Influence of different sheet compositions and commercial adhesives on the performance of multilaminated plywood

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Abstract

The quality of plywood panels depends on factors such as the forest species and the adhesive used in their production, and understanding the interferences of these factors in the final properties of the plywood is of fundamental importance. The study aimed to develop multilaminate plywood panels with two forest species and two types of adhesive and to evaluate the influences of these factors (forest species and adhesive) on the physical and mechanical properties of the plywood. The panels were produced with sheets of parica and pine with two types of adhesives, urea-formaldehyde and phenol-formaldehyde, with a weight of 150 g/cm². Then, each set was pressed for 10 minutes under a specific pressure of 0.98 MPa at a temperature of 150 °C. Three panels were produced for each type of blade and adhesive, totaling four treatments. The plywood was evaluated for physical properties (humidity, bulk density, and water absorption) and mechanical properties (parallel and perpendicular static flexion and resistance to mechanical shear). The results showed that the forest species had a greater influence on physical and mechanical properties, with the best results being observed for plywood produced with pine. The panels with sheets of parica and phenol-formaldehyde adhesive showed less moisture. The apparent density of the panels should be considered as it positively influenced the mechanical properties and negatively impacted water absorption. It is concluded that the plywood produced can be used for internal and external applications. However, it is indicated for structural purposes as it did not meet the requirements of the NBR 31.000.001/2:2001.

Introduction

Wood panels are products composed of elements of wood disaggregation, such as veneers, slats, particles, and fibers, which are later reconstituted through adhesive bonding. These new products are also known as “reconstituted wood products”, and their properties are different from those of the original material (de Almeida Mesquita et al. 2015).

The plywood panel is the product formed from wood veneers, usually composed of an odd number of veneers, orthogonally positioned, and joined with adhesive. The orthogonal orientation of one veneer in relation to another adjacent one limits the tangential movement of the layers, which gives the plywood panel more dimensional stability and uniformity in mechanical properties (Bortoletto Júnior and Garcia 2004). These characteristics contribute to the wide application of the compensated panel, for example in the manufacture of furniture, in civil construction as a structural or non-structural component (floors, doors, scaffolding, walls, among others), industrial packaging, and decoration pieces.

The demand for wood-based products, including plywood, medium-density fiberboard (MDF), oriented fiberboard, and other wood-based composites has increased exponentially and, in particular, the global plywood market is expected to reach approximately US$ 128.3 billion by 2022, representing a compound annual growth rate of 7.8% for the period 2017–2022 (BCC Research 2018). In this context, the use of wood from planted forests is a potential alternative to supply the consumer market, considering the increasing deforestation of native tropical forests.

Pinus oocarpa is a species with great economic importance in Brazil. According to Ferro et al. (2018), pine plantations represent the second largest reforested area in the country, and within the pine genus, the species *Pinus oocarpa* stands out due to its high growth potential in areas of low fertility. In addition to presenting the highest average values of mechanical properties among the tropical pine species, it is one of the most suitable species for applications requiring greater resistance and rigidity (Trianoski and Iwakiri 2014).

Another species of rapid growth that has been studied is *Schizolobium amazonicum* Herb., popularly known as parica, pinho-cuiabano, bandarra, among other common names. It is native to the Amazon region and has important characteristics of economic and ecological interest for use in reforestation, implementation in degraded areas and agroforestry systems, commercial value, easily adapting to various soil and climatic conditions. Such aspects have contributed to its large-scale cultivation with planted forests in northern Brazil (Almeida et al. 2013; Gondin et al. 2015). It is also seen as a valuable forest species for the timber industry, mainly in the laminated wood industry (Baldoni et al. 2020).

This species stands out for its fast growth, upright stem with branches above 7 meters, and high market value of sawn timber. Some characteristics benefit the processing of this species, such as easy debarking, fast drying, scarcity of knots, and the possibility of being debarked in rotation to produce veneer without pre-treatment and rounding of logs (Zeller et al. 2013; de Melo and Del Menezzi 2014; Tourne et al. 2016). As plywood is a wood-based material, wood properties have a relevant influence on its performance and vary according to species, growth rate, grain orientation, water content, defects, among others.

Woods with higher density, in general, are less porous and have a thicker cell wall and smaller fire; these characteristics can limit the penetration of adhesives into the woody structure. On the other hand, in woods with low density and high porosity, they may induce excessive adhesive penetration in the wood structure, resulting in a "hungry" glue line (Albuquerque et al. 2005).

According to Kim et al. (2018), apart from the forest species and its inherent characteristics, the properties of the plywood are also influenced by the quality of the blade, the blade number, and the type of adhesive. Among these, the type of adhesive and its intrinsic properties mostly interfere with the bond strength between the blades that compose the plywood. The synthetic adhesives urea formaldehyde (UF) and phenol-formaldehyde (FF) are widely used in the wood-based panel sector, such as in the production of MDF, medium-density particleboard (MDP), and plywood. Among these, plywood uses around 23% of the UF adhesives produced in the world (Hemmilä et al. 2017).

