Article

Sustainable use of *Erythrina poeppigiana* in formaldehyde-free plywood: environmental and energy analysis

Uso sustentável da Erythrina poeppigiana *em compensado com adesivo sem formaldeído: análise ambiental e energética*

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Abstract

The study analyzed the technical and environmental feasibility of using Erythrina poeppigiana to produce plywood with different adhesives: phenol-formaldehyde (PF), urea-formaldehyde (UF), and castor oil-based polyurethane (PUA). The physical and mechanical properties of the plywood were evaluated, including apparent density, moisture content, water absorption, thickness swelling, shear resistance, and static bending. Tests proved erythrina's suitability for non-structural plywood production. The environmental impact of the production process was also evaluated, using embedded energy and CO_2e emissions as indicators. The results showed that plywood produced with PU adhesive had better environmental performance compared to panels with FF and UF adhesives. T1 treatment (PF) had the highest embodied energy, while T2 (UF) had the highest CO_2e emission. Overall, the study suggests that using erythrina to produce plywood can be a viable option for promoting regional socioeconomic development while also being environmentally sustainable and presents an advantage over foreign plywood in terms of environmental performance.

Keywords: Castor-oil resin. Life cycle assessment - LCEA and CO_2 emissions - $LCCO_2A$. Environmental performance. Physical and mechanical properties.

Resumo

Analisou-se a viabilidade técnica e ambiental da Erythrina poeppigiana para produzir compensados com os adesivos: fenol-formaldeído (FF); uréia-formaldeído (UF) e poliuretano à base de mamona (PU). Avaliou-se as propriedades física e mecânica: densidade aparente, teor de umidade, absorção de água, inchamento em espessura, resistência ao cisalhamento e flexão estática. Os testes apontaram a viabilidade da eritrina para produção de compensados não estruturais. A avaliação ambiental, através dos indicadores, quantificação da energia embutida e emissão de CO_2e, demonstrou que os pain compensado produzido com adesivo PU teve melhor desempenho que os painéis com FF e UF. O tratamento T1 (FF) apresentou maior energia embutida, o T2 (UF) a maior emissão de CO_2e. A viabilidade técnica e ambiental da eritrina para produzir compensados pode promover o desenvolvimento socioeconômico regional, ambientalmente sustentável, com vantagens em relação aos compensados estrangeiros, bem como ao desempenho ambiental.

Palavras-chave: *Adesivo PU mamona. ACVe. $ACVCO_2$. Desempenho ambiental. Propriedades físicas e químicas.*

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Introduction

Abundant in the cocoa plantations of Bahia, the species of the genus Erythrina have provided excessive shading, one of the main factors contributing to the low productivity of cocoa clones resistant to witches' broom disease (Marques; Monteiro, 2016). Excessive shading is blamed for the increased infestation of cocoa trees by witches broom disease and the greater longitudinal growth of the plant, making harvesting difficult (Piasentin; Saito; Sambuichi, 2014). In addition, there is a tendency to replace and reduce the native flora of cocoa plantations with exotic species for sale, with the increase in logging as a consequence of the cocoa culture crisis (Piasentin; Saito; Sambuichi, 2014). On the other hand, adequate forest management provides carbon storage and sustainable biomass harvest.

After decades of cocoa monoculture for export, the southern region of Bahia faced, in the late 1980s, the worst crisis of cocoa farming due to the appearance of the fungus *Moniliophthora perniciosa*, the witches' broom disease. The economic decline of cocoa led to socioeconomic reorganization, rural exodus, and population reduction in the countryside (Aguiar; Pires, 2019). The stock of exotic wood from regional agroforestry systems, SAFs, is a potential economic activity to be explored, offering conditions for community maintenance and development. Despite Agroforestry Systems (SAFs) having a high potential for wood production and the generation of ecosystem services, such as carbon sequestration, they still have untapped potential for the production of high-quality solid wood (Piotto; Marques; Nunes, 2020). This reinforces the need for a better utilization of SAFs, alongside sustainable management of native forests, as proposed in National Forests (FLONAS) (Brazil, 2000), considering the critical situation of timber exploitation in natural forests. Although the use of Erythrina for shading cocoa is systematic, it still has no commercial use, with the tree currently considered a problem in regional cocoa plantations. However, low-density woods, such as Erythrina, have viability to produce panels, *Sequoia sempervirens*, 0.31 g/cm^3 (Iwakiri *et al*., 2013), *Schizolobium amazonicum* (paricá), 0.31 g/cm^3, (Setter *et al*., 2021; Lima *et al*., 2022), *Schizolobium parahyba* (guapuruvu), 0.31 g/cm^3 (Palma; Moreno; Ballarin, 2017), *Cryptomeria japonica*, 0.25 g/cm^3 (Pinto; Iwakiri, 2013), setting up a potential for regional income diversification.

The substitution of exotic Erythrina for native trees of the Atlantic Forest would contribute to biodiversity. Considering the enormous availability in the southern region of Bahia and the damages to cocoa cultivation, *Erythrina poeppigiana* emerges as an option to produce panels. Despite the widespread use of Pinus to produce panels, the concentration on certain species causes scarcity and high prices, fostering research on alternative species (Trianoski *et al*., 2014).

Setter *et al*. (2021) produced plywood with *Schizolobium amazonicum*, 0.31 g/cm^3, UF, and PF adhesives. They obtained lower modulus of elasticity (MOE) and modulus of rupture (MOR) compared to commercial *Pinus taeda* panels. However, the low specific mass of paricá compared to Pinus did not proportionally influence the reduction of properties, making paricá viable for producing plywood.

Lima *et al.* (2022) evaluated the physical-mechanical properties of paricá wood, 0.31 g/cm^3, for producing plywood. They concluded that parica is viable for producing plywood, but improvements are needed in normal and parallel to grain compression resistance properties, MOR, MOE, glue line resistance to shear stress (GLSS).

Iwakiri *et al.* (2013) evaluated plywood produced from *Sequoia sempervirens*, with a basic density of 0.31 g/cm^3 and PF adhesive. They concluded that there was no significant influence of the grammage and adhesive formulation on the properties, an economically important aspect, and the viability of *Sequoia sempervirens* as a core material for exterior plywood.

There has also been research into natural adhesives as substitutes for formaldehyde-based adhesives. One of the main environmental problems with these adhesives is the emission of formaldehyde into the air, which is toxic to humans and the environment, with a high potential for causing cancer, and there is no safe level of exposure.

As an alternative to these adhesives, there is castor oil-based polyurethane, which has shown excellent performance in reconstituted wood panels. Polyurethane is water-resistant, and castor oil (*Ricinus communis*) is renewable and abundant in Brazil. It is energy-efficient, and does not require pressing temperature, whereas formaldehyde-based adhesives require around 160 °C, are non-toxic, and do not emit gases. However, the cost is still higher than other adhesives. Pressing is relevant because energy consumption accounts for most environmental impacts. The possibility of reducing the pressing temperature of the PU adhesive contributes positively to various impact analysis criteria and reduces production costs.

In addition to contributing to environmental sustainability, the utilization of erythrina wood through agro-biodiversity management to produce reconstituted wood panels can contribute to regional socioeconomic development by increasing the income of family farmers and small cocoa producers.

Therefore, this study proposes to evaluate the technical viability in terms of meeting normative physical-mechanical properties and to perform an energy balance and greenhouse gas emission assessment, considering the life cycle of panels produced from *Erythrina poeppigiana* wood, using both conventional and natural (castor oil-based PU) adhesives.

Materials and methods

Wood collection site

The trees were harvested from the Jorge Amado campus of the Federal University of Southern Bahia, Brazil, located at kilometer 22 of the BR-415 highway, 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. The altitude ranges from 50 to 56 meters above sea level. With a hot and humid climate and well-distributed rainfall throughout the year, 1200 to 1800 mm, the average annual temperature ranges from 22 to 25 °C. The soil is predominantly classified as Luvic soil (Lobão *et al*., 2011).

