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ARTÍCULO

Bonding performance of *Pinus caribaea* varieties under different adhesives systems for edge glued panels production

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Abstract:

The performance of bonded wood products depends on wood properties and adhesive systems, resulting in variability in bonding. Although *Pinus caribaea* has been introduced in Brazil since the mid-20th century and presents potential for commercial use, there is still a lack of studies evaluating the bonding performance of its different varieties. In particular, comparative analyses of bonding behavior among varieties under different adhesive systems remain limited, especially for industrial applications such as edge glued panels.
In the context, this study evaluated the bonding performance of three *Pinus caribaea* varieties affects using different adhesive systems (PVAc and EPI), for the production of edge glued panels using *Pinus taeda* as a reference. Wood samples from three varieties originating from 17- and 18-year-old experimental plantations were characterized in terms of physical and chemical properties according to COPANT and TAPPI standards. Bonding performance was assessed through finger joint (bending and tension) and edge bonding (shear strength) tests using PVAc and EPI adhesives, following ASTM and EN standards, with statistical analysis based on a factorial design.
The results indicated that all varieties of *Pinus caribaea* exhibited low density, similar to *Pinus taeda*, although with higher extractive contents. All varieties achieved satisfactory performance in finger joint tests, meeting or exceeding ASTM requirements and showing results comparable to the reference species. In edge bonding, the varieties performed similarly or superiorly to *Pinus taeda,* with emphasis on the *bahamensis* variety. The EPI adhesive showed superior performance compared to PVAc.
These findings demonstrate that intra-species variability does not limit bonding performance and confirm the technical feasibility of using *Pinus caribaea* varieties in the production of edge glued panels. The results contribute to expanding the industrial applicability of this species, supporting its use as an alternative raw material in the wood products sector.

Keywords: Wood adhesives, wood bonding, *Pinus caribaea* varieties, shear strength.

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Introduction

The use of wood bonding technology plays a fundamental role in the efficient use and conservation of forest resources, as it enables the integration of wood elements of different sizes and geometries into reconstituted products with high added value (Albuquerque et al., 2020).

Edge-glued panels represent an important value-added wood product, widely used in the furniture industry and in civil construction, however, their performance depends on reliable bonding quality, which varies depending on wood characteristics and adhesive systems.

The main raw material for this type of panel comes from planted forests, particularly loblolly pine (*Pinus taeda* L.), due to its good adaptation to the Brazilian climate, high silvicultural potential, abundant supply, and relatively low cost. In addition to these advantages, Vick (1999) reports that this species is classified as having satisfactory bonding performance, as it presents density and chemical properties suitable for this purpose.

Although *Pinus taeda* is widely used due to its satisfactory bonding performance, the behavior of alternative species or varieties remains insufficiently explored, particularly regarding their adhesion properties and suitability for panel production.

On the other hand, it is worth noting that the genus *Pinus* has more than 100 species (Businský 2016), some better known technologically than others, but most with great market potential and the possibility of numerous uses.

Among the species of this genus, pitch pine (Pinus caribaea Morelet), which comprises three varieties: bahamensis, caribaea, and hondurensis (Sebbenn et al. 2010, Shimizu 2008, Gonçalez et al. 2009), which have good adaptation, good stem shape, rapid growth and high resin production, especially in hot regions with water deficit (Gibson 1987). Furthermore, Foelkel (2008) complements that these varieties have different morphological characteristics and regions of origin, where some taxonomists question their grouping and describe them as distinct species.

Pinus caribaea var. bahamensis has its origin in the Bahamas Islands, at altitudes ranging from sea level up to 30 m. Although it originates from places close to sea level, in Brazil it has shown good growth even in plateau regions, including the southern region, where the cold is more intense, and thus representing species of great importance for wood production (Shimizu 2008). According to this same author, few studies have been developed regarding the technology of use of its wood, but it tends to have a higher density, and consequently, better physical and mechanical quality when compared to the Pinus hondurensis variety.

The Pinus caribaea var. caribaea has Cuban origin, occurring at altitudes from sea level to 280 m. The growth of this variety is slower compared to the other two. Regarding the technological characteristics, its wood is easy to work with, however, the presence of resin can cause some difficulties in its processing and bonding (Chudnoff 1984).