As a substitute for phenol, urea was successfully inserted in FF adhesives. Many researches point out that the addition of urea not only contributes to reduced economic costs of the FF adhesive, but also improves the curing and the bond strength of the blades (Tomita and Hse 1998; Fan et al. 2011). However, its use is not indicated for outdoor applications due to its low resistance to moisture (Liu et al. 2020). On the other hand, phenol-formaldehyde adhesives present high resistance to humidity, resistance to weathering, and good resistance in the glue line. Ayrilmis et al. (2012) showed that panels produced with UF adhesive absorbed a greater amount of water and swelled twice as much as those produced with FF adhesive. Therefore, the type of application of the compensated panel can be determined by the type of adhesive used in its production.

Considering that both the species and the type of adhesive can influence the final properties of plywood, this study aimed to develop multilaminate plywood panels with two forest species and two types of adhesive and to evaluate the influences of these factors (forest species and adhesive) on the physical and mechanical properties of the final products.

Materials And Methods

Collection of raw material and preparation of blades

Blades with dimensions of 480 x 480 mm and nominal thickness of 2 mm, obtained from two forest species, parica (*Schizolobium amazonicum* Herb.) and pine (*Pinus oocarpa*), were used to produce the compensated panels. The blades of the Amazonian species parica, 6 years old, were ceded by the Concrem Group company, located in the Dom Elizeu municipality, Pará, Brazil. The pine slats were obtained from 18-year-old trees planted at the Federal University of Lavras - UFLA, Minas Gerais, Brazil. The pine trees were laminated in a rolling mill at the Experimental Wooden Panel Production Unit (UEPAM) at the UFLA. Before the panels were produced, the veneers were properly stacked in a kiln for subsequent drying, reaching 8% humidity on a dry basis.

Production of compensated panels

Two types of adhesives were used to make the plywood panels with parica and pine blades: urea formaldehyde (UF) and phenol-formaldehyde (FF). The UF adhesive had a solid content of 51.49%, a pH of 12.86, a viscosity of 590 cp, and a Gel Time of 49 seconds. The solids content of the FF adhesive was 53.69%, at a pH of 8.32, a viscosity of 465 cp, and a Gel Time of 49 seconds. The experimental design is shown in Table 1. Three panels were produced for each type of adhesive and blade (forest species).

For each treatment, with the aid of a spatula, the adhesive was spread evenly on the faces of the blades, with a weight of 150 g/m². After the production, the panels were left (assembly) for approximately 15 minutes. This assembling period is important to ensure that the adhesive is compatible with the wood veneer before being pressed. After that, the set was pressed for 10 minutes under specific pressure of 0.98 MPa at 150°C. The manufactured panels were conditioned in an air-conditioned chamber at a temperature of 20 ± 2°C and a relative humidity of 65%, leading to an equilibrium humidity of approximately 12%.

Physical properties of compensated panels

All physical tests were performed according to ABNT 31:000.05-001/1 (2004) guidelines (Associação Brasileira de Normas 2004). The apparent density of the compensated panels was determined according to the stereometric method. Briefly, the mass of the specimens was obtained on a laboratory scale with a precision of 0.001 g, and the volume was determined with the aid of a digital pachymeter with a precision of 0.01 mm, where the length, width, and thickness were measured.

To determine the equilibrium humidity of the compensated panels, initially, the wet mass of the specimens was taken, and the samples were oven-dried until constant mass. The specimens were weighed again to determine humidity. To evaluate the water absorption of the panels, first, the mass of the specimens was measured in a laboratory scale with a precision of 0.001 g. Subsequently, the samples were immersed in a container of water and kept for 24 hours. After the immersion period, the samples were weighed again to determine water absorption.

Mechanical properties

The static bending mechanical tests with fiber direction parallel and perpendicular to the test body length (of the cover sheets) and glue line resistance to shear stress in dry condition were also performed according to the recommendations of ABNT 31:000.05-001/1 (2004) (Associação Brasileira de Normas 2004). The mechanical tests were conducted on a universal testing machine (EMIC DL-30000).

Statistical analysis

The design used was entirely random, arranged in a factorial design composed of two factors: forest species and adhesive, with three repetitions, totaling 12 panels. For the statistical analysis, we considered each type of panel produced (treatments) and the species x adhesive interactions. The results of physical and mechanical properties were submitted to analysis of variance (ANOVA) and those detected as significant by the F test were evaluated by the Scott-Knott test at 5% significance, using the statistical program SISVAR - System of Analysis of Variance. Pearson's simple linear correlation analysis was performed among all properties evaluated for plywood, considering all treatments. For Pearson's correlation, the significance levels of $p < 0.01$ and $p < 0.05$ were adopted; the analysis was performed in the R software.

Results And Discussion

Physical properties of compensated panels

The apparent density and equilibrium humidity of the compensated panels produced from parica sheets, UF and FF pine, and adhesive are presented in Table 2. The use of different adhesives (UF and FF) did not significantly affect ($p \leq 0.05$) the apparent density for the same lamina composition, that is, the same forest species. On the other hand, independently of the type of adhesive, the apparent density was statistically higher for the compensated panels produced from the pine slats. Knowing that the production conditions were the same for the treatments, it is inferred that the difference observed in this physical property of the compensated panels is mainly related to the basic density of the different forest species used.