Harvesting, transportation, and wood preparation

Four specimens of *Erythrina poeppigiana*, with an average diameter of 45 cm, were felled and converted into 06 logs of 4 meters, transported by truck from Ilhéus (BA, Brazil) to the Department of Forestry Sciences of the Federal University of Lavras, Minas Gerais, Brazil, where they were processed.

Wood characterization

The wood of *Erythrina poeppigiana* had its chemical characteristics (lignin, extractives, ashes, holocellulose) and physical characteristic (density) determined according to NBR 14853 (ABNT, 2002), NBR 7989 (ABNT, 2003a), NBR 13999 (ABNT, 2003b) and NBR 11941 (ABNT, 2003c), to correlate with the physical-mechanical properties of the panels. The percentage of holocellulose was determined by difference.

Properties of adhesives

Each treatment used an adhesive: phenol-formaldehyde (PF), urea-formaldehyde (UF), and two-component polyurethane based on castor oil (PUA). The following properties were determined with three repetitions: contact angle, viscosity, and solids content. The contact angle was determined by goniometer by depositing one drop of 15 μL of the adhesive and taking measurements for up to 4 seconds. Wetting was determined between 5 and 55 seconds. The viscosity was determined using a Ford Cup No. 4 viscometer, following the parameters established in D-1200 (ASTM, 2018).

Production of plywood panels

Laminates were generated from wood using a rotary lathe, then cut to dimensions of 480×480×2.43 mm, and dried in an oven to approximately 8% moisture content. The panels, with five layers, were produced on a laboratory scale where adhesives were manually applied to the laminates using a spatula at a gram weight of 200 $g.m^{-2}$ (single line). After adhesive application, the laminates were coldly pre-pressed for 5 minutes, promoting contact between the layers and assisting in the transfer and distribution of the adhesive. Subsequently, the laminates were hot-pressed (UF and PF treatments) in a press cycle consisting of a pressure of 0.7845 MPa, temperature of 150 °C, and pressing time of 10 minutes. After pressing, they were left to cool to room temperature and then conditioned (22±2 °C, humidity: 65±5%). The PUA panels were cold-pressed at 0.9806 MPa for 10 minutes, without temperature for adhesive curing, and remained stapled for 6 hours.

Physical-mechanical characterization of panels

After conditioning, the panels were squared using a circular saw. Physical tests were carried out: density (ABNT, 1986a) and moisture content (ABNT, 1986b). The water absorption test was performed after 24 hours of immersion (WA24h) according to NBR 9486 (ABNT, 1986c), as well as static bending (ECS, 1993) and shear strength (ECS,1993) tests. For thickness swelling after 2 hours (TS2h) and 24 hours of immersion (TS24h), the same specimens (cp) used for water absorption were used by measuring the central part of the cp to calculate the TS by difference.

Statistical analysis

The results were subjected to statistical analysis using the Shapiro-Wilk test to verify normality and the Bartlett test to verify homoscedasticity, and finally, ANOVA. If the null hypothesis was rejected, the Tukey post hoc test was applied to compare means. The R Studio program was used at a 95% probability.

Plywood inventory

Figure 1 shows the plywood production process.

Unit of analysis

The unit of analysis encompasses the extraction of raw material (wood) for the production of panels in the sawmill, comprising two subsystems:

(a) Forest Production; and

(b) Sawmill.

Definition of objective and scope

The objective is to describe quantitatively and qualitatively the embedded energy and CO_2 emissions of the plywood manufacturing process.

Reasons for development can be considered the need for information on the environmental performance of inputs in the Brazilian context.

The purpose of this application is to provide stakeholders in the plywood production chain relevant information with the target audience being forest industries, construction, and researchers interested in the life cycle and related areas. The analysis boundary is limited to the panel production phase and the declared unit is considered as 1 m^3 of plywood.

The reference scenario considered the implementation of a plywood industry in Ilhéus, southern Bahia, Brazil, within a radius of 50 km, using the regional stock of exotic wood. Inputs are transported by highways, by trucks with a capacity of 10 to 15 tons and diesel consumption of 0.42l/km (CBCS, 2022), Table 1.

Figure 1 - **Plywood production process**

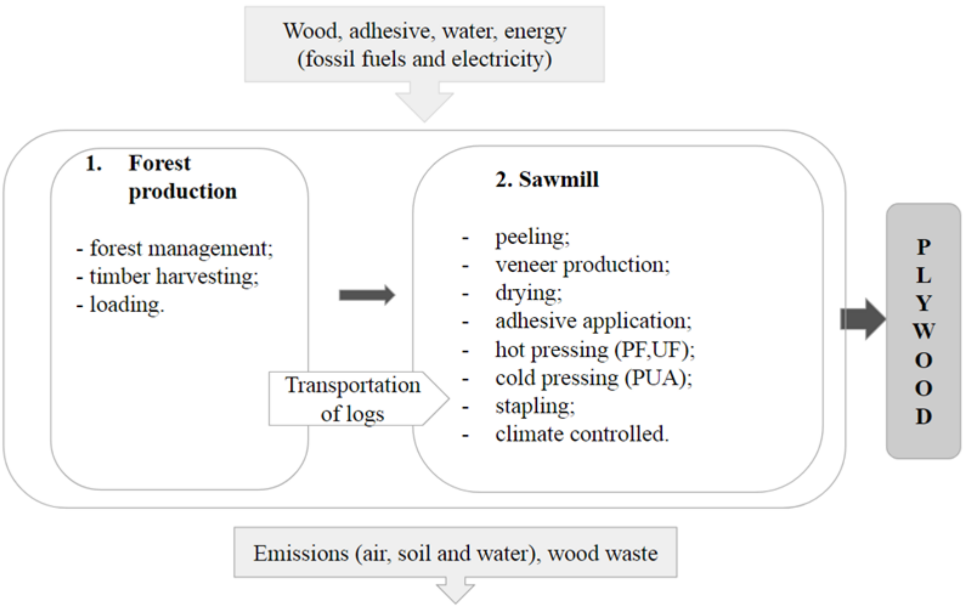


Table 1 **- Distance of transportation of inputs**

Inputs	Origin City	Destination City	Distance (km)	Diesel consumption (l/km)	Diesel consumption (l)	Specific consumption (l/t)
Wood	Ilhéus (BA, Brazil)	Ilhéus (BA)	50.00	0.42	21.00	0.0014
Urea-formaldehyde	São Paulo (SP, Brazil)	Ilhéus (BA)	1,697.50	0.42	712.95	0.04753
Phenol-formaldehyde	Rio Claro (SP, Brazil)	Ilhéus (BA)	1,696.20	0.42	712.40	0.04749
Castor oil-based polyurethane	Aguaí (SP, Brazil)	Ilhéus (BA)	1,622.90	0.42	681.62	0.045441

The values to estimate the amount of embedded energy (EE) and CO_2 emissions were separated between fossil and renewable sources. The CO_2 emissions considered refer to the burning of transportation fuels and the use of electricity. CO_2 emissions related to the decomposition of forest biomass from pruning and forest clearing were not considered. As the wood was collected from an experimental cocoa production area, CO_2 emissions from land use change were not considered. The solar energy required for tree growth was not evaluated.

Equation 1 was used to calculate diesel consumption.

$$Cdiesel = D \; x \; fc \qquad \text{Eq. 1}$$

Where:

Cdiesel: diesel consumption (liters);

D: transport distance; and

fc: fuel consumption factor, according to the vehicle.

The trucks were considered to be going and returning loaded, counting the distance only once.

The conversion of fuels into EE was carried out according to Table 2.