Regarding the Pinus caribaea var. hondurensis, its origin and natural distribution occurs in Honduras, Nicaragua, Belize, Guatemala and Mexico (Freitas et al. 2005), at altitudes ranging from sea level to 500 m (Shimizu 2008). According to Shimizu (2008) and Gonçalez et al. (2009), Pinus caribaea var. hondurensis is one of the most widely planted tropical pine varieties in the world. Its wood has important characteristics for the forest-based industry, being particularly suitable for the production of sawn wood, lamination, and panels (Almeida et al. 2014).

As described above, pitch pine (*Pinus caribaea* Morelet) varieties differ from one another in terms of growth or volumetric production depending on the planting location, wood density, which directly affects dimensional stability and mechanical resistance, and the presence or variation in the amount of resin (chemical properties).

Density and resin content directly impact bonding technology, which, according to Belleville *et al.* (2024), is considered one of the most important technologies in the generation of value-added wood products, whether appearance elements such as furniture and flooring, or structural elements

(LVL, CLT, among others). Lower-density woods have higher porosity, which results in easier adhesive penetration (Frihart and Hunt 2021, Gomes *et al.* 2025), however, they can generate excessive adhesive absorption, resulting in a fragile glue line with poor adhesion. Chemical properties, especially extractives or resins, can inhibit the chemical polymerization reactions of the adhesive, preventing fluidity, wettability and absorption, thus impairing the development of adequate strength and cohesion of the glue line (Albuquerque *et al.* 2020, Bilik *et al.* 2025).

In addition, Belleville *et al.* (2024) report that to meet the requirements and criteria for the strength and performance of bonded components and products, in addition to solid knowledge of the characteristics of wood, knowledge for the selection of adhesives is necessary. Pizzi *et al.* (2020) state that the choice of adhesive for bonding wood products is fundamental and Barboutis and Kamperidou (2021) reinforce that in any industrial application, the choice of adhesive type is influenced by many factors, such as cost, application process, end use and performance.

Different adhesive systems, such as PVAc and EPI, present distinct performance characteristics, particularly in terms of moisture resistance and curing mechanisms. However, their interaction with wood variability remains a critical factor influencing bond quality and durability. Variations in wood density, anatomical structure, extractives content, and moisture levels can significantly affect adhesive penetration, wetting behavior, and interfacial adhesion.

Considering the importance of these *Pinus caribaea* varieties and the development of bonding technology for generating value-added wood products, this research aims to evaluate how intra-species variability among *Pinus caribaea* varieties affects bonding performance in edge-glued panels under different adhesive systems, using *Pinus taeda* as a reference.

Materials and methods

For the development of this research, three varieties of the *Pinus caribaea species* were used, namely, *Pinus caribaea* var. *bahamensis*, *Pinus caribaea* var. *caribaea,* and *Pinus caribaea* var. *hondurensis*. Loblolly pine (*Pinus taeda* L.) was used as a reference species. The species come from experimental plantations with 17 and 18 years old located in Ventania - PR (24º 14' 45' S; 50º 14' 34' W, 990 m altitude) and Itararé - SP (24º 06' 33' S; 49º 19' 57' W; 750 m altitude), owned by the company Valor Florestal, installed in spacing of 2,5 m x 2,5 m and whose genetic material comes from the CAMCORE Program (Central America and Mexico Coniferous Resources Cooperative) and the CCGMPT (Center for Genetic Conservation and Improvement of Tropical Pines).

Five trees per species or variety were sampled; these were felled and sectioned into 2,65 m logs (four per tree and twenty per species) and later unfolded into planks and boards. Samples in the positions of 0 %, 25 %, 50 %, 75 % and 100 % of the commercial height were collected with the objective of determining the basic density according to COPANT 461-1972 (1972) and the chemical properties of total extractives, pH and inorganic materials (TAPPI 204 cm-97 1997, TAPPI 252 om-02 2002, TAPPI 211 om-02 2002, respectively). Material was collected from the DAP region to determine contraction anisotropy in accordance COPANT 462-1972 (1972).

The lumber was naturally dried in a sheltered place and after the initial moisture content was reduced, the lumber was stored in a climatic chamber until reaching equilibrium humidity (12-13 %). These were converted into battens with dimensions of 22 mm x 55 mm x 310 mm (thickness, width and length, respectively), which were measured to determine the apparent specific mass according to EN 323-2002 (2002).

The bonding performance of the species and varieties was evaluated from the finger joint and edge bonding. For finger jointing, the battens underwent a routing process to produce finger-joint, and then, they were glued in pairs with the polyvinyl acetate adhesive D3 (PVAc), which was applied manually at a rate of 180 $g \cdot m^{-2}$ and ensuring adhesive coverage of at least 75 % of the joint area.

