Production and Evaluation of Particleboards Made of Coconut Fibers, Pine, and Eucalyptus using Bicomponent Polyurethane-Castor Oil Resin

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This research examined the influence of the compositions between coconut fiber (*Cocos nucifera*) and wood particles (*Pinus taeda* L. and *Eucalyptus saligna*) on physico-mechanical properties of homogeneous particleboards. The exploratory study was carried out under Tukey's contrast test of means, at 5% significance level, with the following compositions: 100% coconut fiber (F100 P0 E0); 50% coconut fiber, 25% pine particles, and 25% eucalyptus particles (F50 P25 E25); and 50% of pine particles and 50% of eucalyptus particles (F0 P50 E50), with particle moisture content between 0% to 2% and 10%, in mass, of polyurethane-castor oil (PU-Castor) resin. Three panels were produced for each composition. The physico-mechanical properties such as density, moisture content, swelling in thickness after 24 h of immersion in water, perpendicular tensile strength, static bending strength, and modulus of elasticity were evaluated using standard methods. The results obtained indicated the potential for using coconut fiber for the production of homogeneous particleboards in view of the minimum criteria required by the normative documents, with emphasis on the physical property of swelling after 24 hours, which obtained a statistically equivalent average relative to the treatment that contained only wood particles.

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INTRODUCTION

The use of lignocellulosic materials in particleboards is an attenuator of the demand for wood as a raw material and destination for agro-industrial by-products. However, the production and quality of the product need improvement. Diverse lignocellulosic materials have been used to produce particleboards (Farag *et al.* 2020; Nguyen *et al.* 2020; Wong *et al.* 2020; Mahieu *et al.* 2021; Martins *et al.* 2021; Santos *et al.* 2021). Among the wide range of lignocellulosic materials studied, the residual natural fibers of coconut shell are abundant in Brazil. These fibers can be used in particleboards with promising physico-mechanical characteristics (Fiorelli *et al.* 2019).

The potential for using coconut shell in association with pine wood for the production of medium density particleboard was evaluated by Narciso *et al.* (2020). Associating agricultural residues with wood for the production of panels adds value to the product, ensures proper disposal, and promotes satisfactory properties in the panels.

Zhang and Hu (2014) studied the composite panels of coconut fiber particles associated with rice straw as a filling material, with particle moisture content of (3% ± 1%). The results pointed to less swelling in thickness after 24 h when coconut fiber concentrations were increased.

In order to describe the production process of panels with coconut fiber as raw material, Freire *et al.* (2017) proposed a rigorous life cycle assessment to identify the real advantage of using this type of agro-industrial residue. The researchers noted that coconut shell-based panels had a high potential in terms of environmental performance.

Owodunni *et al.* (2020) used coconut fiber (*Cocos nucifera*) bonded with potato starch-based green adhesives in three proportions, concluding that coconut fiber has the potential to be used as a raw material and add value to the panel produced.

Plant-based green resin, such as polyurethane-castor oil (*Ricinus communis*) resin, PU-Castor has been recently studied for the production of particleboard (Cravo *et al.* 2017; Fiorelli *et al.* 2019; Silva *et al.* 2021). In addition to not releasing formaldehyde during production, it demonstrates high efficiency and can improve the physico-mechanical results of the panels against urea formaldehyde (UF), as observed by Sugahara *et al.* (2019).

In Brazil, the Brazilian Association of Technical Standards – ABNT NBR 14810-1 and 2 (2013; 2018) is responsible for defining, establishing evaluative methods, and defining parameters for classifying medium density particleboards. The ANSI 208.1 (1999) standard describes evaluating the performance of particleboards.

This research examined the influence of the compositions between coconut fiber (*Cocos nucifera*) and wood particles of pine (*Pinus taeda* L.) and eucalyptus (*Eucalyptus saligna*) on the physico-mechanical properties of homogeneous particleboards bonded with PU-Castor adhesive, using Turkey's mean contrast test at a 5% significance level.

EXPERIMENTAL

The exploratory studies were carried out at the Central Laboratory of Civil Engineering, Department of Civil Engineering, Faculty of Engineering of Ilha Solteira (FEIS), State University of São Paulo Júlio de Mesquita Filho (UNESP).