According to Silva et al. (2016), the Amazonian species parica presents a basic density between 0.31 and 0.35 g/cm³. The forest species *Pinus oocarpa* has a basic density close to 0.45 g/cm³ (Mendes et al. 2015). Thus, the basic density of pine is at least 1.28 times higher than that of parica, and therefore, this characteristic influenced the apparent density of the compensated panels. The apparent density values of the panels are close to those found in the literature for *Pinus oocarpa* panels (0.54 g/cm³) (Lisboa et al. 2016) and for parica panels (0.40 g/cm³) (Machado et al. 2018).

In relation to the equilibrium humidity, only the panels produced with parica sheets and FF adhesive (PAFF) differed statistically from the other treatments. However, all treatments were below the 12% limit suggested by the Brazilian Association of the Processed Wood Industry - ABIMCI (Associação Brasileira da Indústria de Madeira Processada Mecanicamente - ABIMCI 2007). As plywood is commonly used as a building material for outdoor applications, understanding its behavior in relation to moisture is of extreme importance (Windt et al. 2018) because the moisture absorbed by the plywood can compromise the mechanical and physical properties and the durability of the material.

The average values for water absorption did not differ and ranged between 62.43 and 82.84%. Regarding the results presented in the literature, for water absorption of plywood, Lisboa et al. (2016) worked with native species of the Brazilian Cerrado and with the species *Pinus oocarpa* and reported values for water absorption, ranging from 27.43 to 71.58%, being the highest value found for pine. Costa and Menezzi (2017) reported water absorption values of 59.58% for plywood produced with parica blades, whereas Machado et al. Machado et al. (2018) found values of 86.30%.

The results of the breakdown of the species x adhesive interaction for each physical characteristic of the panels are presented in Table 3. For moisture, apparent density, and water absorption, the most influential parameter was the wood species. For group I (PAFF and PIFF), both humidity and apparent density were higher for the panels produced with FF (PIFF) glued pine blade. The apparent density of the panels produced with pine blade, but with UF adhesive (PIUF, group II), was also statistically higher than that for the PAUF panels. In contrast, the PAUF treatment absorbed more water after 24 hours of testing compared to the PIUF panels (group II).

The interaction of UF adhesive with the different wood species (parica and pine) showed that the density and anatomical structure of the species affected the water absorption of the panels (group II). The number of voids in the glue line increases with the increase of the pot size of the forest species used, causing greater water absorption. Bekhta et al. (2020) showed that water absorption is related to panel density, where higher density results in a lower number of pores and, consequently, lower water absorption. This is in accordance with the results observed for the composite PIUF, which presented a density of 0.55 g/cm³ and lower water absorption (62.43%) compared to the panel PAUF, which has a density of 11.58 g/cm³ and higher water absorption (82.84%).

The species of wood used in the production of plywood has a significant impact on the dynamics of moisture, since the wood contains a peculiar anatomical structure and several substances that may have a hydrophobic character and that, in turn, will influence the wetting capacity (Aydin et al. 2006; Brischke et al. 2013). Therefore, to enhance the properties of the plywood panel in addition to the choice of a water-resistant adhesive, it is also essential to choose forest species that have low absorption and high-water desorption.

The results presented for the analysis of the adhesive unfolding indicated that the type of adhesive influenced only the humidity of the panels (group III), indicating that the use of UF adhesive on the composites produced with parica blade was higher (11.58%) in relation to the PAFF panels (10.10). Therefore, possibly, the glue barrier formed by the FF adhesive affected the humidity dynamics of the parica compensated panels; however, this effect was not evidenced in the water absorption test, in which the results were statistically equal. The FF adhesive is commonly used in panels destined for external applications due to its excellent resistance to humidity. No statistical difference was observed in the physical properties of the pine plywood (group IV).

Mechanical properties of compensated panels

Static bending

The results obtained through the static bending test in the parallel direction of the fibers showed that the rupture modulus (MOR) was statistically similar among the treatments (Fig. 1). On the other hand, the modulus of elasticity (MOE) was higher for the compensated panels produced with pine sheets. The PIUF treatment presented a percentage increase, for the MOE, of approximately 105.44%, in relation to the PAUF panels. The panels made with pine and FF adhesive (PIFF) had a perceptual increase of 169.95%, in comparison to the parica and FF adhesive (PAFF) panels.

Regarding the results presented in the literature, the mean values of MOR in the parallel direction obtained in this study, for the parica panels, were similar to the values reported by Iwakiri et al. (2011), which ranged from 21.20 to 33.20 MPa for parica plywood glued with UF and FF adhesive, respectively. In contrast, the MOE values are below the average values in the range of 3.44 to 5.28 found by Iwakiri et al. for parica composites with UF and FF adhesive, respectively. In the literature, results close to those found in this study are reported for the values of MOR and parallel MOE for pine plywood, with 40.28 MPa and 4.90 GPa, respectively (Matos et al. 2019).

The results of the MOR and MOE show that the plywood panels tested in the parallel direction the fibers were considerably larger than those of the samples tested perpendicular to the fibers. This behavior was consistent with the findings of Auriga et al. 2020). Although the values of MOR and MOE in the parallel direction were higher than those of MOR and MOE in the perpendicular direction, the results did not meet the requirements of the NBR 31.000.001/2:2001 standard, which establishes values of MOR for concrete-shaped plywood (FOR) of at least 45 MPa. For the parallel MOE, the standard establishes a minimum value of 5.00 GPa, and therefore, only the multilaminated PIFF plywood met the requirements.

