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ARTICLE

Evaluation of particleboard with Pine wood particles using polyurethane resin and polyethylene terephthalate

Evaluación de tableros de partículas de madera de pino utilizando resina de poliuretano y tereftalato de polietileno

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Abstract: The use of recycled polyethylene terephthalate (PET) with pine wood shavings was analyzed in the particleboard manufacture using hot-pressing. 160 °C was considered to avoid moisture build-up in the resin structure and polymer degradation and, property losses. 50% Pine with 40% PET and 10% polyurethane resin (PUR) and 50% Pine with 50% PET and 0% PUR were studied traits. Density, thickness swelling, water absorption, modulus of rupture, modulus of elasticity, perpendicular tensile properties and scanning electron microscopy (SEM) were studied. Density was close to 1 g/cm³, classifying both traits as high-density panels according to the standard code. SEM showed that 160 °C provided an effective envelopment of wood shavings. Physical and mechanical panel properties were superior to the minimum values of standard codes in 10% PUR trait, while they were lower with 0% PUR.

Keywords: Particleboard; Pinus; Polyethylene terephthalate; Waste; PUR.

Resumen: Se analizó el uso de PET reciclado con virutas de madera de pino en la fabricación de tableros aglomerados prensados con calor. Se consideró 160 °C para evitar la acumulación de humedad en la estructura de la resina y la degradación del polímero y las pérdidas de propiedades. Se estudiaron las características de 50% Pino con 40% PET y 10% PUR y 50% Pino con 50% PET y 0% PUR. Se estudiaron la densidad, el hinchamiento en espesor, la absorción de agua, el módulo de ruptura, el módulo de elasticidad, las propiedades de tracción perpendicular y la MEB. La densidad fue cercana a 1 g/cm³, clasificando los paneles como alta densidad según el código. la MEB mostró que 160 °C proporcionó una envoltura efectiva de las virutas. Las propiedades fueron superiores a los valores mínimos de los códigos en la característica 10% PUR, mientras que fueron inferiores con 0% PUR.

Palabras clave: Tablero aglomerado; Pinus; Tereftalato de polietileno; Residuo; PUR.

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Supplementary information ↓

1. INTRODUCTION

In Brazil, forestry sector moves about 37 billion Dollars (3.5% national gross domestic product) and 10 billion Dollars in exportations (7,3% of exported products), while lumber-plywood and subproducts segment represents almost US$ 3 billion Dollars, demonstrating a certain relevance for this national economy (1). According to the Brazilian Associations of Furniture Industry and for Mechanically Processed Timber, the most dependent wood sectors are furniture and construction, which consumed 8.8 million and 8.3 million of cubic meters of logs in 2020, respectively (2, 3).

The rational use of natural resources in timber forest products is crucial for bioeconomy, as it involves a fundamental principle of the sustainable development goals (4, 5). Promoting the initiatives and maximizing the uses of responsible forest management are important, as they are good ways to utilize bioresources in the manufacture of particleboard panels with a noble purpose of wood featured by lower dimensions and qualities (6). Reconstituted wood panels are produced from different stages of wood disintegration, in which synthetic adhesives are incorporated under the action of pressure and temperature in order to form panels for multiple applications, including furniture, flooring manufacturing and construction sectors (7-10).

Polyethylene terephthalate (PET) is a synthetic thermoplastic polymer widely used in the textile, packaging, and fiber sectors due to interesting mechanical and physical features. Discovered in the United States during 1950s, PET became a relevant material for the market, especially for the beverage sector for bottling carbonated liquids due to its efficient gas barrier (11). In Brazil, 359 thousand tons of PET were duly recycled by the national industry, which represented a growth of 15.4% over the volume recorded in 2019 (12).

Adhesives are polymers defined as organic or inorganic agents used to bind wood particles or lignocellulosic materials in the production of particle boards (13-16). Resin composes the main component that influences the production cost of particleboards (17-18), which is why its use must be optimized to minimize the final cost of glued products and meet the required properties. Maloney (19) confirmed that the physical and mechanical properties of particleboards improve proportionally with the increase in the amount of adhesive, especially the perpendicular tensile strength. However, this practice significantly increases production costs, making it few feasible.

