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Production and analysis of the physical and mechanical of particleboards panels produced with *Acrocomia aculeata* endocarp

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TECHNOLOGY OF FOREST PRODUCTS

ABSTRACT

Background: The macauba (*Acrocomia aculeata* (Jacq.) Lodd. ex Mart.) is a palm tree native to tropical regions and occurs in much of the Brazilian territory. Current studies are focused on the extraction and exploitation of vegetable oil from this fruit. However, there are few studies on the residue, the endocarp, which represents approximately 25% of the total mass of the fruit. Studies that search for solutions for using residue, thus adding value, and generating environmentally friendly products, are of fundamental importance. Thus, this research aimed to evaluate the physical and mechanical properties of reconstituted wood panels produced with different proportions of macauba endocarp particles to replace pine wood particles, in addition to characterize the physical and chemical properties of macauba endocarp. The chemical characterization tests were performed according to applicable standards. The basic density was determined according to the NBR 11941 standard. Thermogravimetric analysis (TGA), X-ray diffractometry (XRD) and Fourier transform infrared spectroscopy (FTIR) were also performed. The particleboards panels were produced with a nominal density of 0.70g/cm^3 and dimensions of 25x25x1.5cm. Five different treatments were evaluated with variations in the proportion of macauba endocarp particles in the core of the panel. For particle agglutination, phenol-formaldehyde adhesive was used at a proportion of 9% for the core and 12% for the faces, based on the dry mass of each panel. Scanning electron microscopy (SEM) was used to analyze the panel surfaces.

Results: The endocarp of *Acrocomia aculeata* has low extractive content, high lignin content and high densification, 1.23g/cm^3, when compared to *Pinus oocarpa* wood, 0.43g/cm^3. All panels were classified as low density according to CS 236-66 and had an average apparent density between treatments of 0.586g/cm^3. A greater dimensional stability and a decrease in the static bending properties of the panels was observed as the proportion of macauba endocarp particles increased. The internal bonding of the panels showed a positive result with the increase in the use of particles of the residue.

Conclusion: The panels produced have potential for use for non-structural purposes.

Keyword: Macauba; Residue utilization; Lignocellulosic residues.

HIGHLIGHTS

Sustainable production by applying lignocellulosic residue in the production of reconstituted wood panels.
Adding value to a lignocellulosic residue.
Chemical, physical, and mechanical analysis of the macauba and panels produced.
The panels produced have potential for use for non-structural purposes.

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INTRODUCTION

The industrial production of reconstituted wood panels, according to Lahar et al., (2011), was mainly developed after World War II, aiming to reduce the consumption of raw materials and the reuse of wood waste. The growing concern with reducing environmental degradation has increased the interest in studying new alternatives that allow the sustainable construction, promoting the use of natural renewable natural resources (Sánchez et al., 2017). Over time, particleboard became one of the main raw materials for the Brazilian furniture industry (Azambuja et al., 2018; Iwakiri et al., 2015, 2005).

According to Iwakiri et al., (2017), Mendes et al., (2011) and Protásio et al., (2015), the potential for the production of these panels, especially particleboard, is associated with the fact that they present some advantages, such as reducing the heterogeneity of wood or residual lignocellulosic biomass, making the material produced more homogeneous in its characteristics, and adding value to materials with low acceptance. However, although reconstituted wood panels allow for the possibility of using less acceptable materials in their manufacture, in Brazil pine and eucalyptus are still the main raw materials used in their production (Guimarães et al., 2013).

Different residues have already been employed in the production, as reinforcement, sugarcane bagasse (Lahar et al., 2011; Ligowski et al., 2015; Soares et al., 2017); rice husk (Brand et al., 2021; Souza, 2017); coffee husk (Scatolino et al., 2017); corn cob (Protásio et al., 2015); sorghum (Guimarães Júnior et al., 2016); Parica and Embauba (Colli et al., 2010; De Melo and Del Menezzi, 2014; Zeller et al., 2013) and recyclable paper chips (Calegari et al., 2004).

One of these possible residues for reinforcement, according to (Rigueira et al., 2017), is the macauba, considered the most widespread palm tree in Brazil, native to tropical forests and native to forests from the north to the southeast of Brazil. Macauba is member of Arecaceae family with great dispersion in America and common in areas of the Brazilian Cerrado (Moura et al., 2010). Its fruit consists of an outer bark (epicarp), pulp (fibrous mesocarp), one or two oily kernels in the innermost region and an endocarp, a lignified tissue of high mechanical strength, which represents about 25% of the total mass of the fruit (Río et al., 2016).

Due to its chemical and mechanical properties, it is believed that it is possible to add value to this lignocellulosic waste, incorporating it in the production of new materials. Given the above, the objective of this work was to evaluate the influence of reinforcing macauba endocarp particles, an agroforestry residue, on the physical and mechanical properties of particleboards panels produced with the *Pinus oocarpa* wood matrix.

MATERIAL AND METHODS

Obtaining *Pinus oocarpa* wood and *Acrocomia aculeata* endocarp

Pinus oocarpa five trees were cut at approximately 28 years of age on the campus of the Universidade Federal de Lavras - UFLA, Brazil, under the coordinates 21°22"90' S 44°97"01' W. From the base of the trees, 0.60 m long logs were removed. According to Iwakiri et al., (2002) recommendations, veneers were obtained on a veneer lathe. The veneers reached a nominal thickness of 2 mm and after lamination were dried in an oven at 105 ± 3 °C for 24 hours to reduce moisture to a final value of 3%.

The endocarps of Acrocomia aculeata were collected at the Faepe experimental farm, located in the municipality of Ijaci, in the southern region of Minas Gerais, under the coordinates 21°09'40.7 "S 44°55'30.2 "W. The endocarps were dried at a temperature of 105 ± 3 °C. After drying, the Pinus veneers and the macauba endocarp were processed in hammer mill to obtain the sliver particles. The *Pinus oocarpa* particles were those retained between sieves of 10 and 30 mesh. For the macauba endocarp particles were used particles with a particle size of 30 mesh.

Physicochemical characterization of *Pinus oocarpa* wood and *Acrocomia Aculeata* endocarp

The basic density was determined according to the NBR 11941 standard (ABNT 2003). The quantification of the total extractive content was performed with the fraction of biomass retained between the sieves of 40 and 60 mesh, according to NBR 14853 (ABNT, 2010). The determination of insoluble lignin content was performed using the procedure described in NBR 7989 (ABNT, 2010). For the quantification of ash contents, the methodology provided in the NBR 13999 standard (ABNT, 2017) was considered. The holocellulose content was obtained by difference in relation to the other molecular and mineral components of the biomass. The pH of the particles was also determined using the Tec - 3MP pH meter equipment.

Slenderness index of *Acrocomia aculeata* endocarp particles

The anatomy of the macauba endocarp particles was determined using Image J software. Thirty particle length and diameter measurements were taken and then the slenderness index was calculated.