After applying the adhesive, the top joints were pressed in an automatic press with a specific pressure of 2 MPa for 30 s. 16 replications were produced per species/variety.

For edge bonding, polyvinyl acetate D3 (PVAc) and polymeric isocyanate emulsion (EPI) adhesives were used, which were applied at a rate of 180 $g \cdot m^{-2}$ with the use of a foam roller to ensure uniform adhesive distribution on the battens, and then the joints were joined and pressed with a specific pressure of 0,6 MPa for 1 h, and 4 repetitions per treatment. From each repetition (joint), 10 specimens were obtained, totaling 40 specimens per treatment. The experimental design of finger joint and edge bonding is presented in Table 1.

Table 1: Experimental design.

Treatment	Species	Adhesive
Finger joint bonding		
1 – *Pcb*	*Pinus caribaea* var. *bahamensis*	PVAc
2 – *Pcc*	*Pinus caribaea* var. *caribaea*	PVAc
3 – *Pch*	*Pinus caribaea* var. *hondurensis*	PVAc
4 – *Pt*	*Pinus taeda*	PVAc
Edge bonding		
5 – *Pcb*/Pvac	*Pinus caribaea* var. *bahamensis*	PVAc
6 – *Pcb*/Epi	*Pinus caribaea* var. *bahamensis*	EPI
7 – *Pcc*/Pvac	*Pinus caribaea* var. *caribaea*	PVAc
8 – *Pcc*//Epi	*Pinus caribaea* var. *caribaea*	EPI
9 – *Pch*/Pvac	*Pinus caribaea* var. *hondurensis*	PVAc
10 – *Pch*/Epi	*Pinus caribaea* var. *hondurensis*	EPI
11 – *Pt*/Pvac	*Pinus taeda*	PVAc
12 – *Pt*/Epi	*Pinus taeda*	EPI

PVAc: polyvinyl acetate; EPI: polymeric isocyanate emulsion.

After complete curing of the adhesives and conditioning (20 ºC ± 2 °C; 65 % ± 5 %), the joints were converted into specimens for bonding evaluation. The evaluation of the finger joint bonding quality was conducted according to the ASTM D5572-95 (2005) standard, through bending and tension tests, and the specimens underwent dry, high temperature and triple cycle pretreatments. The edge bonding was evaluated from the shear strength test and followed the methodology recommended by EN 13354-2009 (2009) standard with pretreatment indicated for SWP/1 panels, whose use is in dry conditions, and consisted of immersing the samples for 24 h in water at a temperature of 20 ºC ± 3 °C, in addition to the dry test, performed as a control. In the tensile and shear strength specimens, wood failure was also analyzed.

The results were subjected to statistical analysis using outliers tests, normality, homogeneity of variance, simple analysis of variance and factorial arrangement (4x2: 4 species and 2 adhesives for edge bonding), and Tukey's mean comparison, all at 95 % reliability and in the Statgraphics Centurion XVII (2018) statistical package. The results were also compared with the regulatory requirements of ASTM D5572-95 (2005) and EN 13353-2008 (2008).

Results and discussion

Properties of wood

Table 2 shows the average results of the physical and chemical properties of the woods of the varieties of pitch pine (*Pinus caribaea* Morelet), as well as the reference species, loblolly pine (*Pinus taeda* L.).

Table 2: Physical and chemical properties of the varieties of pitch pine (*Pinus caribaea* Morelet) and loblolly pine (*Pinus taeda* L.).

Species/varities	D_{basic} (kg/m^3)	$D_{ap12\%}$ (kg/m^3)	Contraction anisotropy	Total extractives (%)	pH	Inorganics materials (%)
Pinus caribaea var. *bahamensis*	423 ab (9,77)	420 c (9,13)	2,51 b (25,67)	8,76 a (4,20)	4,60 ab (2,71)	0,32 a (2,24)
Pinus caribaea var. *caribaea*	418 b (8,82)	452 b (12,02)	2,45 b (20,38)	8,01 ab (2,47)	4,34 c (0,27)	0,20 a (3,63)
Pinus caribaea var. *hondurensis*	431 ab (8,58)	459 b (8,50)	2,52 b (28,36)	6,96 b (4,17)	4,45 bc (0,85)	0,27 a (3,08)
Pinus taeda	485 a (6,08)	491 a (8,30)	2,20 a (28,08)	3,34 c (6,18)	4,68 a (1,42)	0,28 a (2,45)

$D_{basic:}$ Basic density; $D_{ap12\%:}$ Apparent density 12 %; Means followed by the same letter within the same column are statistically equal by Tukey's test at 95%. Values in parentheses indicate the coefficient of variation of the samples in percentage.