Widely used in several scientific areas, polyurethanes include applications in foams, elastomers, fibers, coatings and adhesives (20). Produced by polymerization of hydroxyls with isocyanates, these materials have urethane groups (21). Polyurethane adhesives can be single-component or two-component (22). *Ricinus communis* L., or castor oil plant, produces castor oil, used in several industrial processes (23). Thus, polyurethane adhesives derived from castor oil are biodegradable and non-polluting (24, 25).

Recent studies have addressed innovation in the use of sustainable materials for construction from alternative gluing agents. Maderuelo-Sanz *et al.* (26) analyzed the development of acoustic panels based on cork and water-based resins to be applied for acoustic ceiling, and their results showed good sound absorption and acceptable flexural strength. In addition, Suoware *et al.* (27) studied the development of flame retarded composite fiberboard using residual palm oil with polyester resin, where 18% retardant formulation meets fire safety standard codes for indoor application. In other way, the use of recycled plastics emerges as another alternative to reduce generated waste.

Wood-plastic composites (WPC) are formed by two elements, that is, matrix and reinforcement. In the first type, matrix is predominantly made of thermoplastic material, while wood element acts as a filler or a reinforcement with a content typically less than 60% by mass (28, 29).

For other type, composites have a low thermoplastic content, where thermoplastic acts more as a fiber binder with a content less than 30% by mass. WPC are manufactured by extrusion, injection, and high-temperature compression. Unlike particleboards, these composites do not use adhesives, although agents can be used to improve the adhesion (28, 29).

The reuse of thermoplastics in the production of composites through flat pressing with heat or extrusion, using lignocellulosic residues from the agroindustry or sawdust from wood processing, has been the subject of global research. Researchers have explored many combinations to improve the properties of composites and promote the sustainability of the industry, such as the use of recycled thermoplastics combined with corncob (30), coconut fiber (31), and sawdust without the use of adhesives (32-35).

Rahman *et al.* (36) evaluated wood-plastic composites (WPC) using sawdust and recycled polyethylene terephthalate (PET) in proportions of 40/60, 50/50, 60/40 and 70/30, without the addition of binder adhesives. The methodology involved flat compression with heating at 190 ºC, 5 MPa pressure for 25 minutes, parameters which are similar to the particleboard production. Physical-mechanical properties such as density, water absorption, thickness swelling, modulus of elasticity (MOE) and modulus of rupture (MOR) in static bending were analyzed. Results indicated that increasing the PET proportion resulted in a 15.7% reduction in water absorption in 24h and 4.3% in thickness swelling, comparing the 70/30 and 40/60 proportions. Furthermore, MOE and MOR increased significantly with the reduction of sawdust and the increase of PET, ranging from 1433.93 MPa (70/30) to 2008.34 MPa (40/60) and from 11.68 MPa (70/30) to 27.08 MPa (40/60), respectively.

In a subsequent study, Rahman *et al.* (37) investigated WPC with different proportions of wood and PET particles, such as 40/60, 50/50, 60/40, and 70/30, as well as different wood dimensions (from 0.5 to 1.0 mm and 1.1 to 2.0 mm) combined with PET particles smaller than 0.25 mm. The methodology involved flat compression at 190 °C for 5 min, followed by pressing without heat for 6 min, both processes at 5 MPa. Results showed that increasing the proportions of PET increased the composite density. Wood particles between 0.5 and 1.0 mm had higher density than those of 1.1 to 2.0 mm. Panels with particles of 0.5 to 1.0 mm and a 40/60 ratio presented the lowest absorption and swelling values in 24h. The highest MOR and MOE values were observed in panels with particles of 1.1 to 2.0 mm, with the 40/60 mixture having the highest MOR (above 30 MPa) and the 50/50 mixture having the highest MOE (2570 MPa). As conclusion, the size of wood particles directly influenced the composite properties and 50/50 ratio between wood and PET is the most promising and technically viable.