FT-IR Spectroscopy -Attenuated Total Reflectance (ATR)

Macauba endocarp samples (maximum size 0.250 mm) were analyzed using Fourier transform infrared spectroscopy (FTIR) coupled with an attenuated total reflectance (ATR) accessory was performed using a Varian 600-IR Series FT-IR spectrometer equipped with Pike Technologies' GladiATR for FTIR-ATR measurements. Samples were scanned from 4000 to 400 cm^{-1} with 32 average scans for each spectrum at a resolution of 4 cm^{-1} (Tondi and Petutschnigg, 2015).

X-ray Diffraction (XRD) analysis

X-ray diffraction patterns were acquired by a Bruker D2 Phaser 2nd generation diffractometer, with Cu-Kα source (λ= 1.5418 Å) in the range of 10 to 40º (2θ) at a scan rate of 0.5°/min and increment of 0.02°. The acquired patterns had the noise removed, using OriginPro version 2022b software (Origin Lab, USA) by using the adjacent average method with 20 points per window with no peak information loss.

The patterns were deconvoluted using Gaussian function (including non-crystalline fraction) with the software Magic Plot 2.9 (Magicplot Systems, Russia). The theoretical coordinates of native cellulose Iβ (Full Width at Half Maximum; FWHM = 0.1) were extracted from crystallography information data (.cif) using the software Mercury 2020.2.0. (CCDC, UK) obtained from the Supplementary Information accompanying the original work (Nishiyama et al., 2002). For the amorphous halo, the cellulose II pattern with FWHM = 9, only varying its intensity, was used as suggested in the literature (French, 2020). There is still a discussion around assessing crystallinity, but deconvolution is still a recommended method (French, 2020). Afterwards, crystalline fraction (CF) was calculated based on Equation 1. Where CF is the crystalline fraction, in percentage, A_C represents the sum of the areas bellow the crystalline peaks and A_T is the area under the whole experimental pattern.

$$CF(\%) = \frac{A_C}{A_T} x100 \quad (1)$$

The crystallite size (CS) of the samples was calculated using Scherrer's equation (Equation 2) (Langford and Wilson, 1978). This step was also carried out on the theoretical curves. where CS is the size perpendicular to the lattice plane represented by the (200) peak, K is a constant related to the crystal shape, λ is the wavelength of the incident beam in the diffraction experiment, β is the FWHM, in radians, and θ is the diffraction angle of the peak.

$$CS = \frac{K\lambda}{\beta \cos\theta} \quad (2)$$

Production of particleboards panels

The panels were produced with the dimensions of 250 x 250 x 15 mm and nominal density of 0.700 g/cm^3. Five different treatments were evaluated with variations in the percentage of Acrocomia Aculeata endocarp particles in the core of the panel. The treatments were done in triplicate, totaling 15 panels. The different percentages used in the five treatments are described in Table 1.

Phenol-formaldehyde resin was used for bonding the particles, with a solid content of 47.59%, a viscosity of 191.4 cP, and a pH of 13.56. 9% adhesive was used for the cure and 12% adhesive for the faces, based on the dry mass of the particles in each panel. Then, the Pinus particles and macauba endocarp were mixed with phenol-formaldehyde adhesive. The panels were pressed at a temperature of 160 ºC and a specific pressure of 4 MPa, for 8 minutes, a process similar to that described by Mendes et al., (2014). After pressing, the panels were conditioned in a climate chamber at a temperature of 20 ± 3 ºC and relative moisture of 65 ± 5% until reaching an approximate equilibrium moisture of 12% and completion of the adhesive impregnation process.

Analysis of the physical and mechanical properties of particleboard

To evaluate the physical and mechanical properties of the particleboard panels, the following tests were performed as described in Table 2. The compaction ratio was calculated as described by (Guimarães Júnior et al., 2016; Soares et al., 2017) by dividing the apparent density of each panel by the average of basic density of the particles used.

Table 1: Experimental design.

Treatments	*Pinus oocarpa* (%)	*Acrocomia aculeata* (%)
Reference	100	0
T1	75	25
T2	50	50
T3	40	60
T4	25	75

Table 2: Standards used for the physical and mechanical tests of the evaluated panels.

Property	Dimensions (mm)	Standard
AA2h e AA24h	50 x 50 x 15	ASTM D1037 (2006)
IE2h e IE24h	50 x 50 x 15	
Perpendicular traction	50 x 50 x 15	
Apparent density	250 x 50 x 15	DIN 52362 (1982)
MOE e MOR		
Janka Hardness	50 x 50 x 15	ASTM D 143-94 (1996)
Screw pulling	50 x 50 x 15	NBR 14810 (2006)

Scanning Electron Microscopy – SEM

The prepared specimens were 6 mm in diameter and 3 mm thick. An overview of the microstructure of the panels was investigated using a LEO EVO 40 SEM. The microscope was operated under an accelerating voltage of 20 kV. A pre-coating with a thin layer of gold was done to make the samples conductive and suitable for analysis. The samples were fixed on a metal tip, stubs, covered by a carbon coated tape.

Experimental Design

The experimental design was entirely randomized, with 5 treatments and 3 repetitions. The data obtained were submitted to analysis of variance (ANOVA) ($p < 0.05$). In case of statistical differences between the means, regression equations were adjusted as a function of the addition of macauba endocarp (0%, 25%, 50%, 60% and 75%) in the particleboard panels. The data that did not show significant changes were submitted to the Tukey test at 5% significance level. The analyses were performed using Sisvar 5.6 software.

RESULTS AND DISCUSSION

Chemical and physical properties of the raw material used

The percentages of the chemical constituents of total extractives, insoluble lignin, holocellulose and ash present in *Pinus oocarpa* wood and *Acrocomia aculeata* endocarp are shown in Table 3.

The macauba endocarp has less extractives when compared to *Pinus oocarpa* wood. According to Scatolino et al., (2017), extractives increase hydrophobicity and, consequently, decrease the water absorption of the material, which may imply the production of panels that are less susceptible to moisture. However, as extractives act as a natural waterproofing agent, according to (Iwakiri et al., 2005; Marra, 1992), the higher their concentration, the greater the chances of having problems regarding adhesive penetration, which may lead to a decrease in the mechanical strength of the boards.

For insoluble lignin, the macauba endocarp has an advantage over the wood. Lignin is considered a natural adhesive, giving impermeability to the material due to its hydrophobic properties, in addition to attributing biological and mechanical resistance, because it acts reinforcing the cellulose microfibrils collaborating to reduce perpendicular movements to the grain (Silva et al., 2018; Soares et al., 2017). Thus, high levels of lignin are desirable in the production of reconstituted wood panels. With regard to the holocellulose values, a lower amount is observed in the macauba endocarp.

According to Freire et al., (2011), lower levels of holocellulose and, consequently, hemicelluloses, indicate lower availability of hydroxyl sites in the material, which may result in lower water absorption by panels made with this raw material. Regarding the presence of ash, the endocarp of *Acrocomia aculeata* has disadvantages compared to *Pinus oocarpa* wood, since higher levels of ash can affect the bonding of the particle boards, because they cause the inhibition of chemical groups reactive with polar adhesives, in addition to causing excessive wear of the saws during the obtaining of the material (Iwakiri et al., 2015; Ndazi et al., 2007).