According to the National Agency of Petroleum, Natural Gas and Biofuels (ANP, 2021) Brazilian diesel is composed of 87% pure diesel and 13% biodiesel, and gasoline by 73% of pure gasoline and 27% of anhydrous ethanol, therefore the embodied energy per liter of diesel and gasoline, in Brazil, is presented below:

Diesel oil (pure): 35.52 x 0.87 = 30.90 MJ/L;

Biodiesel: 33.16 x 0.13 = 4.31 MJ/L;

Brazilian diesel = 30.90 + 4.31 = 35.21 MJ/L;

Gasoline (pure): 32.31 x 0.73 = 23.59 MJ/L;

Anhydrous Ethanol: 22.35 x 0.27 = 6.03 MJ/L; and

Brazilian gasoline = 23.59 + 6.03 = 29.62 MJ/L.

Conversion factors from Table 3 were used for quantifying EE and CO_2e emissions.

Life Cycle Energy Assessment (LCEA) and CO_2 Emissions Assessment (LCCA)

Li (2021) defined Life Cycle Energy Assessment (LCEA) and CO_2 Emissions Assessment (LCCA) as simplified but significant ways to conduct an environmental analysis. With a simpler structure than LCA, NBR ISO 14040 (ABNT, 2009), LCEA and LCCA prioritize the survey of direct and indirect energy consumption and the quantification and evaluation of CO_2 emissions from the main stages of the life cycle of a product or process, requiring fewer costs and execution time.

Table 2 - **Conversion of fuels into embedded energy**

Unit	Pure diesel	Biodiesel	Pure gasoline	Anhydrous ethanol
MJ/L	35.52	33.16	32.31	22.35

Source: based on GHG Protocol (FGV, 2021).

Table 3 - **Conversion factors**

Flows	Unid	CO_2e emission (kg/un)	Source	Energy consumption (MJ/un)
Wood	m^3	0.0	Planted, carbon neutral, biogenic CO_2	-
Gasoline	l	2.2	Emission factor from the National Greenhouse Gas Inventory (top-down approach)	29.62
Diesel oil	l	2.6	Emission factor from the National Greenhouse Gas Inventory (top-down approach)	35.21
Electricity	kWh	0.075	CO_2 emission factor for electricity generation in the National Interconnected System of Brazil - MCTI (2019 average) Energy: National Energy Balance (2018)	4.92

Source: CBCS (2022).

All activities occurring within the boundary and their input and output flows were identified to describe the elementary process. This mapping of activities allowed the creation of data collection spreadsheets. After mapping, the input and output flows of the process were quantified. A scenario to quantify the flows, where the plantation of Erythrina and the production of plywood were in Ilhéus (BA), was considered.

Subsystem forest production

Comprises the production of raw material. Considering the pre-existing stock of *Erythrina poeppigiana* planted for shading cocoa, forest production begins with forest management, including harvesting and transportation of wood (Figure 2).

The timber harvest was manual, using a chainsaw, with a production of 200 kg/t of log wood waste. Raw material, inputs, and energy flows were appropriated from the process, and the output was considered in terms of CO_2 emissions associated with energy consumption. One ton of raw wood was considered as the declared unit.

Sawmill subsystem

Comprises the processing of raw wood and the production of plywood. The boundaries are delimited from log reception to the finalization of panel production, as shown in Figure 3.

Inputs of raw materials and energy flows from the plywood production process were considered, as well as the output in terms of CO_2 emissions associated with energy consumption.

Results and discussion

Chemical properties of wood

According to Frihart (2015), lignin, the most hydrophobic component of wood, provides hardness and stiffness to the cell wall, protection against microorganisms, sustainability for fibers and vessels, providing high durability to wood, greater mechanical performance and water resistance, as shown in Table 4.

The extractives content of tropical hardwoods can exceed 10%, as found by Mota *et al.* (2015) of 11.34% for *Schizolobium parahyba*, 14.79% for *Acrocarpus fraxinolius* and 15.94% for *Australian cedar*. The concentration of extractives at 9.54% can be attributed to the age of the trees, estimated to be over 40 years old, as well as to the tropical region of collection. High levels of extractives can impair veneer bonding by promoting premature curing of the adhesive upon contact with the extractives, be related to compression strength, and enhance resistance to microorganisms (Trianoski *et al.*, 2015).

Figure 2 - **Forest Production Subsystem**

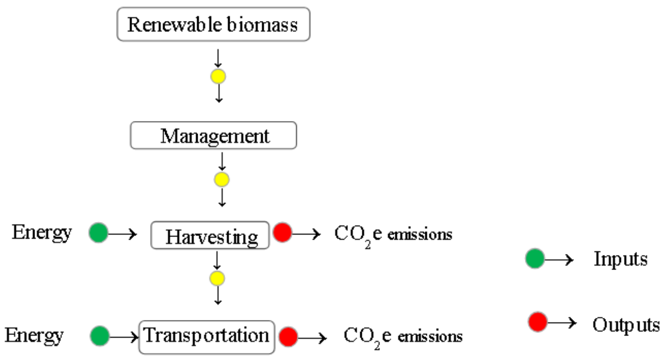


Figure 3 - **Sawmill Subsystem**

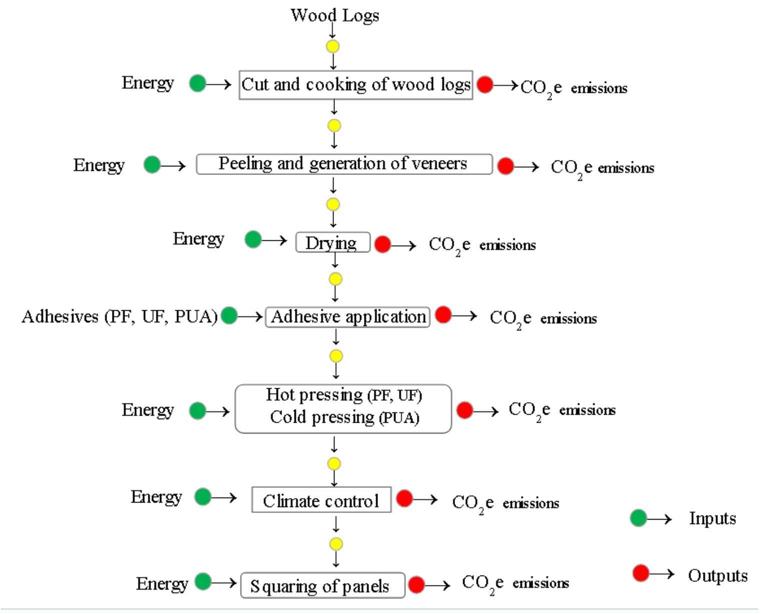


Table 4 - **chemical characterization of *Erythrina poeppigiana***

	Ash	Cellulose	Lignin	Extractives	Holocellulose
Content (%)	3.12 (0.074)	43.01 (1.529)	18.91 (1.027)	9.54 (1.365)	68.43 (0.833)

Note: Holocellulose = cellulose + hemicelluloses. The values in parentheses refer to the standard deviation.

Iwakiri and Trianoski (2020) indicate that ashes, inorganic substances, are usually found below 0.5% and do not have an effect on adhesive bonding but can affect the pH and machinability of the wood due to the presence of minerals such as silica. Higher percentages can be found in tropical woods. In this research, a higher percentage of ashes was obtained, but no negative influence was identified in the tests.

Hardwoods, such as Erythrina, contain a higher proportion of hemicelluloses in the holocellulose content. According to Frihart (2005), hemicelluloses provide additional chemical bonds, improving adhesion between the plywood sheets and the panel strength.