Campos *et al.* (38) evaluated particle boards made from *Pinus elliotti* mixed with PET flakes and 10% castor oil-based polyurethane resin (PUR). Temperature during panel production varied (160 °C and 180 °C) to assess its influence on the physical and mechanical properties. The results showed that increasing the temperature did not significantly improve the properties of the panels, but the results showed potential for application according to standards.

Cazella *et al.* (39) evaluated the influence of recycled PET particles on five prototypes of particle boards based on *Pinus elliotti* wood and castor oil-derived polyurethane resin (CPUR). The mixtures varied between 100% wood and 0% PET, 70% wood and 30% PET, and 50% of each material, with different proportions of CPUR (5% and 10%). Panels were evaluated in terms of physical, mechanical and morphological properties, showing a promising outcome. Particleboards with 50% pine and 50% PET with 10% CPUR showed the best performance in the physical and mechanical tests, with results equivalent to the 70% pine and 30% PET with 10% CPUR and 50% pine and 50% PET with 5% CPUR. Results suggest a significant environmental contribution and economic viability in the production of WPC with recycled PET, reusing this non-biodegradable plastic and using a smaller volume of adhesive.

In view of this scenario, current research focuses on the development of biodegradable, non-toxic, non-polluting materials from renewable sources, such as polyurethane derived from castor oil and polyurethane from starch (40, 41). Regardless of the origin of the adhesive, its main function is to join parts of a set, evenly distributing tensions so that the final product does not require mechanical fasteners (42).

Aiming at the search for alternative and sustainable materials, the polyurethane adhesive obtained from castor oil (CPUR) has been a promising alternative to replace the urea formaldehyde (UF) resin in particleboard panels. This is due to the fact that, unlike formaldehyde-based adhesives, the gases produced by polyurethane are less harmful to human health.

In this study, two traits were evaluated with three panels for each one, in which they were pressed at 5 MPa and 160 °C. Therefore, this work evaluated the production of particleboard panels with pine wood particles and recycled PET as an additive in order to improve the panel waterproofing, including a trait bonded with polyurethane resin (PUR) and another without this bonding agent.

2. MATERIALS AND METHODS

Particleboards were developed based on the guidelines of two Brazilian standard codes: NBR 14810-1 (14), which defines the terminology and components of these panels, and NBR 14810-2 (15), which details the tests and procedures for evaluating any particleboard.

Particles of Pinus ssp wood species were used in the production of the panels, which were supplied by KELAN Indústria e Comércio de Móveis Ltda., a company located in Penápolis, Brazil. This industry has generated a significant volume of wood waste in the furniture production, especially from the turning of 250 x 40 x 40 mm beams, originating from reforested pine wood supplied by plantations of Fazenda Rio Grande city, which are specialized in supplying wood to a series of furniture producers in Brazil.

PET used in this study was supplied by Global PET SA, a company located in São Carlos, Brazil. Small particles, with a grain size of 2 mm, selected and processed by this industry were originated from discarded beverage bottles.

Both plastic and wood particles to be evaluated in both traits were oven-dried at 103 °C ± 2 °C as described by Borysiuk *et al.* (43) and Klímek *et al.* (44) in order to reach a constant moisture from 3% to 5%. Sequentially, the particle size composition was determined through a test adapted from Brazilian NBR NM 248 (45) standard code, as considered in previous studies of Trevisan (46) and Bispo (47) – following these authors, 35 g particle mass was considered.

The Brazilian NBR 6458 (48) and NBR 6457 (49) standard codes were used to determine the particle density. The test consists of using a volumetric flask, a #2 pycnometer calibrated for 500 ml anhydrous ethyl alcohol (99.3% INPM), and a 0.1 °C graduated thermometer with a range of -10 °C to 100 °C.

After particle processing, granulometric selection was carried out to obtain particles in the range of 2 mm to 6 mm and then the test determined the granulometric composition (50). All panels were produced with an 0.55 g/cm³ initial density and 350 x 350 x 12 mm dimension. Particle homogenization followed the methodology successfully used by Buzo *et al.* (51) and Sugahara *et al.* (52). Particles were initially mixed manually and then mixed for five minutes in a rotating drum.