The values found for the chemical components present in *Pinus oocarpa* wood agree with those portrayed in the literature. In their study, Scatolino et al., (2013) found 5.2% for extractives, 28.3% for lignin, 66.2% for holocellulose, and 0.4% for ash. For macauba endocarp, Pereira et al., (2018) found 39.1% insoluble lignin, while Silva et al., (1986) obtained 36.60% for lignin, 52.60% for holocellulose, 0.97% for ash and 10.80% for extractives. The higher extractive value found in the literature is possibly related to the environment to which the plant is exposed, since the extractives are heterogeneous substances influenced by climatic and genetic factors. The difference between the ash content found in the literature and that obtained in this study may be related to the planting location and the levels of minerals present in the soil (Soares et al., 2017). The density of the endocarp of *Acrocomia aculeata* was higher than that found for *Pinus oocarpa* wood (Table 4).

The values obtained in this study are similar to those reported in the literature. In a study on macauba endocarp, Silva et al., (1986) obtained the value of 1.161 g/cm^3 for the basic density. With regard to the wood of *Pinus oocarpa*, Silva et al., (2018) and Scatolino et al., (2013) found a basic density value of 0.473 g/cm^3 while Trianoski et al., (2013) obtained a value of 0.54 g/cm^3.

The production of particleboards panels is favored using low-density materials, since the lower the density of the material to be used the higher is the compaction ratio of the panel, resulting in a higher compression rate and bond between the particles, and possibly in panels with better mechanical properties. However, it is highlighted that the high values of compaction ratio resulting from the insertion of low-density particles in the panels, mean a greater amount of material to reach the nominal density of the sheets, thus, there may be a greater number of hydroxyl sites available in the mixture, which can increase the dimensional instability of the panels (Iwakiri et al., 2005; Scatolino et al., 2013; Soares et al., 2017).

In addition, Scatolino et al., (2017) mention that a larger amount of particles also indicates lower adhesive availability, which can lead to poor panel performance in properties such as internal bonding. The values obtained for the pH of the particles used in the production of the particleboard panels are presented in Table 4. For Maloney (1993), pH is one of the most important factors in choosing the raw material to be used in the production of particleboard panels. This is because it directly influences the curing of the resin and, consequently, the quality of the boards (Marra, 1992).

Table 3: Chemical components present in *Pinus oocarpa* wood and *Acrocomia aculeata* endocarp.

Sample	Total extractives	Insoluble Lignin	Holocellulose	Ash
Pinus oocarpa	4.03 (0.17)	26.08 (2.50)	69.63 (2.63)	0.26 (0.02)
Acrocomia aculeata	3.10 (0.26)	39.60 (0.17)	52.64 (0.10)	4.70 (0.37)

The values in parentheses indicate the standard deviation.

Table 4: Basic density, porosity and pH values obtained for *Pinus oocarpa* wood and *Acrocomia aculeata* endocarp

Sample	Basic density (g/cm^3)	Porosity (%)	pH
Pinus oocarpa	0.48	68.83	5.053 (0.12)
Acrocomia aculeata	1.23	20.13	5.237 (0.06)

The ideal pH range for particles varies from 3.0 to 5.5. Particles with very acidic pH can delay the curing of the phenol-formaldehyde resin, requiring larger amounts of catalyst, while those with a slightly acidic pH tend to cause the pre-cure of this adhesive during pressing, affecting the bonding of the panels and their physical-mechanical performance. It is observed that both particles used have pH in the range indicated by the literature (Iwakiri et al., 2002; Parchen et al., 2016; Zeller et al., 2013).

Particle slenderness

The average values were for length 1.14 (0.18) mm, diameter 0.69 (0.16) mm, and slenderness index 1.66 of the macauba endocarp particles. Particle geometry fundamentally interferes in panel performance, since it influences the contact area and the availability of resin per particle (Ferreira et al., 2014). According to Mutjé et al., (2007), slenderness indexes close to 100 are considered optimal, while those below 10 are inefficient to provide reinforcement to the matrix. Iwakiri et al., (2005) indicates for matrix reinforcement purposes, particles of the inner layer with slenderness index close to 60 and for the outer layer, close to 120.

It is noted that the slenderness index of the macauba endocarp particles used in this work are below the values indicated by the specialized literature. However, Pereira et al., (2019) and Silva et al., (2020) studying the influence of the geometry of the particles of the inner layer on the properties also obtained results lower than those recommended in the literature, pointing out that this fact is related to the origin of the raw material, since it is a waste product. Moreover, it highlights those adjustments in particle processing can result in increased slenderness ratio and improved panel properties.

Fourier Transform Infrared Spectroscopy (FTIR) of macauba endocarp

The spectra of the macauba endocarp showed some characteristic peaks. It is possible to observe all the chemical bond bands of the macauba barks and the macauba residue (Figure 1). The band corresponding to the O-H bond represented by the peak at 3290 cm^{-1} was well defined, with a band well representative of the amount of water present in the sample (Kain et al., 2015; Tondi et al., 2015).

The compounds analyzed in general showed the following absorption behavior in the infrared region: broad band at 3290 cm^{-1} due to hydrogen vibrations of OH groups of water, alcohols, phenols or carboxylic acids, as well as for hydrogen of amides; the bands at 2917 and 2856 cm^{-1} were relative to C-H stretching of methylene groups of fatty acids and various aliphatic compounds; the band at 1716 cm^{-1} was assigned to the C=O stretching of aldehydes, ketones, and carboxylic acids and refers also to C=C vibrations of aromatic structures and of aromatic ring conjugated C=O groups; bands in the region of 1608 cm^{-1} is characteristic of secondary amides; a band at 1435 cm^{-1} caused by the absorption of some aliphatic structures, phenolic OH groups, COO- groups, vibrations of aromatic rings and carbonates; and an absorption band at 1020 cm^{-1} is assigned to silicate groups, to aromatic ethers and finally to C-O stretching of polysaccharides (Faris et al., 2016; Ghahri et al., 2018; Oo et al., 2009; Smidt et al., 2005).

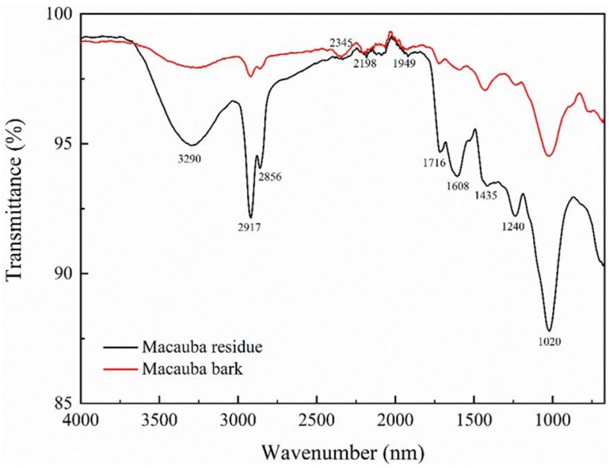

Figure 1: Peaks of the FTIR analysis of the Macauba endocarp.