The used coconut fiber (*Cocos nucifera*) was of agro-industrial origin obtained from Nitran Salts Products for Gardening and Horticulture, Potirendaba, Brazil. Pine (*Pinus taeda* L.) and eucalyptus (*Eucalyptus saligna*) were used as wood particles in this study. The bicomponent polyurethane resin derived from castor oil (PU-Castor) (IMPERVEG Polímeros Indústria e Comércio LTDA, Aguaí, Brazil) composed of polyol and isocyanate was used in a 1:1 ratio as binder for the particles.

Nine homogeneous particleboards were produced using various compositions (F100 P0 E0; F50 P25 E25; F0 P50 E50), with three panels for each composition (Table 1) having dimensions of 35 cm × 35 cm × 1 cm, moisture content of particles (MC-p) between 0 to 2%, and 10% of PU-Castor resin based on mass of dry particles.

Table 1. Particle Proportion for Particleboard Production

Compositions	Coconut (%)	Pine (%)	Eucalyptus (%)	MC-p (%)	PU-Castor (%)
F100 P0 E0	100	0	0	0 – 2	10
F50 P25 E25	50	25	25	0 – 2	10
F0 P50 E50	0	50	50	0 – 2	10

Notes: F – Coconut Fiber; P – Pine fiber and E – Eucalyptus fiber.

Particleboard Production

Pine and eucalyptus wood chips and coconut shell fiber were individually processed in a knife mill (Model 5000, Trapp, Jaraguá do Sul, Brazil) to obtain particles of the same size. In order to standardize the dimensions of wood particles, the selection process was carried out using a sieve shaker (Model G, Solotest, São Paulo, Brazil).

The particles were mixed together following the compositions in Table 1 and dried until they reached a moisture content below 2%. The compositions were characterized for particle size distribution according to the method presented by Sugahara *et al.* (2019). The fineness modulus of the compositions F100 P0 E0 (2.59), F50 P25 E25 (3.70), and F0 P50 E50 (4.48) was also determined.

The specific mass of the compositions was obtained following ABNT NBR 6457 (2016) and NBR 6458 (2017) with values of 0.56, 0.66, and 0.74 g/cm³ respectively for compositions F100 P0 M0, F50 P25 E25, and F0 P50 E50.

The adhesive was mixed to the various compositions in two steps. Initially polyol was added with manual homogenization and later mechanically mixed with a rotary mixer (Model: 120L 2cv, Menegotti, Jaraguá do Sul, Brazil) for 5 min. Then the pre-polymer was added and the homogenization process was repeated. The glued particles were placed in wooden molds measuring 35 cm × 35 cm (UNESP, Ilha Solteira, Brazil). Each particle mattress was pressed with 570 N/cm² and a temperature of 100 °C for 10 min, with an interval of 30 s of stress relief to release gases and reduce the formation of bubbles inside the panel, as proposed by Campos and Lahr (2004).

Twelve specimens (CP's) were extracted, 4 from each panel with dimensions of 50 mm × 50 mm, for the tests of density, moisture content, swelling after 24 h of immersion in water, and resistance to perpendicular traction. For the static bending strength and modulus of elasticity tests, 15 CP's were extracted, 5 from each panel, with dimensions (20 x E + 50 mm) × 50 mm where E is the thickness of the panel. The apparent density of each panel were controlled during production process, with fixed mass and adhesive for every panel produced.

Apparent Density Determination (P)

Initially, measurements of the mass of each specimen were made on a scale with a precision of 0.01 g, then the CP's had their diagonals traced as provided for in Annex - G of ABNT (2018). Thickness was measured at the point of intersection of the traced diagonals, with the aid of a digital micrometer with 0.001 mm precision. The width of the edges was measured using a caliper with 0.1 mm precision.

Moisture Content Determination (MC)

According to Annex - F of ABNT NBR 14810-2 (2018), the wet mass of the CP's was initially determined individually, with a precision of 0.01 g. Then, the CP's were oven dried at a temperature of 103 °C ± 2 °C until constant dry mass was obtained (variation less than 0.1%).

Determination of Thickness Swelling after 24 H of Immersion in Water (TS)

According to Annex - L of ABNT NBR 14810-2 (2018), initially, the thickness (TS) of the CP's was measured with the aid of a micrometer. Then, the CP's were submerged in deionized water for 24 h at a temperature of 20 °C until they were removed and their final thickness was measured.