The results of the modulus of rupture (MOR) and the modulus of elasticity (MOE), determined by means of the static bending test in the perpendicular direction of the fibers, are presented in Figure 2. The resistance to perpendicular flexion (MOR) was significantly higher for the plywood produced with pine sheets, irrespective off the type of adhesive. The PIUF treatment presented a percentage increase, for the MOR, of approximately 225.97% in relation to the PAUF panels. The plywood produced with pine and FF adhesive (PIFF) had a percentage increase of 45.56% in comparison to the plywood with parica sheets and FF adhesive (PAFF).

According to Kretschmann (2010), the bending resistance and the elasticity modulus of the plywood panel are affected by several factors, such as forest species, wood quality and humidity, density, number of layers, veneer thickness, and binder adhesive. Taking into account that the panels were produced with the same glue grammage, the same layer number and thickness of sheets, and under the same conditions of pressure and temperature, it can be inferred that the density influenced the results of perpendicular bending. This relation was expressly linear for the perpendicular elasticity modulus, in which the PIFF panel presented higher density (0.58 g/cm³) and higher MOE (4.24 MPa) values. The PIFF treatment presented a percentage increase of 731.37, 311.65, and 85.15% in relation to the PAUF, PAFF, and PIFF composites, respectively.

Regarding the values presented in the literature for the perpendicular MOR, the results found by Machado et al. (2018) were higher for parica panels, with 24.70 MPa. The perpendicular MOE results obtained for parica plywood were also lower compared to parica panels with FF and UF adhesive produced by Iwakiri et al. (2011), whose minimum average values were 1.18 and 1.23 MPa, respectively. The result obtained for the PIFF treatment for the perpendicular MOE was well above those found for *Pinus taeda* plywood, i.e., 2.24 MPa (Mendes et al. 2013). Reis et al. (2019) studied the mechanical properties of plywood produced with *Pinus oocarpa* and found a value higher than that observed in this study for perpendicular MOR, namely 31.5 MPa.

Although the values of MOR were better for the plywood produced with pine blades, with the exception of the PAUF, all other treatments exceeded the values required by the NBR 31.000.001/2 (2001) standard, which establishes a minimum value of 15.59 MPa. However, only the PIFF plywood reached the required values for the perpendicular MOE, at least 2.50 GPa.

The results presented for the breakdown analysis of the species and adhesive indicated that only the species influenced mechanical properties (Table 4). Therefore, the type of adhesive (UF and FF) did not influence the results obtained for the mechanical properties of the panels produced with the same composition of blades (group III and IV). Analyzing the panels produced with parica blades (PAFF) and pine blades (PIFF) and glued with FF adhesive, we observed that the parallel and perpendicular MOE was higher for the PIFF treatment (group I). On the other hand, there was no statistical difference for the MOE.

For group II (PAUF and PIUF), only the perpendicular MOR showed statistical difference, so that the PIUF treatment obtained a higher rupture module (26.11 MPa). These differences can be attributed to the lower apparent density of parica composites (0.39 to 0.41 g/cm³) in relation to *Pinus oocarpa* plywood (0.55 to 0.58 g/cm³).

Glue line resistance to shear stress

The resistance of the glue line of the panels produced with the different species and adhesives was evaluated through shear tests in dry, wet, and post-boiling conditions. As shown in Table 5, the highest values of shear resistance to dry, wet, and post boiling conditions were obtained for the plywood panels produced with pine blade, independently of the type of adhesive. This can be explained by the higher basic density values of the *Pinus oocarpa* species compared to parica wood. Demirkir et al. (2013) proved that shear strength is higher in species with higher densities.

The values found in this study for the resistance of the glue line of the pine panels produced with UF adhesive were higher than those found in the study of Iwakiri et al. (2001), who worked with different species of pine and found values ranging from 1.19 to 1.74 MPa for the dry condition and values between 0.59 to 1.29 MPa for the wet condition. However, for shear resistance under dry conditions, the panels with FF adhesive presented lower values in relation to the results mentioned in the work of Iwakiri et al. (2001), who report values from 2.29 to 3.50 MPa. The resistance of the glue line after boiling, in this study, was higher than that reported by Iwakiri et al. (2009), who worked with five species of tropical pine and found values ranging from 0.88 to 1.42 MPa.

Although the results were better for the plywood made with the pine slats, all samples met the minimum requirements of the European Standard EN 314-2 (CEN, 1993) (1993) for outdoor panels, with reference values from 0.6 to 1.0 MPa. Therefore, multilaminated plywood produced with a pine and parica blade can be indicated for both internal and external use.

The shear strength values of plywood panels depend more on the type of species than on the type of adhesive applied (Table 6). The breakdown analysis of species and adhesive showed that the type of adhesive (UF and FF) did not influence the results obtained for the shear in dry, wet, and post-boiling conditions, for the same blade composition (groups III and IV). On the other hand, the type of forest species influenced the shear strength in dry, wet, and post-boiling conditions. For group I (PAFF and PIFF), only wet shear resistance differed statistically, in which the PIFF treatment showed higher resistance (2.11 MPa). Observing the panels produced with parica sheets (PAUF) and pine sheets (PIUF) and glued with UF adhesive, shear strength in dry, wet, and post-boiling conditions was higher for the PIUF treatment (group III).