The bands at 2917 and 2856 cm^{-1} were both found in all FTIR spectra for the samples which refer to fat and lipids; the band at 1716 cm^{-1} can be attributed as being original to protein; the band around 1608 cm^{-1} is characteristic of absorption from wood, fruits, grasses and other plants, in the range 1608 cm-1 and 1020 cm-1 peaks are representations of C = C stretching bonds, aromatic rings and compounds like flavonoids and C-O-C = stretches, oxo-aromatic compounds, respectively; 1435, 1240 and 1020 cm^{-1} originated from components of the macauba containing lignin, coming from wood and that the band at 1435 cm^{-1} refers to the nitrate group that appears at the end of the process when the material is well composed (Ferreira et al., 2015; Grube et al., 2006; Junaidi et al., 2016; Li et al., 2018).

XRD of macaubaendocarp

The XRD pattern of the macauba endocarp is shown in Figure 2, its presented patterns typical of semi-crystalline materials with an amorphous halo and crystalline peaks. The XRD patterns exhibited a sharp peak near to $2\theta = 22°$, which was assigned to the (200) lattice plane of cellulose I. Cellulose I is a structure comprised of repeating β-(1→4)-D-glucopyranose units with building blocks of parallel glucan chains. The two overlapping peaks at 2θ = 14.8° and 2θ = 16.3° correspond to the (1–10) and (110) lattice planes of cellulose I (Jin et al., 2016). The peak at 2θ = 34.5° corresponds to (004) plane and indicates orientation along the fiber axis (Fonseca et al., 2018). The shift in the diffraction powder pattern at plane (200) may be due to difference in unit cell dimensions of theoretical cellulose pattern and experimental macauba endocarp (French, 2014).

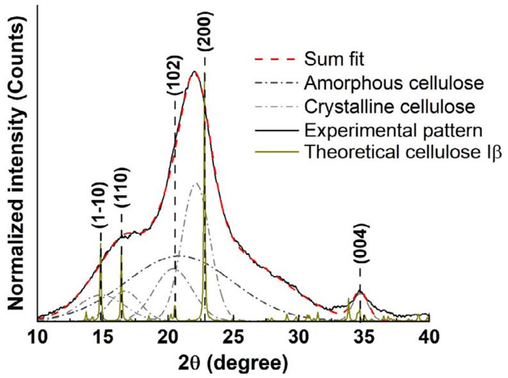

Figure 2: Peaks of the XDR analysis of the macauba endocarp.

The values of crystalline fraction is 43% , crystallite size 3.2nm, and the number of cellulose chains per crystallite of the macauba endocarp, respectively. According to Fonseca et al. (2019), the mechanical reinforcing effectiveness of lignocellulosic materials is related to the nature of cellulose and its crystallinity. The C_F (43%) calculated by curves deconvolution shows that macauba endocarp composition is associated most to amorphous material such as lignin, hemicellulose and extractives that do not contribute to the crystalline fraction of biomass (Fonseca et al., 2019). Furthermore, this C_F value is similar to those found previously by (Lacerda et al., 2016). The macauba endocarp showed a small crystallite size (3.2 nm) which contributed to low crystallinity. Small crystals are appointed as another reason for lower crystallinity and, different cellulosic materials have widely varied crystallite sizes (Machado et al., 2015; Teixeira et al., 2018).

The reduced size of the crystallites may have been due to the sample being ground for analysis, which may have damaged the crystallites, even if the sample is not on the nanometer scale. Decrease in crystallite size is commonly observed in cellulose samples that have undergone strong mechanical shearing, until nano size, as attested by Tonoli et al. (2016).

Physical properties of the panels

Density, moisture, and compaction rate

Table 5 presents the mean values and standard deviation of bulk density and moisture content of the pine and macauba endocarp particleboard panels. The results show that the addition of particles of macauba endocarp influenced the bulk density of the particleboards panels ($p < 0.05$). The bulk density increased significantly with the addition of 60% (0.59 g/cm^3) and 75% (0.61 g/cm^3) of macauba particles, compared to the panel produced with 100% pine (0.55 g/cm^3). Specifically, the bulk density of the panels with 60% and 75% macauba endocarp increased about 7.3% and 10.9%, compared to the pure *Pinus oocarpa* chipboard. The increasing trend in bulk density with the addition of macauba fiber was expected, given that the basic density of macauba was about 2.6 times greater than that of the pine particle (Table 8). Furthermore, due to the difference in particle geometry, it is suggested that the addition of macauba particles filled the empty spaces between the *Pinus oocarpa* particles, resulting in denser panels.

Table 5: Apparent density and moisture content of particleboard panels produced with pine particles and Macauba endocarp.

Treatment	*Acrocomia aculeata* (%)	Apparent density (g/cm³)	Moisture (%)
T0	0	0.55 (0.024) A	13.3 (0.824) B
T25	25	0.58 (0.032) AB	13.3 (0.992) B
T50	50	0.60 (0.015) AB	13.2 (0.587) B
T60	60	0.59 (0.014) B	13.2 (0.507) B
T75	75	0.61 (0.024) B	13.2 (0.681) B

Means followed by the same letter in the same column do not differ by the Tukey test at 5% significance level. Values in parentheses indicate standard deviation.

This behavior coincides with the report of Wong et al., (2020) which observed an increase in the bulk density of the panels according to the addition of denser residues. The mean values of bulk density of the panels with 25% and 50% macauba endocarp were statistically similar to the other treatments. Apparent density is one of the main quality parameters to be evaluated, because it provides prior indications about the physical-mechanical properties of the panels. Despite the statistical differences between the 100% pine panel and the hybrid panels (T60 and T75), in general the apparent density values were between 0.55 and 0.61 g/cm^3. Thus, all the produced panels are classified as low density (< 0.64 g/cm^3) (ANSI A208.1, 1999). Therefore, these panels can be destined to the furniture industry, where low weight is a requirement to facilitate transport and assembly (Monteiro et al., 2019). Another possible application for low density panels is their use as door core filling material, thermal and acoustic insulator (Regmi, 2022).

The lower values found for the densities of the panels in relation to the nominal density 0.70 g/cm^3, as established for the calculation of the materials, is attributed to the laboratory production process, in which material losses occur during the conformation of the panel and the return of the thickness of the panels after the pressing stage. The equilibrium moisture content of the particleboard varied between 13.2% and 13.3%, with no significant differences between treatments (p > 0.05). There was a decreasing relationship between the addition of macauba endocarp and the compaction rate, Figure 3.