After homogenization, each particle mattress was prepared and pressed in a hydraulic press (Figure 1). Equal pressing parameters were strictly considered for both traits, that is, 5 MPa pressure for a total time of 10 minutes at 160 °C, with a 30-second interval for degassing process.

(a) (b) (c) (d)

Figure 1. Preparation and pressing stage of particleboards: (a) particle accommodation, (b) heat-press, (c) mattress conditioned in heat-pressing, and (d) particleboard after pressing.

Regarding the panel characterization, the static bending test in the modulus of rupture (MOR) was performed to obtain the parameters for this test and for the modulus of elasticity (MOE). For MOR test, panels were dimensioned in 50 mm x 50 mm x 12 mm. In sequence, perpendicular tensile (PT), density (D), 24-hour thickness swelling (TS24H), 24h water absorption (WA24H) and moisture content (MC) tests were performed using 10 panel specimens per test according to the considerations prescribed in NBR 14810-2 (15) standard code for particleboards.

All results of the panel characterization tests were analyzed using the Tukey mean contrast test, at a 5% significance level, in order to evaluate the influence of the panel trait on each physical and mechanical property under observation. From Tukey mean contrast test, "A" letter will denote the treatment associated with the highest mean property value, "B" will denote the second highest value and so on. Identical letters will imply distinct treatments with statistically equivalent means. From the Anderson-Darling (AD) normality test, a p-value higher than the significance level (5%) implies normality in the distribution of the ANOVA residuals, validating the results of Tukey test.

Two standard codes were considered in the characterization and evaluation of particleboards, given by the Brazilian NBR 14810-2 (15) and the North American A208.1 (53), in which average parameters are prescribed according to each document and identified in Table 1. This standard information was used to compare and validate the obtained results.

Table 1. Standardized parameters and properties considered according to both standard codes.

Standard code (Source)	Panel category	Thickness (mm)	TS_{24H} (%)	MOR (MPa)	MOE (MPa)	PT (MPa)
NBR 14810-2 (15)	P2	> 6 to 13	22	11	1800	0.40
NBR 14810-2 (15)	P3	> 6 to 13	17	15	2050	0.45
A 208.1 (53)	H-1	Not applicable	Not applicable	14.9	2160	0.81
A 208.1 (53)	H-2	Not applicable	Not applicable	18.5	2160	0.81
A 208.1 (53)	H-3	Not applicable	Not applicable	21.1	2475	0.90
A 208.1 (53)	M-0	Not applicable	Not applicable	7.6	1380	0.31
A 208.1 (53)	M-1	Not applicable	Not applicable	10	1550	0.36
A 208.1 (53)	M-S	Not applicable	Not applicable	11	1700	0.36
A 208.1 (53)	M-2	Not applicable	Not applicable	13	2000	0.40

TS_{24H}: thickness swelling after 24 hours; MOR: modulus of rupture; MOE: modulus of elasticity; PT: perpendicular tensile.

For scanning electron microscopy (SEM), fractured samples after testing (perpendicular tensile) were extracted to be evaluated, being resized to obtain test specimens with 1.0 mm x 1.0 mm x 0.4 mm. Using a Quarum equipment, model Q150TE, all specimens were fixed with double-sided carbon tape using "stub door" and then metallized with a thin layer of gold. Subsequently, these prepared specimens were analyzed on the ZEISS equipment, model EVO LS15, equipped with an Oxford system EDS type, model INCAx-act. SEM was carried out and images were analyzed in the Department of Physics and Chemistry of the São Paulo State University. This stage utilized similar protocols, resources and paths – as follows the way considered by Cazella *et al.* (39).

3. RESULTS AND DISCUSSION

3.1. Particle density

Considering the standardized parameters for the panel manufacture and evaluation, the densities (D) of plastic and wood particles were measured insofar as density is an important parameter for evaluating the compaction index of the particleboards. According to Table 2, it was verified that PET particles were more than twice as dense as softwood.