Pearson´s correlation for physical and mechanical properties

Pearson's correlation analysis was applied to correlate the mechanical properties with each other and with the apparent density of composites (Fig. 3). The results indicate that density correlated significantly with all mechanical properties. The correlations found between the apparent density and the modulus of elasticity in the parallel and perpendicular directions were strong and positive, while the other mechanical properties presented moderate positive correlations. This indicates that mechanical properties tend to increase with increasing apparent density. Density is commonly considered one of the most important characteristics of the material, as it is strongly correlated with the mechanical resistance of wood (Kretschmann 2010).

On the other hand, the correlation between apparent density and water absorption (-0.50) was weakly negative, i.e., the increase in density caused a reduction in water absorption. This fact was confirmed by the Scott-Knott test among the PIUF compensated panels, which presented higher density (0.55 g/cm³) and lower water absorption (62.43%) compared to the PAUF panel with a density of 11.58 g/cm³ and obtained higher water absorption (82.84%). Lisboa et al. (2016) reported a relationship between the apparent density of plywood and water absorption, and in this sense, the increase in density promotes the reduction of empty spaces, impeding/limiting water entry into the wood structure.

Conclusions

The forest species influenced the apparent density of plywood and the dynamics of water absorption. In general, among the treatments, the pine panels presented higher apparent density and the breakdown analysis of the species showed that the PIUF treatment (group I) absorbed less water compared to the PAUF treatment (group II). These differences were mainly attributed to the basic density of the forest species. The unfolding analysis for the adhesive showed that the parica panels glued with FF adhesive absorbed less moisture compared to those glued with UF adhesive.

No statistical difference was observed for the MOR in the parallel direction, and the values did not meet the minimum requirements stated by NBR 31.000.001/2:2001. The pine panels obtained statistically higher values for the parallel MOE and for the perpendicular MOR. However, in relation to the minimum values required by the NBR 31.000.001/2:2001 standard, only the PIFF treatment met the minimum values of parallel MOE, whereas the minimum requirements for perpendicular MOE, with the exception of the PAUF treatment, were met by all other treatments. The PIFF treatment obtained a higher perpendicular MOE and was the only one that met the requirements of the NBR 31.000.001/2:2001.

Analysis of the breakdown of mechanical properties showed that only the forest species interfered significantly with the parallel MOE and the perpendicular MOE and MOR; the values were statistically higher for the pine plywood.

The basic density of the forest species statistically influenced the mechanical resistance to shear; the composites produced with pine showed higher values. However, all treatments met the minimum requirements stated in the EN 314-2 standard. Unfolding analysis confirmed that the shear strength of composites depended more on the type of forest species than on the adhesive used.

Pearson's correlation analysis confirmed that the apparent density of the panels is a relevant characteristic as it positively influences the mechanical properties and negatively impacts the physical properties, such as water absorption.

Declarations

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Author contributions

Carine Setter: Writing - review & editing; Conceptualization; Data curation; Formal analysis; Methodology; Resources. Uasmim Lira Zidanes: Writing - review & editing; Conceptualization; Data curation; Methodology; Resources. Eduardo Hélio de Novais Miranda: Conceptualization; Data curation; Formal analysis. Flávia Maria Silva Brito: Writing – review. Lourival Marin Mendes: Supervision; Validation; Project administration. José Benedito Guimarães Junior: Writing - review & editing; Supervision; Validation; Project administration.

Availability of data and materials

The data that support the findings of this study are openly available on request.

Ethics declarations

Ethical approval and consent to participate

Not applicable. The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. We declared that this manuscript does not involve researching about humans or animals.

Consent to Publish

Not applicable.

Competing interests

The authors declare that they have no competing interests.

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Tables

Table 1 Experimental design to produce compensated panels.

Treatment	Species	Adhesive	Quantity of panels
PAUF	Parica	UF	3
PAFF	Parica	FF	3
PIUF	Pine	UF	3
PIFF	Pine	FF	3

Table 2 Apparent density and equilibrium humidity of compensated panels.

Treatment	Apparent density (g/cm³)	Equilibrium humidity (wt.% on dry basis)	Water absorption (%)
PAUF	0.39 (0.06) a	11.58 (0.49) b	82.84 (12.42) a
PAFF	0.41 (0.05) a	10.10 (0.34) a	72.26 (5.12) a
PIUF	0.55 (0.06) b	11.54 (0.40) b	62.43 (24.30) a
PIFF	0.58 (0.05) b	12.37 (3.01) b	67.49 (4.25) a

Averages followed by equal lower-case letters, in the same column, do not differ statistically from each other by Scott-Knott's test (1974), at 5% significance. Values in brackets refer to the standard deviation.

Table 3 Interaction between species x adhesive variables for physical properties.