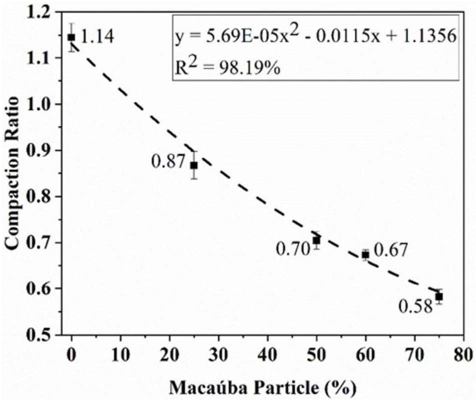

Figure 3: Compaction ratio of particleboards panels as a function of the addition of macauba endocarp.

The addition of 25%, 50%, 60%, and 75% macauba residue caused a reduction in the compaction rate by 23.7%, 38.6%, 41.2%, and 49.1%, respectively. As explained by Faria et al., (2020) the compaction rate is directly related to the density of the raw material and the moisture of the mattress. Knowing that the conditions used in the manufacture of the panels were the same, it can be stated that the statistical difference between the values of compaction rate of the different treatments is related to the density of the materials. Thus, as the proportion of macauba residue increased (higher basic density), there was a reduction in the compaction rate, considering that denser materials result in smaller volumes.

Similar behavior was also found by Azambuja et al., (2018) who found that the compaction rate of particleboards produced with construction and demolition waste reduced with the addition of higher density wood. The authors Carvalho et al., (2017) also reported a decrease in the compaction ratio of the panels according to the addition of lignocellulosic residue with basic density higher than the density of *Pinus oocarpa* wood, inferring that the decrease in this property is due precisely to the high density of the inserted residue.

However, according to Maloney, (1993) the ideal range of compaction ratio of particleboards should be between 1.3 and 1.6. Moreover, studies have demonstrated adequate properties with compaction ratios between 1.5 and 8.3, for particleboards produced with agro-industrial waste (Narciso et al., 2021; Silva et al., 2018). This implies that in this study there was not an adequate densification of the particles. As the compaction ratio is a parameter determined by the ratio between the density of the panel and the density of the raw material, the process conditions and/or the characteristics of the panel components can be altered, ensuring better efficiency in the compaction process and, consequently, better structural properties of the particleboards panels.

Water absorption and swelling in thickness

The curves obtained from the regression models adjusted for the water absorption of the panels after 2 and 24 hours of immersion as a function of the addition of macauba particles are presented in Figure 4.

In both periods analyzed (2 hours and 24 hours) the effect of the addition of macauba was observed in the behavior of water absorption and the best estimates were obtained through the linear regression model. The water absorption after 2 hours of immersion varied between 89.80 and 78.28%, with the lowest values observed for the composites with 75% macauba (Figure 4 A). In specific the water absorption of the panels produced with 75% macauba, reduced about 12.8% compared to the 0% macauba panel. Similar behavior was observed for the water absorption period after 24 hours of immersion. It can be seen that there was a percentage reduction of 4.0% in water absorption for the panels with 25% macauba, compared to the 0% macauba panels. This reduction was even more significant with the increase in the proportion of macauba endocarp to 50%, 60% and 75%, whose percentage reduction was 10.6%, 12.7% and 14.0%, respectively, in relation to the pure pine panel.

The results indicate that, although the compaction rate reduced with the increase in the proportion of macauba, the physical performance of the hybrid panels improved. this behavior of hybrid panels (pine and macauba) under high moisture conditions is due to the less hydrophilic nature of the macauba particles, which had lower holocellulose content and higher lignin content than the pine fibers (Table 3). In fact, cellulose is composed of numerous glucose molecules that have in their structure available hydroxyl groups (C2, C3, C6) that interact with water through hydrogen bonds, giving it a strongly hydrophilic character. Like cellulose, hemicelluloses also have numerous binding sites for water molecules.

Thus, the reduction in water absorption as the percentage of macauba residue increases is related to the concomitant reduction in the proportion of hydroxyl groups, so the amount of polar sites available to interact with water molecules is lower. As a result, less water molecules will accumulate on the particle cell wall and at the particle-adhesive interface, resulting in more dimensionally stable panels. These statements are consistent with the study of Mesquita et al., (2018) who found that the water absorption of the panels increased with the addition of cellulosic fiber. Still, Scatolino et al., (2017) working with hybrid particleboard made from eucalyptus wood and coffee parchment, showed that the water absorption of the panels decreased with the addition of coffee parchment, which contained lower holocellulose content.

Regarding literature, Regmi et al., (2022) The analysis of variance showed a significant effect on the swelling in thickness (TS) of the panels after 2 hours of immersion and 24 hours of immersion. The analysis of variance showed significant effect on the thickness swelling (TS) of the panels after 2 hours and 24 hours of immersion. In both periods analyzed the variables followed a quadratic trend in the fitted regression models, Figure 5.

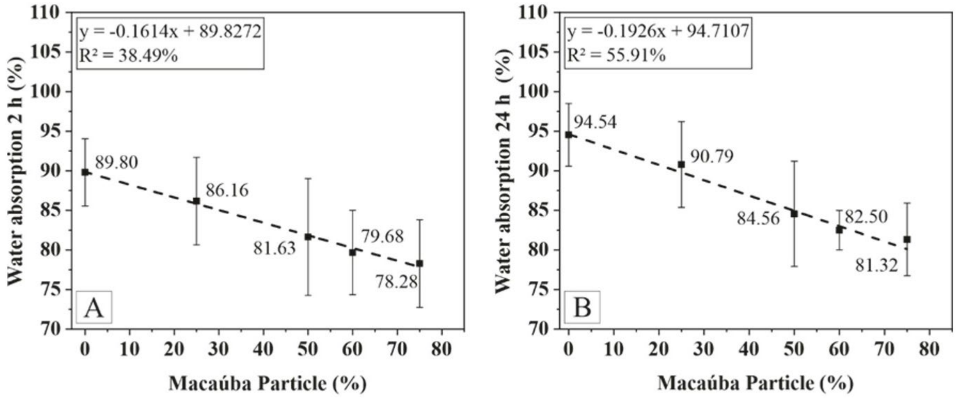

Figure 4: Water absorption of particleboards panels as a function of the addition of macauba endocarp: (A) WA after 2 hours of immersion and (B) WA after 24 hours of immersion.

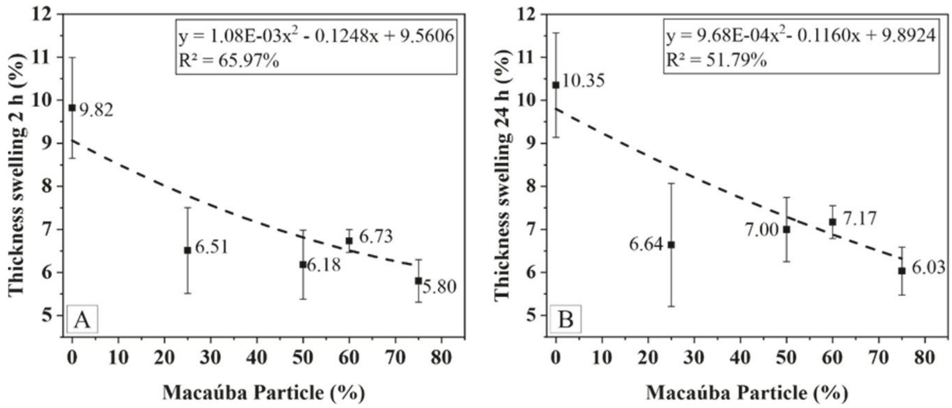

Figure 5: Thickness swelling of the particleboards panels as a function of the addition of macauba endocarp: (A) TS after 2 hours of immersion and (B) TS after 24 hours of immersion.