Table 2. Mean results of density of material particles.

Particle type	$D_{PARTICLE}$ (g/cm^3)
Pine wood	0.605
Polyethylene terephthalate (PET)	1.360

D: density.

3.2. Compaction index and density of each panel trait

For panel production, it is necessary to identify the compaction index. It is an important parameter for manufacturing particleboards and, consequently, defining physical and mechanical properties.

The compaction index was determined by the ratio between the average density of the panels and the specific mass of the particles. Based on wood particle density in Table 2 and medium density for all panel traits under consideration in this research, compaction indexes were determined for each mixture. Additionally, moisture content of each panel trait was verified (Table 3).

Table 3. Mean results of density and compaction index.

Panel trait	$D_{PARTICLEBOARD}$ (g/cm^3)	$D_{WOOD\ PARTICLE}$ (g/cm^3)	$MC_{PARTICLEBOARD}$ (%)	CI
50% Pine 40% PET 10% PUR	1.118	0.605	3.71	1.847
50% Pine 50% PET 0% PUR	0.948	0.605	4.62	1.566

D: density; CI: compaction index; PET: polyethylene terephthalate; PUR: polyurethane resin.

For the 50% Pine with 40% PET and 10% PUR, the compaction index was 1.847. However, it is worth noting that PUR and PET densities are greater than 1 g/cm^3 and, therefore, they influenced this calculated index. For 50% Pine with 40% PET and 10% PUR, the compaction index was 1.566, as seen in Table 3 – this trait is in accordance with Araujo *et al.* (7) and Trianoski (54), which obtained a range of 1.3 to 1.6 for urea-formaldehyde-based panels.

In the research developed by Dotun *et al.* (55) replacing wood particles with PET, panels demonstrated greater densification and compaction compared to panels without the PET addition. In particleboards bonded with 20% urea-formaldehyde resin, the trait with 70% sawdust and 30% PET reached a 0.537 g/cm^3 density, while for panels with 50% sawdust and 50% PET obtained a 0.71 g/cm^3 density. In this replacement, this study confirmed that the increase in PET proportion significantly improved compaction and increased the density of tested panels.

3.3. Thickness swelling and water absorption of each panel trait after 24 hours

Results of thickness swelling (TS24H) and water absorption (WA24H) after 24 hours are indicated in Table 4. Pine-PET particleboards produced with PUR were more efficient from the point of view of waterproofing properties in relation to trait without PUR. Therefore, the absence of resin provided greater moisture contents for TS_{24H} and WA_{24H} compared to glued panels.

In the production of particleboards made from residues of candeia and eucalypt woods developed by Santos *et al.* (56) bonded with 12% urea-formaldehyde resin, the influence of different PET percentages in the presence and absence of paraffin was evidenced. In the absorption results after 24 hours in the 50% PET trait, a significant reduction of 16% water was observed (Table 4), when compared to the mixture with 0% PET. Therefore, it was possible to infer that water absorption in the panels tends to decrease with the increase in the replacement of wood by PET.

In the Cazella *et al.* (39) study, particleboards with 50% PET and 10% PUR showed swelling less than 4%, evidencing good influences of PET and PUR on the panel traits. This provides good agglutination and occupation of empty spaces inside the panels, as well as an efficient enveloping of the particles due to good waterproofing against internal water percolation.

In a study with homogeneous panels using *Hevea brasiliensis* and *Tectona grandis* woods, Gilio (57) also showed that the PUR presents waterproof characteristics when its content is increased from 5 to 10% in the production of the panels.

Table 4. Mean and statistical results of 24-hour thickness swelling and water absorption.

Panel trait	TS_{24H} (%) [%]	WA_{24H} (%) [%]
50% Pine 40% PET 10% PUR	10.69 B [23.45]	6.47 B [27.57]
50% Pine 50% PET 0% PUR	88.16 A [28.42]	48.41 A [30.23]
p-value	0.123	0.245

TS_{24H}: thickness swelling (24h); WA24H: water absorption (24h); PET: polyethylene terephthalate; PUR: polyurethane resin. “A” denotes the treatment associated with the highest mean value, “B” will denote the second highest value and so on, and identical letters imply distinct treatments with statistically equivalent means.