Treatment	Group	Humidity (%)	Apparent density (g/cm³)	Water absorption (%)
Species				
PAFF	I	10.10 a	0.41 a	72.26 ns
PIFF		12.37 b	0.58 b	67.49 ns
PAUF	II	11.58 ns	0.39 A	82.84 a
PIUF		11.54 ns	0.55 B	62.43 b
Adhesive				
PAFF	III	10.10 a	0.41 ns	72.26 ns
PAUF		11.58 b	0.39 ns	82.84 ns
PIFF	IV	12.37 ns	0.58 ns	67.49 ns
PIUF		11.54 ns	0.55 ns	62.43 ns

Averages followed by different upper- or lower-case letters within the same group differ statistically from each other by Scott-Knott's (1974) test, at 5% significance. Ns: not significant.

Table 4 Analysis of the breakdown of species and adhesives for mechanical properties.

Treatment	Group	Parallel (mpa)		Perpendicular (mpa)	
		mor	moe	mor	moe
Species					
PAFF	I	21.54 ns	2.04 a	15.98 ns	1.03 a
PIFF		38.92 ns	5.52 b	23.26 ns	4.24 b
PAUF	II	24.51 ns	2.24 ns	8.01 a	0.51 ns
PIUF		40.97 ns	4.61 ns	26.11 b	2.29 ns
Adhesive					
PAUF	III	24.51 ns	2.24 ns	8.01 ns	0.51 ns
PAFF		21.54 ns	2.04 ns	15.98 ns	1.03 ns
PIUF	IV	40.97 ns	4.61 ns	26.11 ns	2.29 ns
PIFF		38.92 ns	5.52 ns	23.26 ns	4.24 ns

Averages followed by different upper- or lower-case letters within the same group differ statistically from each other by Scott-Knott's (1974) test, at 5% significance. Ns: no significant.

Table 5 Dry, wet, and post-boiling shear strength.

Treatment	Strength (mpa)		
	Dry	Wet	**Post-boiling**
PAUF	1.03 (0.16) a	1.12 (0.17) a	0.91 (0.20) a
PAFF	1.09 (0.20) a	1.11 (0.26) a	1.00 (0.18) a
PIUF	1.99 (1.11) b	1.94 (0.75) b	2.23 (0.87) b
PIFF	1.68 (0.11) b	2.11 (0.34) b	1.76 (0.15) b

Averages followed by equal lower-case letters, in the same column, do not differ statistically from each other by Scott-Knott's test (1974), at 5% significance. Values in brackets refer to the standard deviation.

Table 6 Interaction between species x adhesive variables for dry, wet, and post-boiling shear strength.

Treatment	Group	Dry	Wet	Post-boiling
Species				
PAFF	I	1.09 ns	1.11 a	1.00 ns
PIFF		1.68 ns	2.11 b	1.76 ns
PAUF	II	1.03 a	1.12 A	0.91 a
PIUF		1.99 b	1.94 B	2.23 b
Adhesive				
PAFF	III	1.09 ns	1.11 ns	1.00 ns
PAUF		1.03 ns	1.12 ns	0.91 ns
PIUF	IV	1.99 ns	1.94 ns	2.23 ns
PIFF		1.68 ns	2.11 ns	1.76 ns

Averages followed by different upper- or lower-case letters within the same group differ statistically from each other by Scott-Knott's (1974) test, at 5% significance. Ns: not significant.