In general, the average value of swelling in thickness after 2 hours of immersion ranged between 9.82 and 5.80%. The panels made with 75% of macauba residue obtained the lowest TS value after 2 hours of immersion (5.80%). The other treatments presented similar standard deviation ranges, except for the panel composed of 100% pine (0% macauba), which presented the highest TS (9.82%). The same trend was observed for TS after 24 hours of immersion. There was a gradual reduction of swelling in thickness with higher percentages of macauba particles (Figure 5B).

The decrease in swelling in thickness with the addition of macauba particles is mainly related to the characteristics of the constituent materials, adhesive availability, and compaction ratio. For high density lignocellulosic materials, such as macauba endocarp, a smaller volume of particles is required for the same amount of adhesive to produce panels with the same nominal density; thus, each particle is wrapped with more adhesive and, concomitantly, there are fewer hydroxyl groups to bind to water, resulting in lower swelling in thickness.

Also, as already discussed, the 100% pine panels had a higher compaction rate, i.e., a more cohesive rearrangement of particles, resulting in higher internal tension when immersed in water and, consequently, in higher swelling in thickness. These observations corroborate with Nakanishi et al., (2018) who found higher swelling in thickness for panels made of sugarcane bagasse particles with higher compaction ratio.

The values of swelling in thickness after 2 and 24 hours of the pine particleboards with 75% of macauba endocarp were on average 40.9% and 41.7% lower, respectively, then the values of pure pine panels. This proves that the lower compaction rate and the presence of particles with lower holocellulose content decrease the swelling in thickness of the panels.

According to the guidelines of the ANSI A208.1-2009 standard, the swelling in thickness after 2 hours of immersion should be a maximum of 8% for particleboard that will be used in the manufacture of residential decks. This requirement was met only for hybrid particleboard (pine and macauba endocarp), which showed a significant reduction in swelling values, enabling its application outdoors. On the other hand, all the panels met the requirement of the European standard EN 312 that swelling in thickness after 24 hours of immersion be less than 14% for use in humid conditions.

In addition, the thickness swelling values after 24 hours of immersion were only relatively higher than at 2 hours, indicating that all treatments show good long-term stability. The results obtained in this work for the swelling in thickness of the panels were relatively lower than those found by Regmi et al., (2022) who worked with wheat straw, pine wood, and hybrid (wheat straw and dried distillers grain with solubles - DDGS) bonded panels with phenol formaldehyde resin; in general, the TS values after 2 hours of immersion were between 19.59% and 39.68%, while the TS after 24 hours of immersion ranged between 19.60% and 40.41%.

Mechanical properties of the panels

The regression model adjusted as a function of the increase in the percentage of macauba endocarp particles in the particleboards panels for the modulus of rupture (MOR) to static bending and the modulus of elasticity (MOE) is presented in Figure 6. The quadratic regression was the one that best fitted the data, being statistically significant for the strength and stiffness properties of the particleboards ($p < 0.05$). Contrary to what was observed for the physical properties, the particleboards panels produced only with pine particles showed better performances in the mechanical tests, revealing higher values of MOR (2.0 MPa) and MOE (245.7 MPa).

This improvement may be attributed to the existence of a higher concentration of particles in the same volume, thus the compaction of the pure pine panels resulted in a more cohesive rearrangement of particles, as already discussed in the physical properties. (Azambuja et al., 2018) produced particleboards panels with construction and demolition waste and demonstrated that panels made with lower density raw material and, consequently, higher compaction rate, resulted in superior mechanical properties.

Another possible explanation for the mechanical results is that the macauba endocarp particles presented low slenderness index 1.66, producing panels with lower MOR and MOE. According to Pedzik et al., (2021) particle geometry is an important parameter to be considered in panel production, and longer particles with higher slenderness index tend to provide a more adequate contact surface between the particles during bonding. In this context, given the low slenderness of the macauba particles, they were possibly not efficient in ensuring reinforcement to the matrix, leading to a reduction in the mechanical performance of the panels with regard to the modulus of rupture and modulus of elasticity to static bending. A similar trend was found in the study of Bazzetto et al., (2019) which observed a reduction in strength and stiffness of the particleboards panels as particles with lower slenderness were added.

Also, associated with these factors, the chemical constitution of the raw materials can be taken into account, in which a greater amount of holocellulose and less lignin were detected for *Pinus oocarpa* wood (Table 3). Therefore, as the content of macauba endocarp increased, the lignin content of the particleboard increased and the holocellulose content decreased, which caused the weakening of the mechanical properties to static bending. In fact, it has been widely mentioned in the literature that the low quantity, especially, of cellulose in the particles intended for the production of particleboard panels has caused damage to their mechanical properties (Baharoglua et al., 2013; Klímek et al., 2018; Pedzik et al., 2021; Zhang and Hu, 2014).

The results of this study, obtained for the mechanical properties, agree with Baharoglua et al., (2013) that found superior mechanical properties for particleboards panels manufactured with pine particles. According to these authors, the increase in the mechanical properties of particleboards with pine particles is related to the greater length of the tracheid, greater amount of fiber/tracheid per unit area and higher cellulose content. The ordered structure of the cellulose results in particleboards panels with a more compact and dense structure, giving them greater mechanical strength.

According to ANSI A208.1, (1999) for low density particleboard the minimum requirement for MOR is 3.0 MPa, while for MOE the minimum recommended value is 550 MPa. In this sense, all treatments showed mechanical properties with MOR and MOE below the minimum requirements established by the standard. Values of MOR and MOE below the minimum requirements recommended for low density panels were also reported by Suwan et al., (2020), for particleboard produced with bamboo particles and polyurethane adhesive. In the research of Regmi et

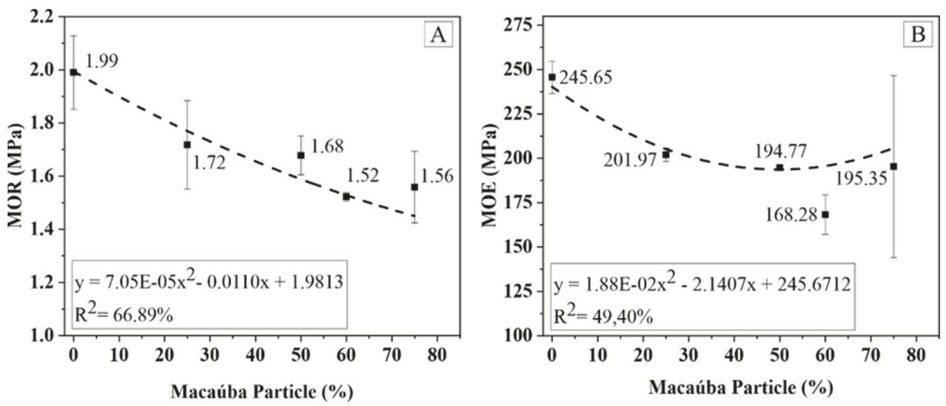

Figure 6: Mechanical resistance to static bending of particleboards panels as a function of the addition of macauba endocarp: (A) Modulus of Rupture (MOR) and (B) Modulus of Elasticity (MOE).

al., (2022) low density particleboard manufactured with wheat straw and DDGS bonded with phenol formaldehyde adhesive also generated mechanical performance below the minimum requirements established by ANSI A208.1, (1999).