Thus, results obtained from the TS_{24H} and WA_{24H} tests, as shown in Table 4, allowed to infer that both PUR and PET materials can provide good waterproofing to the panels. Considering the results obtained in the tests to determine the WA_{24H} and TS_{24H}, a statistical analysis was performed to evaluate both properties from the point of view of the Tukey mean contrast test.

Based on the statistical evaluation for TS_{24H} and WA_{24H}, it is possible to conclude that there was a statistically significant difference, since the panels of PUR trait provided better waterproofing to the panels compared to the panels without PUR.

3.4. Mechanical properties of each panel trait

Results related to the perpendicular tensile test (PT), the static bending in the modulus of rupture (MOR) and the modulus of elasticity (MOE) are identified in Table 5.

Similar to physical properties, mechanical properties demonstrated a better quality of panel trait with PUR. This condition was expected due to the absence of gluing agent for bonding PET and pine particles. Considering MOR, MOE and PT results, a statistical analysis evaluated mechanical properties from the point of view of the Tukey mean contrast test (Table 5).

Table 5. Mean and statistical results of mechanical properties.

Panel trait	MOR (MPa) [%]	MOE (MPa) [%]	PT (MPa) [%]
50% Pine 40% PET 10% PUR	32.64 A [12.72]	2277.77 A [26.42]	1.69 B [15.09]
50% Pine 50% PET 0% PUR	5.43 C [31.72]	530 B [31.59]	0.19 D [38.63]
p-value	0.629	0.837	0.876

MOR: modulus of rupture; MOE: modulus of elasticity; PT: perpendicular tensile; PET: polyethylene terephthalate; PUR: polyurethane resin. “A” denotes the treatment associated with the highest mean value, “B” will denote the second highest value and so on, and identical letters imply distinct treatments with statistically equivalent means.

As revealed by Cazella *et al.* (39), 50% pine with 50% PET and 10% PUR particleboard trait showed an increase about 113% in MOR compared to panels without PET. This allowed to infer that the increase in panel resistance may be related to the inclusion of PET in replacement of the pine wood particles associated with PUR, which improves the panel waterproofing.

Based on the statistical analysis presented for each property described in Table 5, p-values of the Anderson Darling normality test were higher than the 5% significance level, which validated the results obtained from the Tukey mean contrast test. Regarding panels without PUR, their results were significantly lower compared to the values obtained for particleboards with PUR. This fact indicates that the association of PET with PUR was efficient in the panel manufacturing to the point of improving physical and mechanical properties.

Comparing our results with average values described in Table 1, glued-panel traits (with PUR) can be classified according to the Brazilian standard code NBR 14810-2 (15) as “P2”and “P3” and the North American standard code A208.1 (53) as “H-1”, “H-2”, “H-3”, “M-0”, “M-1”, “M-S” and “M-2” panel categories.

3.5. Pearson correlation

Results of Pearson correlation test (- 1 ≤ r ≤ 1) are described in Table 6 for physical and mechanical properties of particleboards produced according to two treatments.

Table 6. Results of the correlation analyses between the physical and mechanical properties considering the two experimental treatments.

Property	Statistics	ρ	MC	WA_{24H}	TS_{24H}	MOR	MOE
MC	r	-0.284					
	p-value	0.224					
WA_{24H}	r	-0.574	0.492				
	p-value	0.008	0.028				
TS_{24H}	r	-0.494	0.432	0.970			
	p-value	0.027	0.036	0.000			
MOR	r	0.572	-0.444	-0.942	-0.936		
	p-value	0.008	0.023	0.000	0.000		
MOE	r	0.537	-0.309	-0.843	-0.834	0.927	
	p-value	0.015	0.185	0.000	0.000	0.000	
PT	r	0.535	-0.485	-0.941	-0.918	0.962	0.897
	p-value	0.015	0.030	0.000	0.000	0.000	0.000