Figures

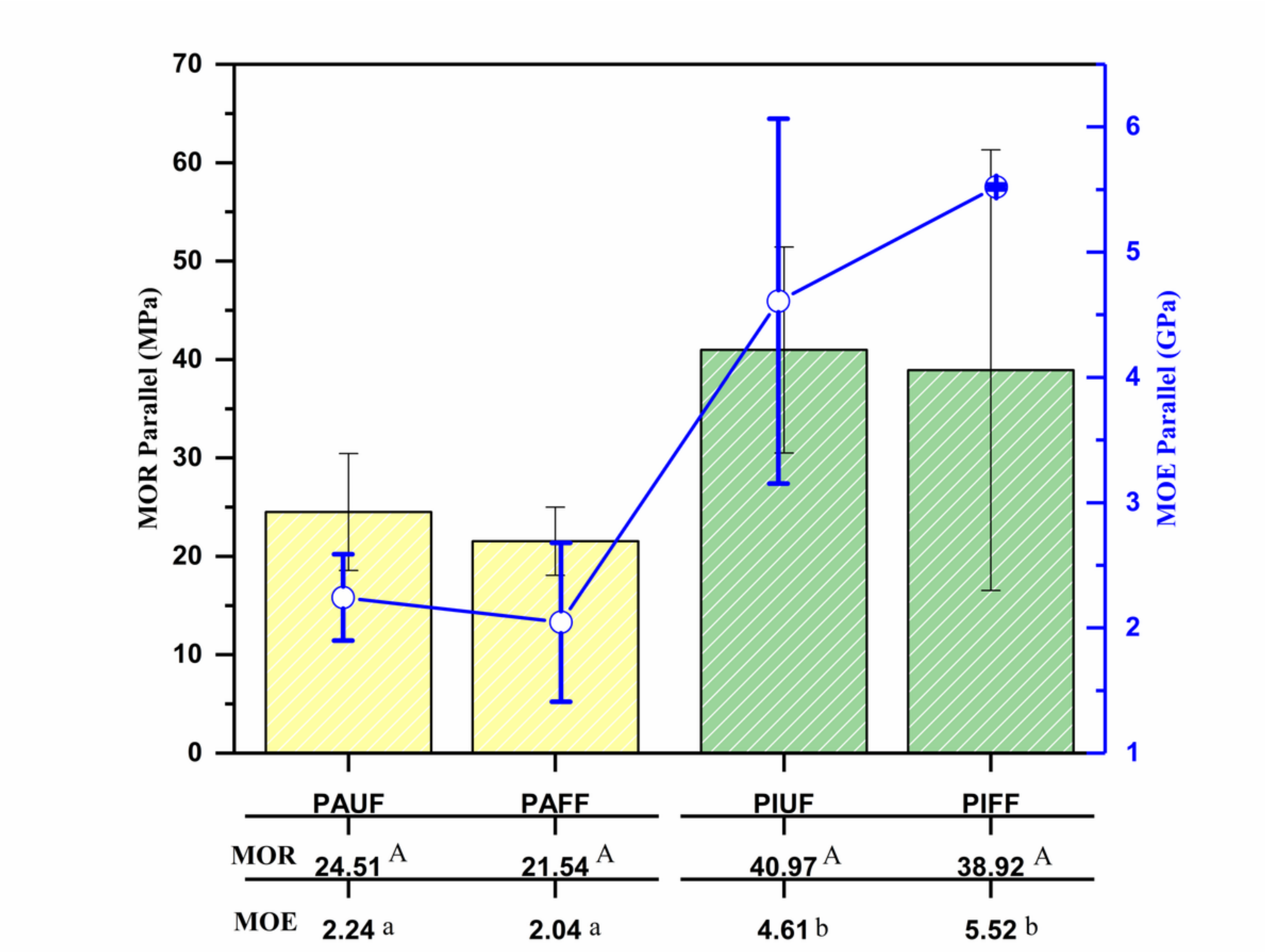

Figure 1

MOE and MOR parallel between treatments.