Determination of Perpendicular Tensile Strength (TP)

Initially, the upper and lower faces of the CP's were polished with sandpaper for wood with 60 grain, and then their dimensions were measured, as provided in Annex J of ABNT NBR 14810-2 (2018). The CP's were then glued to metal sheets with the aid of instant adhesive Loctite 496, after curing under pressure. The sample sets were tensile tested in the universal testing machine EMIC (Model: 23-300, Capacity: 300 kN, INSTRON, São José dos Pinhais, Brazil).

Modulus of Elasticity (MOE) and Modulus of Rupture (MOR)

The dimensions of the width of the CP's were determined with the aid of a caliper; then the thickness of each CP was measured at the intersection point of the diagonals according to Annex - K of ABNT NBR 14810-2 (2018). The universal testing machine was used for modulus measurements. The CP was positioned on two supports with a free span (20 x E) and the load applied so as to coincide with the center of the CP and constant loading speed.

The Tukey mean contrast test, at the 5% significance level, was used to verify the influence of the compositions between coconut fiber and pine and eucalyptus wood particles in the panels produced. The Anderson-Darling test as well as the Multiple Comparisons test, both also evaluated at a 5% significance level, were used to verify normality and equality of variances, premises to be tested to validate the results obtained from the test of Tukey. By formulating both tests, p-value (probability p) greater than or equal to the level of significance implies normality and equivalence of variances.

RESULTS AND DISCUSSION

Table 2 shows the mean values (Avg.), the coefficients of variation (CV), and the confidence intervals (CI) of the mean (95% reliability) of the physical and mechanical properties of the panels manufactured according to the three experimental treatments outlined. It is worth noting that the p-values of the Anderson-Darling normality test ($0.193 \leq$ p-values ≤ 0.822) were both above the 5% level of significance, thus validating the results of the CI. All panels met the range of 5% to 13% moisture content recommended by the Brazilian standard (ABNT) and the 10% limit prescribed by the American standard (ANSI). Controlling the moisture content of the particles (0 to 2%) contributed favorably to the obtained result. According to Iwakiri and Trianoski (2020), the initial moisture content of the particles is an important aspect in controlling the final moisture required.

The F100 P0 E0 treatment met all the minimum values required by ABNT NBR 14810-2 (2018) for type P2 panel (non-structural panels for use in dry conditions) and by ANSI 208.1 (1999) for panel type M-1 (medium density particleboard, grade-1), which points to the potential of using coconut particles agglutinated with PU-Castor for the making particleboards. The results are close to those obtained by Fiorelli *et al.* (2012), who produced particleboards with coconut fiber and beaver-oil with a density of 0.8 g/cm³.

Table 2. Physical and Mechanical Properties of the Panels Manufactured against the Minimum Normative Values

Treatment	Stat.	ρ (g/cm³)	MC (%)	TS 24 h (%)
F100 P0 E0	Mean	0.75	9.37	10.38
	CV (%)	2.09	4.31	17.22
	CI (95%)	(0.75; 0.76)	(9.20; 9.54)	(9.34; 11.42)
F50 P25 E25	Mean	0.85	8.75	14.54
	CV (%)	1.53	2.55	15.36
	CI (95%)	(0.84; 0.85)	(8.58; 8.92)	(13.50; 15.59)
F0 P50 E50	Mean	0.97	8.31	9.33
	CV (%)	1.38	2.28	12.09
	CI (95%)	(0.96; 0.98)	(8.13; 8.47)	(8.28; 10.36)
*ABNT (P2)	-	0.51 a 0.75	5 a 13	< 22
*ASNI (M-1)	-	0.64 a 0.80	< 10	-
Treatment	**Stat.**	**TP (MPa)**	**MOR (MPa)**	**MOE (MPa)**
F100 P0 E0	Mean	0.53	16.70	1841
	CV (%)	6.21	12.38	9.20
	IC (95%)	(0.49; 0.57)	(15.83; 17.5)	(1762.0; 1920.2)
F50 P25 E25	Mean	0.64	19.40	2033
	CV (%)	8.39	5.85	7.09
	IC (95%)	(0.60; 0.67)	(18.54; 20.2)	(1954.0; 2112.2)
F0 P50 E50	Mean	0.89	21.79	2924
	CV (%)	10.75	7.22	4.79
	IC (95%)	(0.84; 0.92)	(20.93; 22.6)	(2845.2; 3003.4)
*ABNT (P2)	-	> 0.40	> 11	> 1800
*ASNI (M-1)	-	> 0.40	> 11	> 1725

* Minimum values recommended by ABNT NBR 14810-2 (2018) and ASNI 208.1 (1999)

Table 3 shows the results of the Tukey test considering the three treatments outlined, allowing for the choice of the best treatment by physical and mechanical properties investigated. The p-values of the Anderson-Darling and multiple comparisons normality tests ranged from 0.069 to 0.726 and 0.093 to 0.572, respectively, which validates the results of the Tukey test.