Physical properties of wood

Density is the main property of wood that affects the properties of the panels (Trianoski *et al.*, 2015). According to Lisboa *et al.* (2015), suitable species for lamination tend to have low to medium density. The basic density of *Erythrina poeppigiana* was 0.26 g/cm^3, classified as low-density wood. This is lower than the value reported by Lorenzi (2016), which is 0.41 g/cm^3.

Trianoski *et al*. (2015) produced plywood with *Melia azedarach*, with a density of 0.48 g/cm^3. Pinto and Iwakiri (2013) produced plywood with *Cryptomeria japonica*, with a density of 0.25 g/cm^3, similar to that of *Erythrina poeppigiana* and lower than that of Pinus, the most commonly used species for producing plywood. Both studies conclude that panels can be produced with low-density wood.

Adhesive properties

PUA had the lowest contact angle, Table 5, indicating greater adhesive strength between the adhesive and the sheet than the cohesive strength between adhesive molecules. It was the adhesive with the highest wettability and wetting with sheets due to the high polymerization reactivity of the PU adhesive in the wood. In addition to hydrogen bonding, covalent bonding occurs between the hydroxyl (OH) groups on the wood surface and the adhesive molecules. The good performance of polyurethane adhesives is due to hydrogen bonding with some substrates and their low viscosity, penetrating into substrate pores and forming covalent bonds with substrates with active hydrogen.

A strong adhesive joint requires good wetting and solidification by the adhesive; sufficient deformability to withstand elastic stresses in the joint formation process (Trianoski *et al*., 2015). No specific test was carried out to verify the adhesive joint, but good results of shear strength were obtained. The low density of *Erythrina poeppigiana*, 0.26 g/cm^3, facilitated the permeability of the adhesives. Mesquita *et al*. (2018) present the polymerization of UF adhesive. By adding two molecules of formaldehyde to the urea molecule, condensation occurs between the oxygen of formaldehyde and the nitrogen groups of urea. The free hydroxyl groups form intra- and intermolecular hydrogen bridges, as shown in Figure 4.

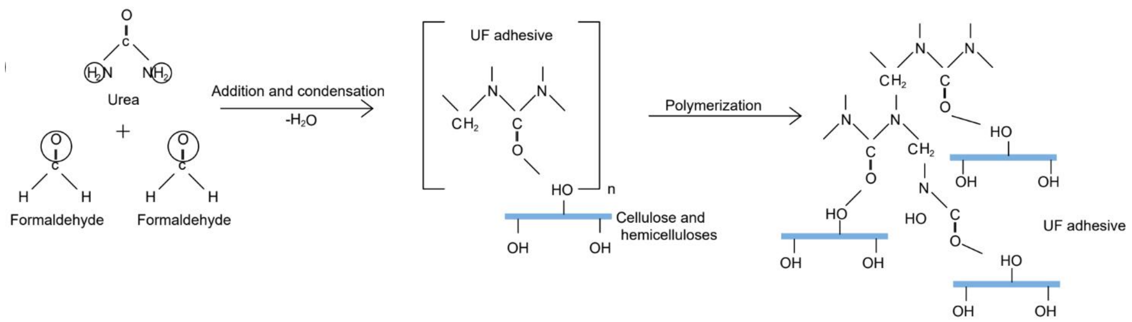
The presence of hydroxyl groups (OH) in the composition of the PF adhesive makes it sensitive to alkaline substances. Cross-linking between the adhesive and the lignocellulosic surface provides the panel with good physical and mechanical performance depending on the adhesive content, pressing time, and temperature (Frihart, 2005), as shown in Figure 5.

A similar reaction occurs between the wood surface and the PU adhesive, where hydrogen and covalent bonds are formed between hydroxyl groups, in addition to mechanical adhesion, where the adhesive penetrates the lumen of fibers and vessels. Increasing the NCO/OH molar ratio in the wood leads to an increase in the adhesive power of the PU since wood is mainly composed of cellulose and contains OH in its composition. The higher the NCO/OH ratio, the more free NCO, increasing the probability of forming covalent bonds between the PU and the wood, Figure 6 (Dunky, 2004).

Table 5 - **Adhesive properties**

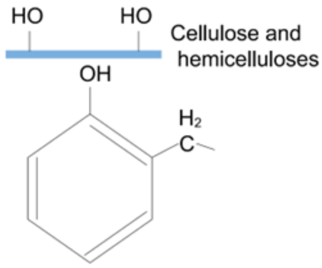
Adhesive	Contact angle and wettability	Viscosity (cP)	Solid content (%)
PF	121.91	643.48	46.20
UF	124.23	350 - 600	63.62
PUA	114.67	402.25 CST	100

Figure 4 - **Chemical scheme of UF adhesive polymerization**



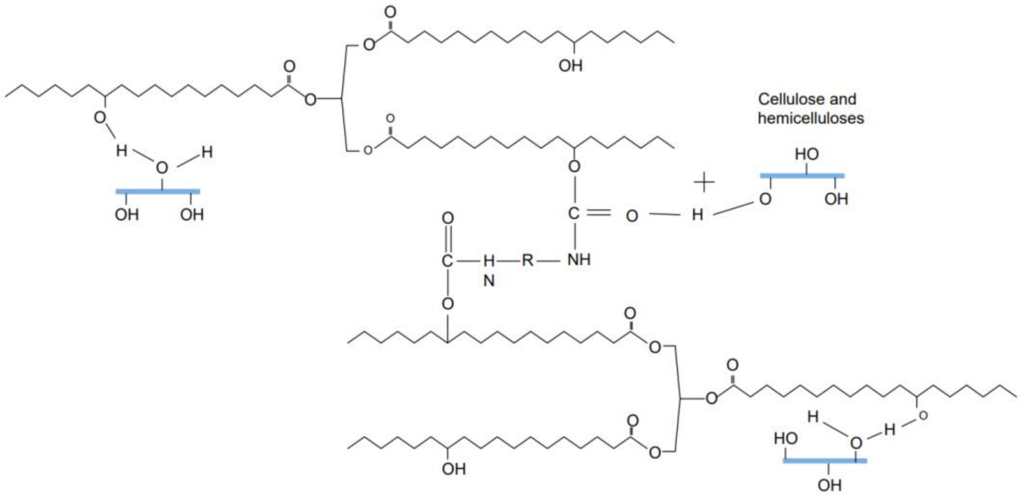
Source: adapted from Mesquita *et al*. (2018) and Frihart (2005).

Figure 5 **- Chemical scheme of PF adhesive polymerization**



Source: adapted from Dunky (2004).

Figure 6 **- Chemical scheme of the PU adhesive polymerization**



Source: adapted from Faria *et al*. (2020).

Physical properties of panels

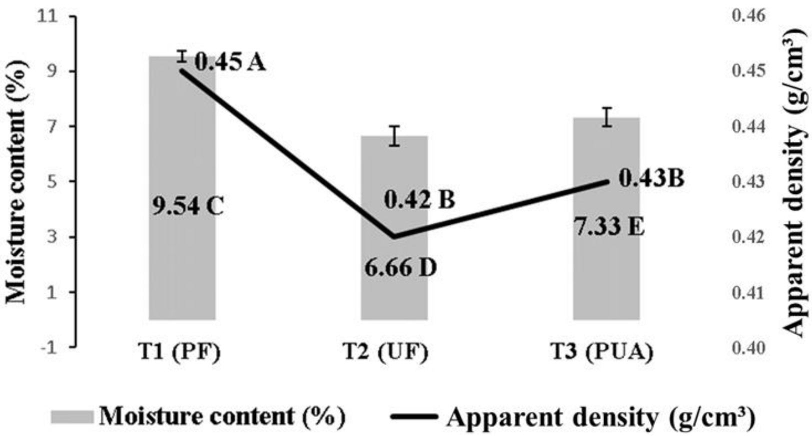
As there were no reports in the literature on plywood produced with *Erythrina poeppigiana*, 0.41 g/cm^3 (Lorenzi, 2016), the discussion was based on panels produced with low-density species such as *Schizolobium amazonicum* (paricá), 0.35 g/cm^3, *Schizolobium parahyba* (guapuruvu), 0.32 g/cm^3 (LORENZI, 2016), and Pinus, 0.50 g/cm^3, the most commonly used species in Brazil for panel production.