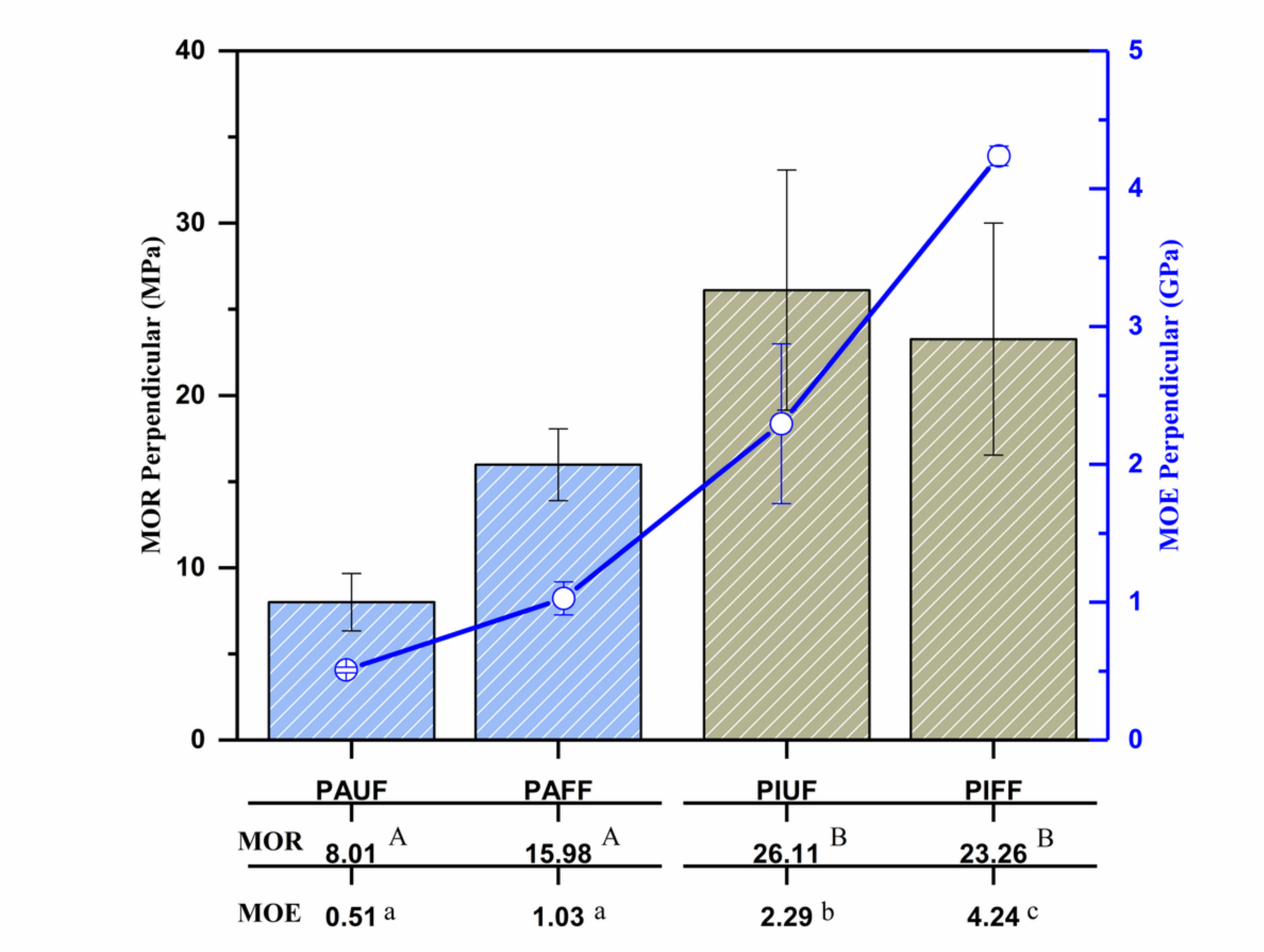

Figure 2

MOE and MOR perpendicular between treatments.

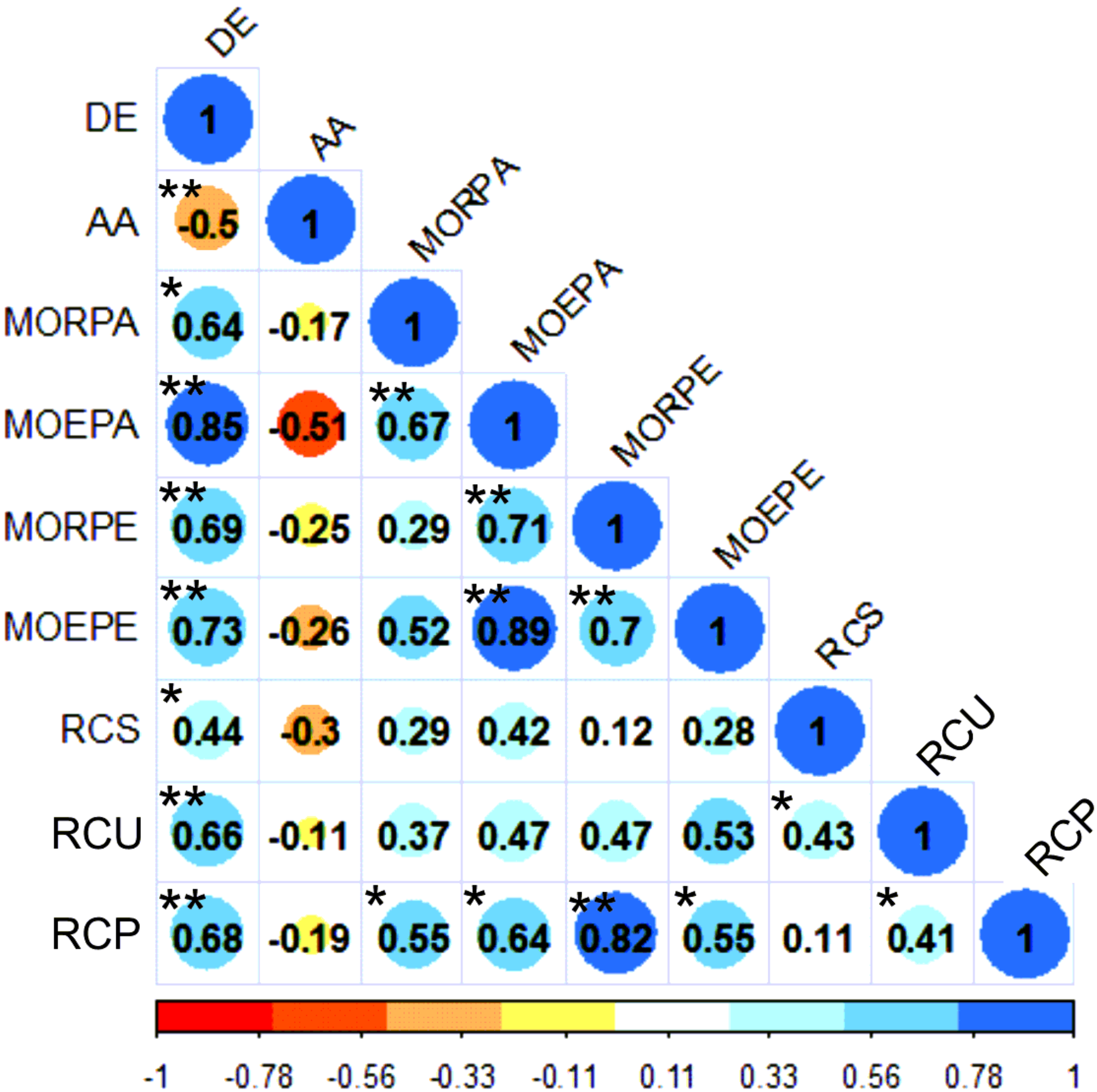

Figure 3

Pearson's correlation between the physical and mechanical properties of the plywood produced. DE: apparent density; AA: water absorption; MORPA: MOR in the parallel direction; MOEPA: MOE in the parallel direction; MOEPE: MOE in the perpendicular direction; RCS: dry shear resistance; RCU: wet shear resistance; RCP: shear resistance after boiling; (*) the correlation is significant at a level of 0.05; (**) the correlation is significant at a level of 0.01.