The basic and apparent density results classify the *Pinus caribaea* varieties as low-density woods This characteristic may have facilitated adhesive penetration. Despite slight differences in density among varieties, no negative effect on bonding performance was detected.

The average results of contraction anisotropy showed that all varieties of pitch pine (*Pinus caribaea* Morelet) presented contraction anisotropy values statistically higher than loblolly pine (*Pinus taeda* L.), however, considering the classification of the anisotropy coefficient related by Klitzke (2007), all are conform to the range of variation of woods of medium stability (2 to 2,5). The higher anisotropy values observed may contribute to reduced dimensional stability, potentially affecting bonding performance.

The higher extractive content observed in the *Pinus caribaea* varieties may influence adhesive interaction by affecting wettability and penetration, which are important factors for bonding performance (Trianoski and Iwakiri 2020), and also reduce the compatibility and adhesion between the varnish and the wood during surface finishing (Ghofrani *et al*. 2016).

The slightly more acidic pH observed in some *Pinus caribaea* varieties could influence adhesive curing behavior, potentially affecting bonding performance. The average values of inorganic materials were statistically equal between the varieties of pitch pine (*Pinus caribaea* Morelet) and loblolly pine (*Pinus taeda* L.). The low inorganic content observed suggests minimal interference in the bonding. Furthermore, low values of these components are desired because high values can excessively wear on the cutting tools during slats preparation, as well as on the abrasive files during sanding or surface preparation for finishing (Trianoski and Iwakiri 2020).

Properties of panels

Finger joint bonding

The average results of the finger joint bonding performance (Table 3) showed that all varieties of pitch pine (*Pinus caribaea* Morelet), in both bending and traction, and in all pretreatments of specimens, were statistically equal to loblolly pine (*Pinus taeda* L.). These results can be considered positive, since the varieties of pitch pine (*Pinus caribaea* Morelet) presented relatively high values of total extractives (Table 2), and, despite belonging to a species commonly used for resin production, they still exhibited satisfactory bonding.

Considering the normative requirements of ASTM D5572-95 (2005) standard, it was verified that both the varieties of pitch pine (*Pinus caribaea* Morelet) and loblolly pine (*Pinus taeda* L.), in all pretreatments evaluated under static bending, met the minimum resistance of 13 MPa in the dry test, and 6,9 MPa in the elevated temperature and three-cycle soak.

Similarly, the minimum tension requirements for both species and in the different test conditions were fully achieved, being 13,8 MPa in the dry test, and 6,9 MPa for the tests after elevated temperature and three-cycle. Furthermore, considering the tensile test requirement, the average wood failure values were high and above those recommended by the reference standard: 60 % for dry testing and 30 % for testing after triple cycle. For the elevated temperature exposure test, no values are suggested for this condition.

Table 3: Mean results of finger joint bonding performance.

Exposure conditions/ Varieties	Bending Modulus of rupture (MPa)	Traction	
		Strength (MPa)	Wood failure (%)
Cured or dry			
Pinus caribaea var. *bahamensis*	31,93 (21,81)	22,19 (14,71)	84
Pinus caribaea var. *caribaea*	34,27 (16,65)	24,20 (13,56)	80
Pinus caribaea var. *hondurensis*	31,96 (10,18)	21,67 (19,77)	95
Pinus taeda	35,14 (13,22)	21,57 (20,71)	80
Elevated temperature			
Pinus caribaea var. *bahamensis*	33,92 (17,01)	23,40 (24,53)	81
Pinus caribaea var. *caribaea*	34,91 (18,07)	22,32 (19,02)	91
Pinus caribaea var. *hondurensis*	36,01 (19,97)	23,44 (21,88)	98
Pinus taeda	38,23 (16,59)	23,63 (19,32)	64
Three-cycle soak			
Pinus caribaea var. *bahamensis*	27,78 (26,75)	21,71 (22,85)	87
Pinus caribaea var. *caribaea*	28,63 (21,27)	20,19 (22,07)	77
Pinus caribaea var. *hondurensis*	32,35 (27,91)	21,24 (21,12)	88
Pinus taeda	34,40 (15,44)	18,21 (18,67)	74

Means of bending and traction, and within all pre-treatments, are statistically equal by Tukey's test at 95 %; Values in parentheses indicate the coefficient of variation in percentage.