Density and moisture content

The mean density values of the produced panels, after conditioning in a climatized room at 20 °C and 65% relative humidity, ranged from 0.42 g/cm^3 to 0.45 g/cm^3, as shown in Figure 7, indicating non-structural use but allowing for other applications. The lower apparent density of panels provides greater lightness and ease of installation and is also interesting for the construction industry, as it has a good relationship between strength and weight

There were no significant correlations observed between density and physical-mechanical properties. Costa *et al*. (2020) found an average density of 0.38 g/cm^3 for parica plywood. The *Erythrina poeppigiana* plywood had a density between 0.42 and 0.45 g/cm^3, 20% higher than that of paricá panels, despite Erythrina being less dense. The average moisture content ranged from 6.66 to 9.54%, lower than that of Ferreira *et al*. (2022), which was 12.26 to 12.61% for thermally treated *Pinus taeda* plywood. The results comply with the limit of 12% according to NBR 9484 (ABNT, 2011). T2 (UF) and T3 (PUA) had similar densities and slight variations in moisture content, indicating that small variations in moisture content do not impact density.

Figure 7 - **Moisture content and apparent density**



Note: PF = phenol-formaldehyde; UF = urea-formaldehyde; PUA = castor oil-based two-component polyurethane. Means followed by the same letter are statistically equal by Tukey's test at 95% confidence level.

Water Absorption (WA)

The average values of 2-hour WA ranged from 29.68% to 37.16%, and 24-hour WA from 63.24% to 76.14%. T2 (UF) showed the highest WA. T3 performed better than T2 and slightly lower than T1, as shown in Figure 8. Tukey's test indicates a significant statistical difference between all treatments in 2-hour WA and T2 of 24-hour WA.

Wood is composed of lignin, cellulose, and hemicelluloses, the latter two being hydrophilic compounds. When exposed to moisture, lignocellulosic materials change their dimensions due to the presence of hydroxyl groups in the cell walls that interact with water through hydrogen bonding (Sinderski, 2020). High levels of holocellulose, due to their hydrophilicity resulting from the presence of OH groups in cellulose and hemicelluloses, as well as low lignin content, favor water absorption. Therefore, the low lignin content combined with the high holocellulose content of Erythrina favor WA, but the results obtained are lower than those reported in the literature for other low-density woods.

Setter *et al*. (2021) pointed out the influence of adhesive type on panel WA. The UF adhesive is highly hygroscopic. Iwakiri and Trianoski (2020) indicated the susceptibility to hydrolytic degradation of urea-formaldehyde polymers in the presence of moisture and/or acids, especially at moderate to high temperatures, situations that promote bond breakage and formaldehyde emission. This situation was observed in T2, the treatment with the highest WA.

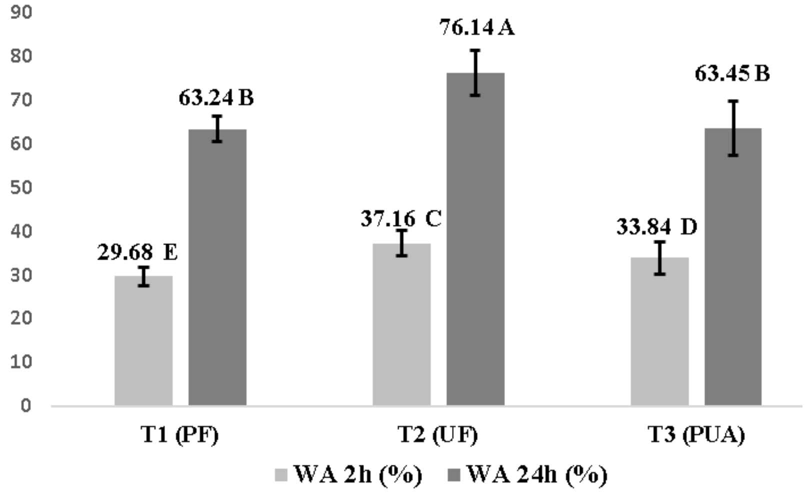
Costa *et al*. (2020) obtained WA2h between 36.55% and 48.18% and WA24h between 63.23% and 81.14% for plywood with seven layers of *Schizolobium amazonicum* and UF adhesive, higher values than T2 (UF). Setter *et al*. (2021) obtained WA24h equal to 62.76% and 67.36% for *Pinus oocarpa* plywood with PF adhesive, gram weight of 150 g/m^2, and UF adhesive, respectively. Values close to those obtained with erythrina plywood, which can be justified by the higher gram weight used, 200 g/m^2. The authors obtained WA24h equal to 71.93% for PF treatment and 82.84% for UF treatment for *Schizolobium amazonicum* (paricá). Despite Erythrina having a lower density than paricá, lower levels of WA were obtained. It is inferred that there may have been an influence by the higher gram weight of the adhesives, 200 g/m^2, since denser wood normally has fewer voids, therefore, less space to absorb water.

Palma, Moreno, and Ballarin (2017) observed a tendency of water absorption reduction with the increase in density and the opposite behavior in thickness swelling. Greater water absorption in less dense panels occurs due to the existence of a greater amount of voids, enabling water filling. The lower WA of Erythrina plywood can be attributed to the gram weight used, 200 g/m^2, higher than that in the cited study.

Thickness Swelling (TS)

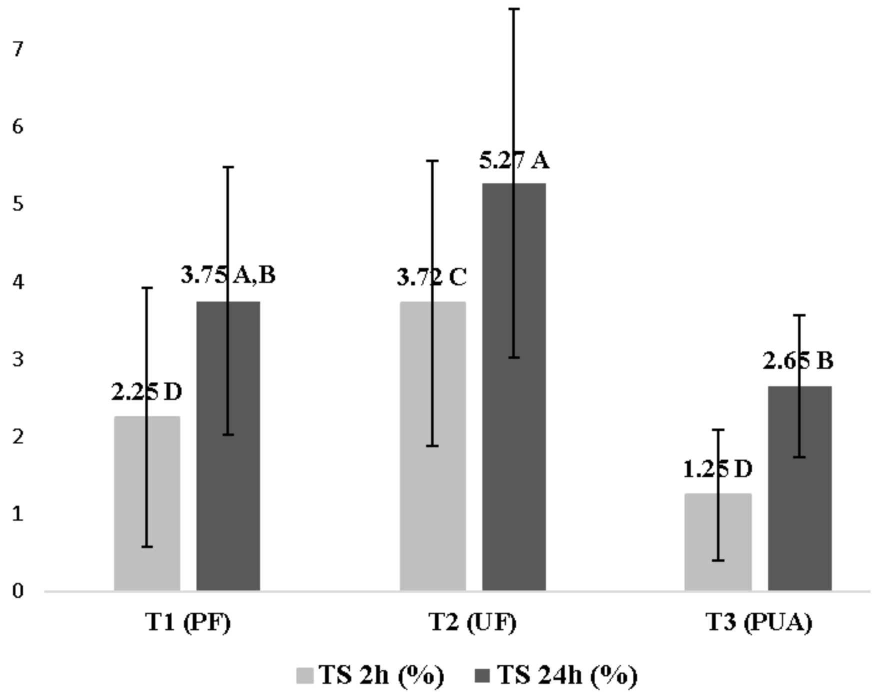
TS2h ranged from 1.25% to 3.72%, and TS24h ranged from 2.65% to 5.27%. The PF adhesive has high resistance to moisture, justifying the better performance of T1 (PF). The highest TS was obtained by T2, whose adhesive is urea-formaldehyde, less resistant to water, and the lowest TS was obtained by T3, produced with PUA adhesive, due to the water resistance of polyurethane, as shown in Figure 9.