However, these studies have shown that the strength and stiffness of the panel can be considerably improved by increasing the addition of binder and particles with a higher slenderness index Pedzik et al., (2021), also report that better mechanical performance can be achieved if the process parameters, such as panel density and pressing temperature, are increased. Thus, strategies such as these can be adopted in the production of the particleboardspanels with macauba particles, aiming to improve the mechanical strength of the panels. Despite these results, the particleboards produced in this study can be used for thermal and acoustic insulation applications, office partitions, bulletin boards, and tabletops, where high mechanical strength is not required.

The addition of macauba endocarp significantly influenced the internal bonding property of the particleboards ($p < 0.05$). Figure 7 illustrates the influence of macauba particle content on the IB of the particleboard, fitted by the quadratic regression model.

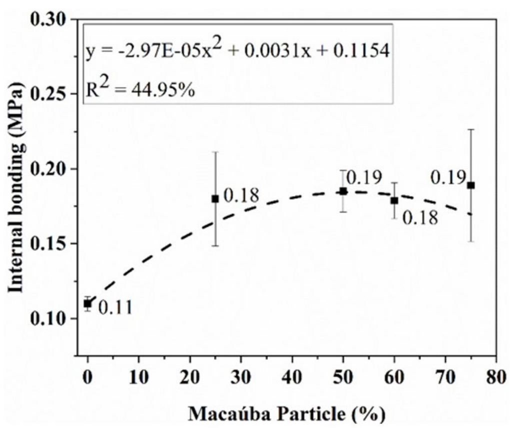

Figure 7: Internal bonding of the particleboardspanels as a function of the addition of macauba endocarp.

Compared with 100% pine panels, the internal bond of panels with 25% and 60% macauba endocarp increased 63.6%, while for the particleboards made with 50% and 75% macauba particles this increase was 72.7%. The properties of particleboardspanels are highly influenced by the type and amount of binder, particle characteristics, and interaction between the binder and the particle (Nicolao et al., 2020). The internal bonding of the particleboards can be improved by using shorter and thicker particles Brito et al., (2020), because when compacted they increase their surface area available for contact between the particles.

Also, Chaydarreh et al., (2021) commented that the lignin content positively influences the internal bonding property. Knowing that in this study the same amount and type of binder was used, the higher values found for the panels produced with macauba particles were probably due to the smaller size and porosity of the particles and the higher lignin content. The pine particles are wider and thinner than those of macauba, and also have greater porosity; therefore, it is suggested that in the 100% pine panels there was greater absorption of binder, resulting in lower availability of adhesive for bonding between the particles and, consequently, lower IB. These statements are consistent with the study of Regmi et al., (2022) who observed that larger particles conferred lower IB value. In addition, these authors verified a relationship between IB and thickness swelling, so that the particleboards with lower IB strength tended to swell more. This relationship was also found in our study, in which the hybrid panels were dimensionally more stable than the 100% pine panel.

Also, it can be stated that the higher lignin content of macauba endocarp (Table 3) positively affected the internal bonding properties of the hybrid particleboards. Lignin is a polymer with thermoplastic characteristics that, when heated above a certain temperature, becomes viscous, acting as an adhesive material. In general, the glass transition temperature of lignin is in the range between 90 °C - 129 °C (Almusawi et al., 2016). This indicates that the temperature employed in this study (160 °C) as well as the other parameters, such as pressing time and pressure, were sufficient for the lignin to become plastic diffusing to the outside of the particles, improving the adhesion between the particles. These observations explain the additional strength in the internal bonding of the particleboards produced with pine and macauba particles. Previous research has shown that the use of longer particles had lower IB value, while particles with high proportion of lignin resulted in panels with improved IB (Chaydarreh et al., 2021; Zhang and Hu, 2014).

Although there was some increasing trend with the addition of macauba endocarp, the average results of internal bonding of the particleboards did not meet the minimum requirement established by the European standard EN 312-2 (EN, 1996), which is 0.24 MPa for panels for general use. The low IB values obtained for all particleboard panels suggest that the adhesive content applied was insufficient, given that this property indicates the degree of bonding between the particles (Monteiro et al., 2019). In addition, the fact that the particleboardspanels did not reach the optimal range of compaction ratio (Figure 7) may also have contributed to these results. Strategies such as plasma treatment of the particles (Hýsek et al., 2018a) and chemical and hydrothermal treatments (Hýsek et al., 2018b) have been suggested to achieve better bonding between the particles and, consequently, better mechanical performance.

Despite this, for low density particleboard the minimum IB recommendation, stipulated by ANSI A208.1, (1999), is 0.10 MPa; therefore all particleboard met the requirements of this standard. Based on the literature, the IB values of the panels with macauba endocarp addition are higher than the IB data presented by (Mahieu et al., 2019) who worked with particleboards produced with flax straw and sunflower husk.

The addition of macauba endocarp in the production of the particleboards did not influence the Janka hardness and screw pull-out properties ($p > 0.05$), Figure 7 and Figure

8, respectively. The Janka hardness test determines the penetration resistance of the material how much stress is concentrated in an area, giving insight into when heavy objects and/or fasteners are placed on the panel (Mascarenhas et al., 2021). In general, the Janka hardness values of the clusters were in the range between 140.7 kgf and 119.7 kgf, Figure 8.

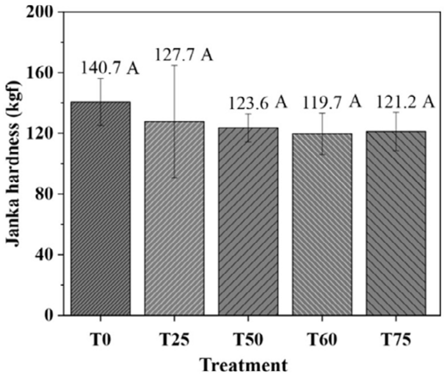

Figure 8: Mean values of Janka hardness of particleboards produced with pine particles and macauba endocarp. Averages followed by equal letters do not differ statistically by the Tukey test at 5% significance level.