These results indicate that the varieties of pitch pine (*Pinus caribaea* Morelet) exhibit similar adhesive quality to each other and to loblolly pine (*Pinus taeda* L.), furthermore, showed potential for edge bonding, demonstrating suitability for application in products such as frames and others that require this type of bonding.

Edge bonding

Table 4 shows the average results of the shear strength test properties of the edge glue line

Table 4: Means results of the edge bonding performance of varities of pitch pine (*Pinus caribaea* Morelet) and loblolly pine (*Pinus taeda* L.).

Treatment	Dry test			Wet test (24 h in water 20 °C ±3 °C)		
	Shear (MPa)	5th Percentile (MPa)	Wood failure (%)	Shear (MPa)	5th Percentile (MPa)	Wood failure (%)
Pinus caribaea var. *bahamensis* - PVA	9,99 A a (10,40)	6,24	99	2,48 C b (15,45)	1,92	0
Pinus caribaea var. *bahamensis* - EPI	9,64 AB a (12,10)	7,83	100	5,62 A a (10,94)	3,53	27
Pinus caribaea var. *caribaea* - PVA	9,07 AB a (8,17)	8,23	100	2,07 C b (18,70)	1,10	0
Pinus caribaea var. *caribaea* - EPI	9,61 AB a (11,17)	7,51	100	4,72 B a (11,86)	3,85	26
Pinus caribaea var. *hondurensis* - PVA	8,99 AB a (8,52)	7,76	100	2,10 C b (13,32)	1,66	0
Pinus caribaea var. *hondurensis* - EPI	9,59 AB a (10,30)	8,26	100	4,65 B a (12,56)	3,84	46
Pinus taeda - PVA	8,64 B a (15,26)	6,37	97	1,99 C b (17,97)	1,44	0
Pinus taeda - EPI	9,32 AB a (11,30)	8,08	93	4,24 B a (11,67)	3,71	29

Means followed by the same capital letter in the same column evaluate the interaction between all treatments and are statistically equal; means followed by the same lowercase letter, also in the column, compare different adhesives within the same variety or species and are statistically equal to each other. Comparison of Tukey's test at 95 %; Values in parentheses indicate the coefficient of variation in percentage.

Under dry conditions, differences among treatments were limited between the joints of the *Pinus caribaea* var. *bahamensis* glued with PVA and joints of loblolly pine (*Pinus taeda* L.) also bonded with PVA. No significant differences between adhesives were observed within the same species under dry conditions. All values in the lower 5^{th} percentile are above the values suggested by EN 13353-2008 (2008) of 2,5 MPa in addition, high values of wood failure were obtained (93 to 100 %), higher than the 40 % requirement for woods with a density of up to 600 Kg/m^3. The high wood failure values indicate that failure occurred predominantly in the wood rather than in the adhesive line, confirming adequate bonding quality. EPI adhesive showed higher shear strength than PVAc, particularly under wet conditions. All other varieties, as well as loblolly pine (*Pinus taeda* L.), bonded with PVA, demonstrated the lowest performance, and were statistically equal to each other and inferior to other treatments bonded with EPI. Within the same variety or species, a statistically significant difference was observed in all cases, where the EPI adhesive was statistically superior to PVA. Only the varieties/species bonded with the EPI adhesive reached the minimum value of the lower 5^{th} percentile of 2,5 MPa, however, in the wood failure issue, only the *hondurensis* variety presented the minimum value of 40 %.

The results of edge bonding (Table 4) indicated, in general, good bonding performace. Although not all varieties met the regulatory requirements, when compared with the control treatment, produced with the species traditionally used for this purpose in Brazil (loblolly pine (*Pinus taeda* L.)), the results were equal or higher, thus proving satisfactory bonding and aptitude of pitch pine (*Pinus caribaea* Morelet), regardless of the variety, for the production of edge glued panels.

The results of the effect of the variety on the bonding performance, presented in Table 5, showed that in the dry test, all varieties of pitch pine (*Pinus caribaea* Morelet) are statistically equal to or greater than loblolly pine (*Pinus taeda* L.), with emphasis on the *Pinus caribaea* var. *bahamensis*. High values of the lower 5^{th} percentile, as well as wood failure were obtained.

Table 5: Means results of the effect of the variety and the adhesive on the edge bonding performance.