Figure 8 - **Mean values of water absorption**



Note: PF = phenol-formaldehyde; UF = urea-formaldehyde; PUA = castor oil-based two-component polyurethane. Means followed by the same letter are statistically equal by Tukey's test at 95% confidence level.

Figure 9 - **Average values of TS**



Note: PF = phenol-formaldehyde; UF = urea-formaldehyde; PUA = castor oil-based two-component polyurethane. Means followed by the same letter are statistically equal by Tukey's test at 95% confidence level.

By Tukey's test, a significant difference was observed between the means of T2 and T3 for TS24h. In TS2h, there was a significant statistical difference for T2. According to Palma, Moreno, and Ballarin (2017), a greater quantity of wood input in TS promotes a higher supply of hygroscopic sites. Contraction and swelling are attributed to the thickness of the cell wall and to the gain or loss of moisture below the fiber saturation point (FSP). Denser woods have a greater cell wall thickness. Ferreira *et al.* (2022) obtained TS values ranging from 7.88% to 8.69% for thermally treated *Pinus taeda* plywood. Sugahara *et al.* (2022) obtained 6.85% TS for *Pinus taeda* plywood produced with PF adhesive and 6.13% with castor oil-based PUA adhesive. The lower density of Erythrina favored lower TS for the panels.

Trianoski *et al.* (2015) pointed out the influence of wood chemical composition, especially the extractive content, on moisture adsorption, desorption, shrinkage, and wettability, as they are components occupying the cell wall that could be occupied by water. This study did not detail the erythrina extractives, only measuring their total percentage. The high extractive content may have contributed to the lower TS and WA in this research.

PUA adhesive in plywood significantly influences the reduction of absorption and swelling levels because it is hydrophobic. The primary covalent bonds formed between the wood hydroxyl groups and the isocyanate of the PUA adhesive are strong and stable, establishing adhesion forces much greater than those obtained by UF and PF adhesives, justifying the lower TS values for T3.

Mechanical properties of panels

Glue Line resistance to Shear Stress - GLSS

The average dry GLSS values ranged from 3.35 MPa to 5.06 MPa, and from 2.77 MPa to 4.14 MPa for wet conditions, as shown in Figure 10. All treatments had GLSS means higher than the EN314-2 (1993b) minimum, ruling out the evaluation of wood failure.

In both dry and wet conditions, statistical analysis using Tukey's test showed significant differences only in T3. All results exceeded the standard established by ABIMCI (2002), which requires a GLSS of 2.74 MPa for structural Pinus plywood with a thickness of 12 mm and five plies.

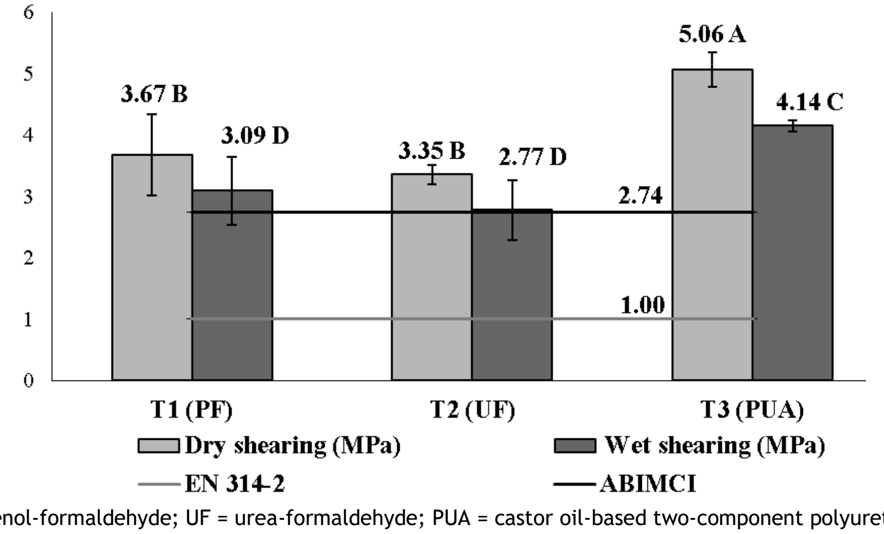
Erythrina poeppigiana wood showed satisfactory bonding, meeting the minimum normative requirements with a wide margin of safety. The low density of Erythrina (0.26 g/cm^3) may have influenced better penetration of the adhesive into the veneers, improving the bonding and increasing the GLSS (Costa *et al*., 2020). Despite high levels of extractives (9.54%) and ashes (3.12%), no negative effects on the bonding of the veneers were observed.

The average GLSS values obtained in this study were higher than those reported by Matos *et al*. (2019), who obtained a GLSS of 3.28 MPa for *Schizolobium amazonicum* plywood, with a density of 0.31 g/cm^3, produced with UF adhesive at a grammage of 150 g/m^2, and 3.24 MPa when PF adhesive was used. The higher grammage used in all treatments in this study (200 g/m^2) may have influenced this result.

Sugahara *et al*. (2022) found GLSS of 2.87 MPa for *Pinus taeda* plywood using PF adhesive, a grammage of 395 g/m^2, a double line, and 2.35 MPa when using PU castor oil adhesive, lower than the results of this study, even with equivalent grammage. The influence of wood density (Erythrina) on GLSS results can be inferred because less dense wood allows greater penetration of the adhesive, providing better adhesion quality and, consequently, higher GLSS.

T3 showed the highest average strengths, which may be attributed to the lower contact angle formed by the PU adhesive, compared to the angles of PF and UF adhesives, as a lower angle favors bonding, resulting in higher strength.

Figure 10 - **Shear strength (MPa)**



Note: PF = phenol-formaldehyde; UF = urea-formaldehyde; PUA = castor oil-based two-component polyurethane. Means followed by the same letter are statistically equal by Tukey's test at 95% confidence level.

According to EN 314-2 (ECS, 1993), *Erythrina poeppigiana* plywood can be classified as Class 1 (dry conditions) and Class 2 (wet conditions). Post-boiling tests were not performed to evaluate the possibility of external use.