Thus, Janka hardness of the particleboard panels did not meet the requirements set by ANSI/A 208.1 (1993), since the minimum allowable value for general purpose particleboard is 285.5 kgf. Janka hardness is a property that is highly affected by the production parameters of particleboard, which include pressure and temperature, as well as by the density of the samples (Büyüksarı, 2013) and, consequently, the compaction ratio. Also, Mitchual and Mensah, (2020) produced particleboards panels with different types of waste and showed that particles with higher slenderness index (135.03) produced panels with higher Janka hardness (692.4 kgf - 895.3 kgf). In this sense, the low Janka hardness values of the pine and hybrid particleboards are probably related to the low slenderness index of the particles and the low compaction ratio (Figure 9), which are below the recommended ranges to obtain particleboards with improved mechanical performance. Therefore, it can be stated that the characteristics of the particles will vary with the raw material employed, a fact that should be considered in the production processes.

Figure 9 shows that the screw pull-out force of the particleboard panels was 366 N - 260 N (S-SH) and 186 N - 149 N (E-SH).

The average values of screw pull-out at the surface were higher than those at the top, and there is a statistical difference between the two results. This is related to the fact that when the screw is fixed at the face, it goes through the entire thickness of the panel, while when inserted at the top it reaches only the central layer of the panel, characterized by having lower density than the face and, therefore, lower resistance to screw pullout (Bazzetto et al., 2019). The corresponding bolt pull-out values of the particleboard panels did not meet the minimum requirements stipulated by ANSI A208, (1999), for low-density particleboard (≥ 400 N). Comparing with the literature, higher values were found by Narciso et al., (2021) for particleboards produced with coconut fiber and *Pinus oocarpa* particle (S-SH between 657 - 802 N and E-SH between 268 628 N).

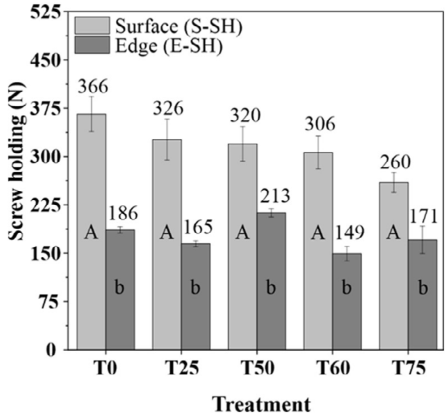

Figure 9: Mean values of screw pull-out of particleboard panels. Averages followed by equal upper-case letters between S-SH and lower-case letters between E-SH do not differ statistically from each other by the Tukey test at 5% significance level.

Indeed, in this study, the screw pull-out results were low, suggesting that this effect may be associated with insufficient amount of adhesive and low compaction ratio. In addition, particle geometry is also a factor that interferes with screw pull-out resistance. Studies have shown that there is a linear relationship between particle size and screw pull-out strength, i.e. larger particles with higher slenderness index promotes higher S-SH and E-SH values (Chaydarreh et al., 2021; Karlinasari et al., 2021).

Although the mechanical results were not satisfactory, one of the focuses of the research work was to produce a new particleboards panel with Acrocomia aculeata palm endocarp, aiming to add value to this residue, as well as contribute to the management of available resources. The production of particleboards with macauba residues, besides being a viable raw material alternative to wood resources, also offers economic benefits of using the residue instead of burning or landfilling. Considering the constant growth in demand for reconstituted panels (Pedzik et al., 2021), the availability of macauba residue and the excellent physical properties of hybrid panels (pine and macaúba) obtained in this research, a continuous effort in the development of new panels made of macauba particles that achieve better mechanical performance is a very attractive advance.

Scanning Electron Microscopy (SEM)

Figure 10 shows the SEM images of the core of the bonded panels. It is apparently observed a higher compaction of the particles of the reference panel, which was already expected due to the high density of macauba endocarp.

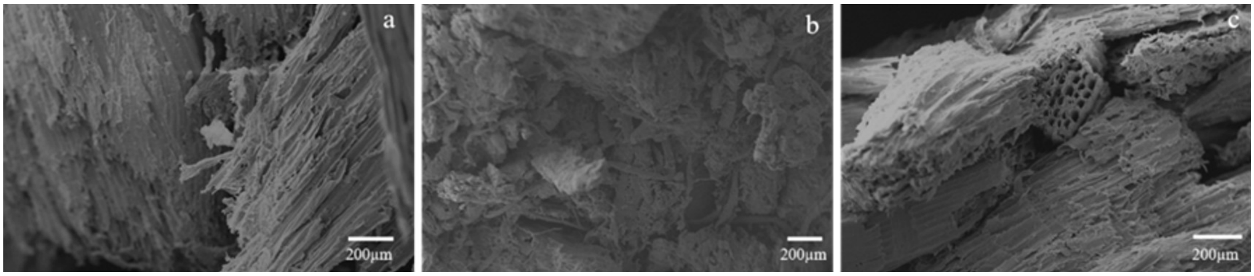

Figure 10: SEM image of the core of the panels. a: Reference panel (100% Pinus); b: Treatment T1 (25%) of macauba; c: T3 (75%) macauba treatment.

This results in a lower compaction ratio and, therefore, in a smaller contact surface between the particles, causing a drop in the transmission of stresses between them and thus, a low performance of the panels in static bending properties (Carvalho et al., 2015). Furthermore, it is noted that the particles were efficiently enveloped by the adhesive, and in Figure 10a there is a distribution in thinner and more homogeneous layers, due to the higher concentration of particles. In Figures 10b and 10c a distribution in coarser layers is observed, with resin accumulation in some areas, resulting from the lower concentration of particles in the same volume.

CONCLUSIONS

In general, it is concluded that the properties of the panels were significantly affected by the characteristics of the raw materials, mainly slenderness index, chemical constitution, and basic density. The use of higher percentages of macauba particles provided low values of modulus of rupture (MOR) modulus of elasticity (MOE) for the particleboards panels, due to the low compaction rate and the chemical and geometric characteristics of the particles. Although the panels made with pine particles and macauba endocarp did not reach the minimum values stipulated by the standards in force, the panels produced have potential for non-structural use. Furthermore, the results of this study suggest that additional studies seeking to improve the mechanical properties of the particleboards can be carried out by applying pre-treatments to the raw material, modifications in the geometry of the particles and/or changes in the production parameters; considering that the use of viable alternative materials, such as the macauba endocarp brings numerous ecological and economic benefits.

AUTHORSHIP CONTRIBUTION

Project Idea: LOM, ULZ, MCD, CS, MNLS, DLF, FAM, JBGJ, SRF
Funding: LOM, ULZ, MCD, CS, MNLS, DLF, FAM, JBGJ, SRF
Database: LOM, ULZ, MCD, CS, MNLS, DLF, FAM, JBGJ, SRF
Processing: LOM, ULZ, MCD, CS, MNLS, DLF, FAM, JBGJ, SRF
Analysis: LOM, ULZ, MCD, CS, MNLS, DLF, FAM, JBGJ, SRF
Writing: LOM, ULZ, MCD, CS, MNLS, DLF, FAM, JBGJ, SRF
Review: LOM, ULZ, MCD, CS, MNLS, DLF, FAM, JBGJ, SRF

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