Table 3. Tukey Mean Contrast Test Results for the Three Treatments Evaluated

Treatment	ρ	MC	TS 24 h	TP	MOR	MOE
F100 P0 E0	C	A	B	C	C	C
F50 P25 E25	B	B	A	B	B	B
F0 P50 E50	A	C	B	A	A	A

Note: The same letters in the columns imply different treatments with statistically equivalent means (5% significance).

Table 4 presents the results of the Tukey Test, considering the variation in the contents of coconut fiber, pine wood and eucalyptus, which makes it possible to better understand the results obtained from the Tukey Test related to the three treatments (Table 3). The p-values of the Anderson-Darling and Multiple Comparison normality tests ranged from 0.081 to 0.453 and 0.105 to 0.792, respectively, which validates the results of the Tukey test.

Table 4. Results of the Tukey Mean Contrast Test Considering the Contents of Coconut Fiber with Pine and Eucalyptus Wood Particles

Property	Coconut (%)			Pine (%)			Eucalyptus (%)		
	100	50	0	0	25	50	0	25	50
ρ	C	B	A	C	B	A	C	B	A
MC	A	B	C	A	B	C	A	B	C
TS 24 h	B	A	B	B	A	B	B	A	B
TP	C	B	A	C	B	A	C	B	A
MOR	C	B	A	C	B	A	C	B	A
MOE	C	B	A	C	B	A	C	B	A

Note: The same letters in the columns imply different treatments with statistically equivalent means (5% significance).

Composition F100 P0 E0 resulted in the lowest average density value (C), followed by composition F50 P25 E25 (B) and finally composition F0 P50 E50 (A), the latter being the combination of particles that resulted in the highest density values. According to Maloney (1977) the best way to improve the properties of a reconstituted wood panel is to increase its specific mass. Density is the most important factor to be observed in the raw material, as it directly affects the density and quality of the panel. The gradual reduction in coconut fiber contents (100%, 50%, and 0%) promoted progressive increases in the density values of the panels of 13.33% and 14.12%, respectively. The same behavior was observed in the mechanical tests of TP (20.75% and 39.06%), MOR (16.17% and 12.32%), and MOE (10.43% and 43.83%). Zhang and Hu (2014) also observed the same behavior. As the amount of coconut fiber increased from 0 to 100%, the MOR and MOE values decreased significantly by 23.62% and 58.68% respectively, noting that there was a strong significant correlation between MOR and MOE and the content of coconut fiber.

In this sense, Narciso *et al.* (2020) obtained reductions in the values of TP, MOR, and MOE with the gradual increase in contents of the coconut husk (0, 25%, 50%, 75%, and 100%), however, as they meet the minimum normative criteria, the authors state the possibility of producing particleboards using only coconut fiber.

Finally, the composition F100 P0 E0 presented mean swelling in thickness after 24 h, statistically equivalent to the composition F0 P50 E50. Lower values of (24 h TS) were found by Owondunni *et al.* (2020) using coconut fiber bonded with green resins based on potato starch. According to Narciso *et al.* (2020) fibers of lignocellulosic origin present a highly hydrophilic chemical behavior, and the swelling in thickness may be affected by several factors, including the density of the materials and the type of resin used.

CONCLUSIONS

1. Medium-density particleboards produced with only coconut fiber as filling material and PU-Castor as adhesive met the minimum normative criteria of ABNT NBR 14810-1 and 2 (2013; 2018) and ANSI 208.1 (1999), pointing to the potential for use.
2. As the content of coconut fiber was lowered in relation to the wood particles, better performance of particleboard regarding the mechanical properties of MOR, MOE, and TP was observed. However, for the physical test of TS 24 h, it was observed that panels containing only coconut fiber presented mean values statistically equivalent to those that contained exclusively wood particles.

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