Parallel static bending

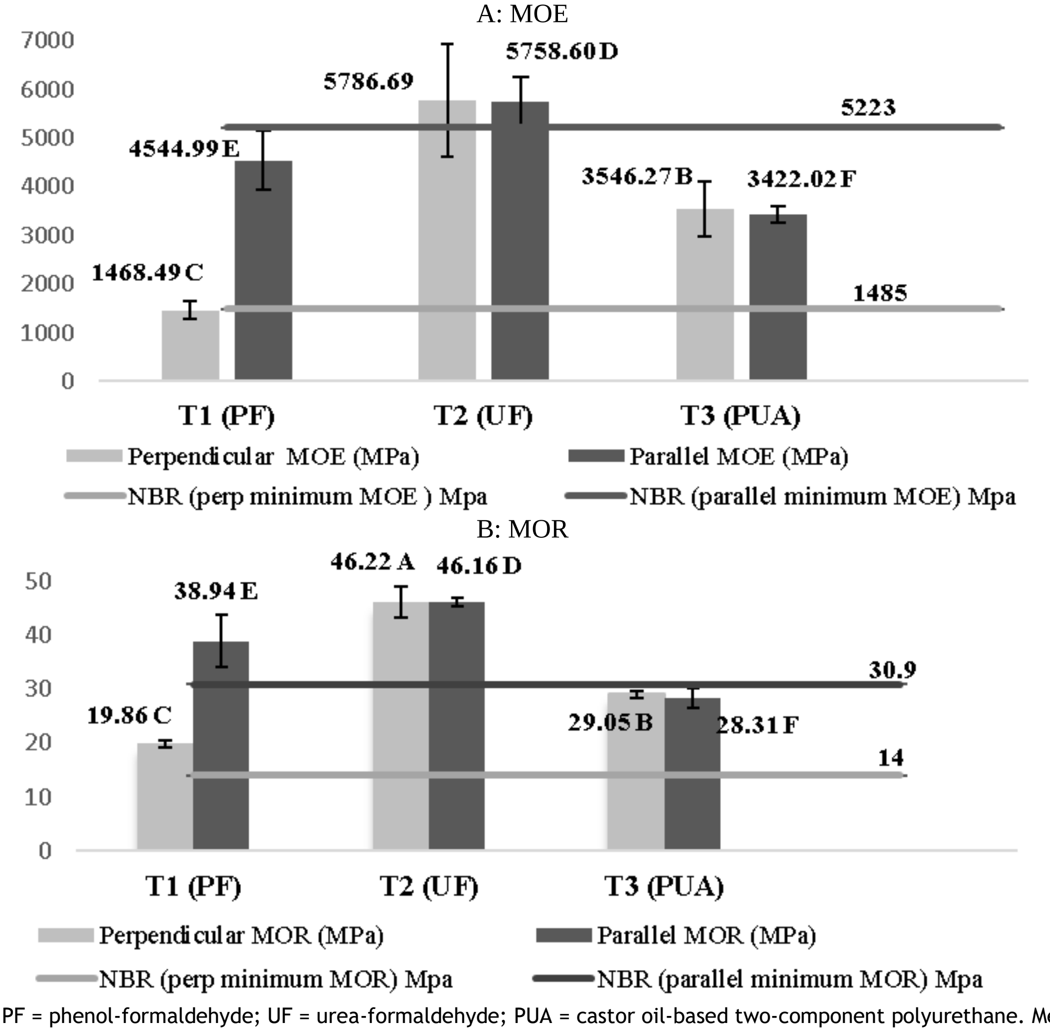
The modulus of elasticity (MOE) ranged from 5,758.60 MPa to 3,422.02 MPa. The modulus of rupture (MOR) ranged from 28.31 MPa (T3) to 46.16 MPa (T2). T2 (UF) showed the highest values of MOE and MOR, as shown in Figures 11a and 11b.

Statistically significant differences were found between the means of all treatments for both parallel and perpendicular MOE and MOR, according to Tukey's test. T1 (PF) and T2 (UF) easily meet the ABIMCI parameters for MOE and MOR. T3 (PUA) partially meets the criteria, as it reaches 99.68% of the minimum MOE required for external structural use.

Compared to NBR 31:000.05-001/2 (ABNT, 2001), only T3 (PUA) does not meet the minimum value for parallel MOR. Only T2 (UF) meets the minimum MOE for structural use. However, T1 and T3 may have used such as walls, partitions, furniture, or non-structural purposes.

The DIN 68792 (DIN, 2016) establishes minimum MOR and MOE of 45 and 5000 MPa. In this case, only T2 meets the requirement, and it can be used for concrete forms or construction. However, the urea-formaldehyde adhesive makes it unsuitable for external or humid conditions.

Figure 11 - **Average behavior for static bending**



Note: PF = phenol-formaldehyde; UF = urea-formaldehyde; PUA = castor oil-based two-component polyurethane. Means followed by the same letter are statistically equal by Tukey's test at 95% confidence level.

Matos *et al*. (2019) obtained MOE of 2154 MPa and MOR of 22.48 MPa for *Schizolobium amazonicum* plywood with a grammage of 150 g/m^2 and a 2 mm veneer thickness. Comparatively, the higher values obtained in this research may be attributed to the thicker veneers, 2.43 mm, and higher grammage, 200 g/m^2.

Sugahara *et al*. (2022) obtained an MOR of 46.92 and MOE of 4,758.58 MPa for *Pinus taeda* plywood with a grammage of 395 g/m^2 and double lines using PF adhesive. For PUA castor oil adhesive, they found MOR of 30.67 and MOE of 3,969.92 MPa. It can be inferred that all values higher than those obtained in this research, respectively by 20.5%, 4.7%, 8.3%, and 16%, may be due to the higher density of pine compared to Erythrina.

The parallel MOR values obtained are compatible with the literature and above the ABIMCI (2002) standards, except for T3 (PUA).

Static perpendicular bending

T2 (UF) showed higher values for MOE and MOR, Figures 11a and 11b, indicating the influence of the adhesive on strength. Despite the higher average strength, treatment T2 is recommended for indoor use only due to the low moisture resistance of the UF adhesive.

Only T1 (PF) did not meet the minimum of 1.485 MPa for perpendicular MOE stipulated by NBR 31:000.05-001/2 (ABNT, 2001). The results found for perpendicular MOR, between 19.86 and 29.05 MPa, comply with NBR 31:000.05-001/2 (ABNT, 2001).

The minimum values required by DIN 68792 (DIN, 2016) are 30 MPa for MOR and 2500 MPa for MOE. Thus, T1 (PF) does not comply, T2 (UF) fully complies, and T3 (PUA) partially complies, as the MOR reached 96.83% of the minimum.

ABIMCI (2002) indicates average values of MOE and MOR equal to 2,839 MPa and 25.3 MPa for commercial panels of *Pinus taeda* with a specific mass of 0.53 g/cm^3. T2 (UF) and T3 (PUA) meet the ABIMCI parameters. Considering that *Erythrina poeppigiana* has a lower specific mass equal to 0.262 g/cm^3, the MOE and MOR values can be considered satisfactory for all treatments.

Sugahara *et al*. (2022) obtained, in *Pinus taeda* plywood, a weight of 395 g/m^2, double line, MOR, and MOE with PF, respectively 18.95 and 1,648.34 MPa, compatible with the results of T1 (PF). For the treatment with castor oil-based PU, they obtained a MOR of 18.52 MPa and MOE of 1,372.75 MPa, results lower than those of T3 (PUA). As Erythrina has a lower density than Pinus, the results can be attributed to various causes, such as pressure applied to the sheets, moisture content of the sheets, and age of the trees.

Matos *et al*. (2019) obtained, for *Schizolobium amazonicum* plywood and UF adhesive, 0.31 g/cm^3, perpendicular MOE, and MOR equal to 1,027 and 15.98 MPa, respectively, values much lower than those of T2 (UF), which used a higher weight, 200 g/m^2. Using PF adhesive, they obtained a MOE corresponding to 1,507 MPa and a MOR of 18 MPa, compatible with the results of T1 (PF), produced with Erythrina, less dense but with a higher weight of 200 g/m^2.

It is concluded that the low density of Erythrina did not influence the results of static bending, which can occur because wood is a biological, heterogeneous material with great variability.

Production process inventory for plywood

To produce 1 m^3 of 12mm plywood, wood, adhesive, and energy are needed, as shown in Table 6.

Table 6 – **Production process inventory for plywood**

Inputs	Unit	Amount		
		T1 (PF)	T2 (UF)	T3 (PUA)
Wood	kg/m^3	262.00	262.00	262.00
Adhesive (PF, UF e PUA)	kg/m^3	6.66	6.66	6.66
Energy	MJ/m^3	3,105.07	3,031.81	2,927.94
Outputs				
Plywood	m^3	1	1	1
CO_2e	kg/m^3	63.68	64.96	54.58

Based on the results of parallel and perpendicular MOE and MOR, treatment T1 (PF) did not reach the minimum values of perpendicular MOR and MOE.

To quantify the energy consumption within the plywood system, considering the Forest Production and Sawmill subsystems, the electricity consumption was measured by the relation between the power and processing time of the electric motor of the equipment used, as shown in Table 7. The inputs and outputs related to the production of PF and UF adhesives were obtained from Wilson (2010) for adhesives produced in the USA. The author considered coal, natural gas, petroleum, and uranium to produce electricity. As for the castor oil-based PUA adhesive, data was only available for the isocyanate, from Franklin Associates (2022), due to a lack of information from the manufacturer regarding the polyol.