**In the ANOVA at 5% significance, p-value lower than 0.05 indicates significance and, therefore, the same is not significante otherwise.*

Among all the correlations, only one was not considered significant by ANOVA, which relates density (ρ) to moisture content (MC). Due to this correlation, the increase in panel density did not promote significant reductions in moisture content values. For density, negative correlations were verified in this property with water absorption (WA24H) and thickness swelling (TS24H). This implies that increases in density can impact reductions in these two properties based on water influences. Positive correlations were obtained among density with modulus of rupture (MOR), modulus of elasticity (MOE) and perpendicular tensile (PT) – that is, increases in density impacted increases in these three mechanical properties, as results evinced by Table 6.

For moisture content, positive correlaitons were confirmed among the same and water absorption and thickness swelling – that is, increases in moisture also increase the values of these water-influenced properties.

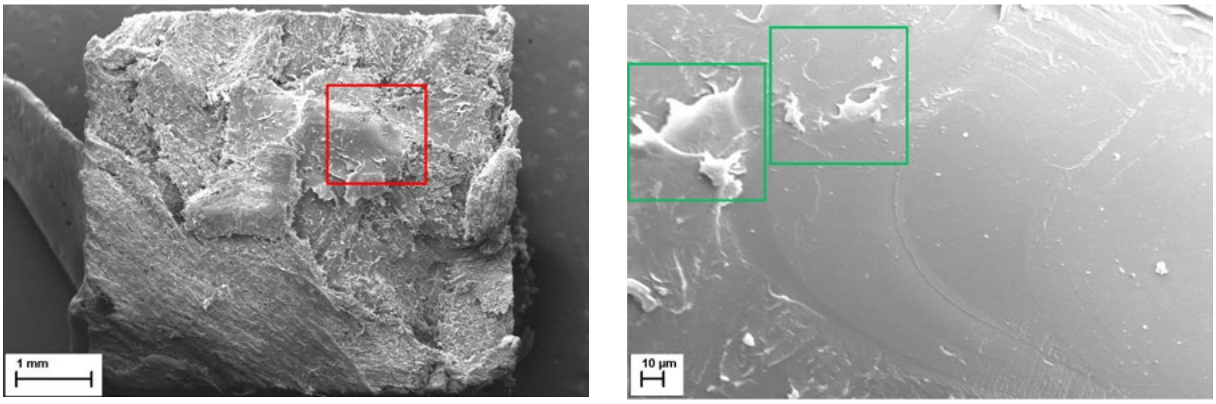
With respect to modulus of rupture, modulus of elasticity and perpendicular tensile, both correlations are negative – that is, increases in moisture resulted in increases in these three mechanical properties. This condition was also confirmed by (58, 59).

Water absorption presented a positive correlation with the thickness swelling, where increases in absorption impacted in increases in swelling. Negative correlations with modulus of rupture, modulus of elasticity and perpendicular tensile were verified, where increases in water absorption reduced these three mechanical properties. A similar effect was verified in the thickness swelling. Positive correlations were obtained for three mechanical properties, where increases in the average modulus of rupture are related to increases in modulus of elasticity and perpendicular tensile (Table 6). This behavior was also confirmed by (60).