Varieties	Dry test			Wet test (24 h in water 20 °C ± 3 °C)		
	Shear (MPa)	5th Percentile (MPa)	Wood failure (%)	Shear (MPa)	5th Percentile (MPa)	Wood failure (%)
Pinus caribaea var. *bahamensis*	9,80 a (11,25)	7,68	99	3,88 a (42,84)	2,08	13
Pinus caribaea var. *caribaea*	9,34 ab (10,15)	7,75	100	3,51 a (42,20)	1,22	14
Pinus caribaea var. *hondurensis*	9,29 ab (9,91)	7,87	100	3,37 a (40,64)	1,71	23
Pinus taeda	8,98 b (13,61)	6,77	95	3,20 a (38,25)	1,73	15
Adhesives						
PVA	9,14 b (11,83)	7,10	99	2,17 b (20,64)	1,25	0
EPI	9,54 a (11,03)	7,90	98	4,77 a (15,28)	3,63	32

Means followed by the same letter within the same column are statistically equal by Tukey's test at 95 %. Values in parentheses indicate the coefficient of variation of the samples in percentage.

In the test under wet conditions, there were no significant statistical differences between varieties/species, lower 5th percentile values below those recommended by EN 13353-2008 (2008), as well as low values of wood failure. These less expressive results are justified based on the grouping of data by species/variety and disregarding the type of adhesive.

However, it is worth mentioning a detail observed during the development of this research. The *bahamensis* variety presented higher numerical values of shear strength of the edge glue line than the other two varieties and loblolly pine (*Pinus taeda* L.) in the dry tests (sometimes statistically superior). In the wet test, it also stood out for its better performance in the general interaction and in the main effect, as well as in comparison with another variety or species glued with the same adhesive. According to Table 2, the bahamensis variety presented the highest extractive content; however, it also showed superior bonding performance. This result indicates that extractive content alone does not necessarily reduce adhesion, suggesting that extractive composition may play a more relevant role in bonding behavior.

The effect of adhesive type on the bonding performance (Table 5) showed that, both in the dry and wet tests, the EPI adhesive was statistically superior to PVA. In the wet test, only the EPI adhesive met the minimum requirement of the lower 5th percentile of 2,5 MPa, however, the wood failure was less than 40 %.

This difference in performance of adhesives can be explained primarily by their composition and specific characteristics. PVA adhesive results from the polymerization of vinyl acetate in aqueous dispersion and the products glued with it tend to present high resistance in dry environments, but great limitations of use in humid environments (Frihart and Hunt 2021), even easily degrading under temperature and/or humidity conditions (Claub *et al*. 2011, Barboutis and Kamperidou 2021). EPI adhesive, despite also having vinyl polyacetate in its composition, has a polymeric isocyanate (diphenylmethane-diisocyanate), which acts as a catalyst and catalyzes the curing reaction of the adhesive that occurs through the reaction of isocyanate groups with the hydroxyls of wood (Sellers 1994). As a result, it develops greater resistance to temperature, water and solvents when compared to PVA (Frihart and Hunt 2021).

Conclusions

The results demonstrated that, despite presenting low to medium density, moderate dimensional stability, and relatively high extractive content, all evaluated *Pinus caribaea* varieties showed satisfactory bonding performance. Both finger-joint and edge bonding results were comparable to or higher than those obtained for *Pinus taeda*, consistently exceeding minimum standard requirements. These findings indicate that intra-species variability did not negatively affect bonding quality.

Adhesive type proved to be a more determining factor than wood physicochemical variability. The polymeric isocyanate emulsion (EPI) adhesive showed superior bonding performance compared to PVAc, particularly under more demanding conditions.

From a scientific perspective, the results indicate that bonding performance cannot be reliably predicted based solely on parameters such as extractive content or density. In addition, intra-species variability should not be considered a limiting factor for the technological use of *Pinus caribaea* wood.

In practical terms, the evaluated varieties of *Pinus caribaea* demonstrate strong potential for industrial application in edge-glued panel (EGP) production. The findings reinforce that these materials can be reliably used, provided that appropriate adhesive systems are selected, with emphasis on the superior performance of EPI adhesives, especially in conditions involving moisture exposure.

Authorship contributions

R.T.: Conceptualization, methodology, investigation, resources, visualization, project administration, supervision, writing – review & editing, writing – review & editing. S.I: Writing – review & editing. J.L.M-M.: Resources. D.P-P: Methodology, investigation. N.R-J.: Methodology, investigation.

Conflicts of interest

The authors declare no conflicts of interest.

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