. M.; HUBBE, M. A. Hydrophobic molecular treatments of cellulose-based barrier layers for sustainable food packaging. BioResources, v. 17, n. 2, p. 3551–3673, 2022.