The use of biomaterials such as wood, when sourced from plantations rather than native forests, promotes lower CO_2 emissions and reduces atmospheric CO_2 through forest management for timber production.

Puettmann and Wilson (2005) conducted a cradle-to-gate life cycle assessment (LCA) for plywood, considering the southern east coast and northern west coast of the US. Embodied energy (EE) in harvesting ranged from 148 to 206 MJ/m^3; log transportation between 90 and 196 MJ/m^3; manufacturing between 2700 and 4227 MJ/m^3; and adhesive production between 699 and 1021 MJ/m^3. Manufacturing had the highest EE values due to wood drying. The southern east coast uses 46% fossil fuels, while the northern west coast uses about 74% hydroelectricity to generate electricity. Thus, the northern region yielded 202 $kgCO_2/m^3$ (0.43 $kgCO_2/kg$) of plywood and the southern region 357 $kgCO_2/m^3$ (0.60 $kgCO_2/kg$).

This study obtained 6.13 MJ/m^3 for harvesting EE, corresponding to less than 1% of what the authors mentioned. The significant difference in values may be attributed to the US energy mix using coal and petroleum-derived products compared to Brazilian gasoline, which uses 27% biofuels for harvesting.

Puettmann *et al*. (2013) cradle-to-gate data for plywood produced in the Pacific Northwest of the United States using PF adhesive show emissions of 10.74 $kgCO_2/m^3$ for forestry operations (seedling cultivation, planting, thinning, fertilization, final harvest) and 103.36 $kgCO_2/m^3$ for production, totaling 114.10 $kgCO_2/m^3$ of plywood. It was concluded that 1 m^3 emits 114 $kgCO_2e$ and stores 846 $kgCO_2e$. As for EE, they obtained 159.89 MJ/m^3 for forestry operations and 4,826.25 MJ/m^3 for production.

Table 7 – **Embodied energy and CO_2e emissions per m^3 of plywood**

Subsystem stages	Embodied energy (MJ/m^3)	CO_2e emissions ($kgCO_2e/m^3$)
Forest Production Subsystem		
Harvesting	6.13	0.45
Transportation	61.62	4.55
Total Forest Production Subsystem	**67.75**	**5.00**
Sawmill Subsystem		
Cut of wood logs	5.5	0.41
Cooking of wood logs	1,032.10	15.73
Peeling and generation of veneers	32.56	0.49
Drying	273.85	4.17
Adhesive application		
PF (T1)	268.73*	16.17*
UF (T2)	195.47*	17.45 *
PUA (T3)	93.24**	7.09***
Hot pressing (PF, UF)	1.64	0.025
Cold pressing (PUA)	0	0
Climate control	1,322.49	20.16
Squaring of panels	100.45	1.53
Subtotal Sawmill Subsystem T1(PF)	**3,037.32**	**58.68**
Subtotal Sawmill Subsystem T2(UF)	**2,964.06**	**59.96**
Subtotal Sawmill Subsystem T3(PUA)	**2,860.19**	**49.58**

Note: based on: *Wilson (2010); **Khoshnevisan, Rafiee and Tabatabaei (2018); and ***Franklin Associates (2022).

This research obtained 5.0 $kgCO_2e/m^3$ of plywood for forestry production. Unlike Puettmann *et al*. (2013), this study considered log transportation in forestry production, which contributes 4.55 $kgCO_2e/m^3$, corresponding to 91% of the CO_2e emission from the subsystem. Only 0.45 $kgCO_2e/m^3$ corresponds to harvesting. The EE in forestry production was 67.75 MJ/m^3. The EE obtained in this study corresponds to 42% of what was obtained by Puettmann *et al*. (2013), which can be justified by considering fewer procedural steps. It should be noted that 91% of the EE and CO_2e emissions from forestry production correspond to log transportation, demonstrating the relevance of proximity between harvesting and wood processing sites.

According to Tavares and Bragança (2016), plywood used in Brazilian constructions emits 0.41 $kgCO_2/kg$ and has an EE of 8.0 MJ/kg. This study obtained 84.13 $kgCO_2/m^3$ and 4,446.801 MJ/m^3 for T1 (PF), corresponding to 0.31 $kgCO_2/kg$ and 16.55 MJ/kg.

Wang *et al*. (2017) identified that producing wood panels in China causes CO_2 emissions, 4.61 Mt CO_2/year. Between 2008 and 2015, despite the increase in production, they were a carbon sink due, 15.17 Mt CO_2/year, to the reduction of EE in the production process. When they were an emitter and then a sink, plywood was the most contributing panel.

Puettmann (2022) highlighted the ability of wood panels to store more carbon than is emitted in their production. In 2019, 291 million m^3 of panels in North America stored 354 million tons of CO_2e, enough to offset 24 years of carbon emissions from the production of these panels.

Lao and Chang (2023) quantified the cradle-to-gate GHG footprint of wood panels produced in China and obtained, disregarding biogenic carbon storage, 538 $kgCO_2e/m^3$ for plywood, which is more than eight times higher than the highest emission in this study (T2), which can be attributed to China's energy mix, which is more dependent on fossil fuels than Brazil's.

Wang *et al*. (2019) quantified the energy used in the pressing stage of plywood and found the possibility of reducing it by 23-27% by using an eco-friendly soy protein adhesive, reducing temperature and curing time. The lowest GHG emissions in this research were from T3 produced with castor oil-based PU adhesive, which does not require temperature during pressing.

T1 (PF) had the highest GHG emissions, and T2 (UF) had the highest CO_2e emissions. T3 (PUA) had the lowest GHG and CO_2e emissions, as shown in Table 8. However, since the manufacturer of the castor oil-based PU adhesive does not provide information on the inputs and production processes, it was not possible to perform the ICV and calculate the impacts of the polyol. Therefore, data on the isocyanate were obtained from Franklin Associates (2022), assuming a 1:1 ratio between the polyol and the isocyanate (MDI).

Despite the low density of Erythrina, the results obtained for the RLC, based on EN 314-2 (ECS, 1993), are excellent, allowing us to conclude that all panels showed good bonding quality and are suitable for internal and intermediate use. According to the results obtained in the static bending tests and compared to DIN 68792 (DIN, 2016), all treatments are suitable for use as partitions, furniture, and non-structural uses. The T3 (PUA) showed good physical-mechanical properties, and the natural adhesive does not require hot pressing, which is energy-intensive and relevant in the plywood's life cycle. The T1 (PF) showed higher formaldehyde emissions (EE), and the T2 (UF) showed the highest CO_2e emissions. The T3 (PUA) showed the lowest EE and CO_2e emissions. Compared to the literature, most studies conducted in North America and China, where energy matrices depend much more on fossil fuels than in Brazil, the values found are lower, demonstrating that Brazilian plywood can have better environmental performance and, combined with the good performance of the Brazilian forest industry, become a potential export product.

Table 8 – **Embodied Energy and CO_2e Emissions**

Treatment	**Embodied Energy (MJ/m^3)**	**CO_2e Emissions ($kgCO_2e/m^3$)**
T1 (PF)	3,105.07	63.68
T2 (UF)	3,031.81	64.96
T3 (PUA)	2,927.94	54.58

Conclusions

Thus, based on the analyzed properties, normative parameters, and environmental performance concerning embedded energy and CO_2e emissions, it is concluded that *Erythrina poeppigiana* wood is viable for producing plywood for internal and intermediate use, contributing to the socioeconomic development of southern Bahia through sustainable forestry production and diversifying the income generation of small farmers and cocoa producers.

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