3.6. Scanning electron microscopy

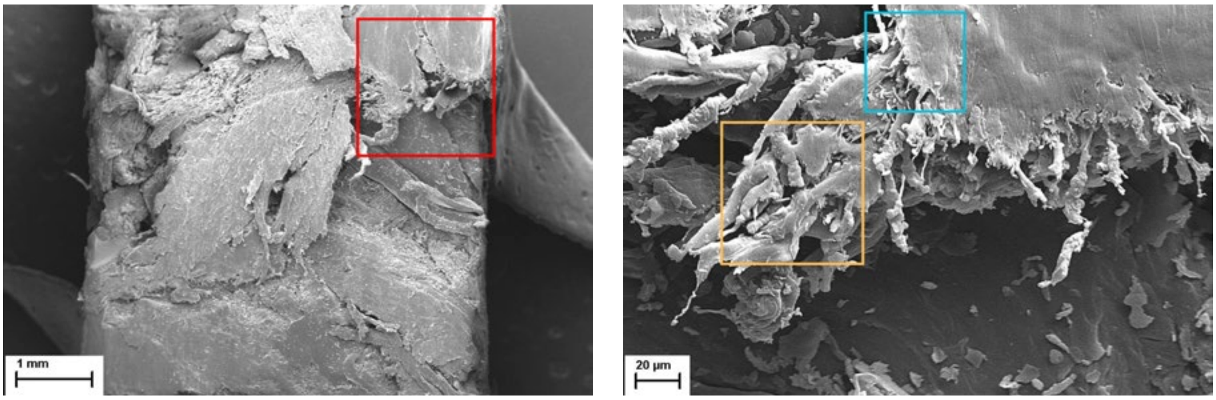
In the context of particleboards, scanning electron microscopy (SEM) test allows a detailed analysis of the internal structure of the material, revealing the distribution and size of the wood particles, as well as the quality of the bonds between the particles and the binding resin. This information is essential for understanding the durability and physical and mechanical properties of panels, enabling improvements in the manufacturing processes and the final product quality.

In order to analyze the SEM images, two images with different resolutions are presented to show and highlight the details of the area scanned by the SEM for each studied trait (Figures 2 and 3).



(a) (b)

Figure 2. SEM images and details for trait with PUR (50% pine with 40% PET and 10% PUR) for: (a) 1 mm and (b) 10 µm resolutions.



(a) (b)

Figure 3. SEM images and details for trait without PUR (50% pine with 50% PET and 0% PUR) for: (a) 1 mm and (b) 20 µm resolutions

Considering the SEM of trait with PUR (50% pine with 40% PET and 10% PUR), the region under analysis is completely enveloped by PET and PUR. It is not possible to identify details of the anatomical structures of the wood. A very relevant analysis of the region is evidenced in the green-highlighted squares (Figure 2b), where we can observe the ruptured part of the material, with morphology characteristic of rounded ruptures of polymers originating from PET and PUR.

Comparing this SEM of glued-particleboard (Figure 2) with the SEM of trait without PUR (50% pine with 50% PET and 0% PUR), it is possible to verify the existence of evidence of wood structures. These aspects differentiate the morphology between images. Surface aspects presented in Figure 3 are quite different compared to both images in Figure 2. These aspects characterize and define the presence of PUR in the images in Figure 2 and of PET in the images in Figure 3. Regarding glue-free particleboards in Figure 3b, we can see two regions under the PET influence. The region of blue-highlighted square shows some aspects of the wood substrate covered by PET, while yellow-highlighted square presents the presence of fibrillar elements, which is one of the main characteristics of PET fracture.

4. CONCLUSIONS

From foregoing, the statistical analyses and scanning electron microscopy images indicated that:

- The use of polyurethane resin (PUR) in association with polyethylene terephthalate (PET) particles was efficient in the panel production, as it contributed with the enveloping of wood particles and, therefore, this double presence positively affected physical and mechanical behaviors of panels.
- Given the results obtained by two traits comparing to the recommendations from standard codes, the particleboard with 50% pine with 40% PET and 10% PUR can be utilized for furniture applications, while the other composite solution (50% Pine with 50% PET) can be used as non-structural finishing panels.
- The use of PET without the presence of PUR, it is necessary to evaluate the use of other pressing temperatures so that the PET can occupy more space inside the panel and, consequently, it allows greater cohesion between the particles and a better enveloping, features which can improve the panel waterproofing.
- As implications of this study, we could point out the limitations on the use of different mixture compositions to verify the properties in other different traits, additional tests on DRX and FTIR to verify the material interactions, and the identification of details of the anatomical structures of the wood.
- As suggestion, further studies on pinewood particleboards with recycled PET and castor-oil PUR may consider the evaluation of thermal and acoustic properties, environmental impacts of the whole manufacturing process, and a complete life-cycle analysis to endorse the benefits the reuse of recycled PET particles.

Supplementary information ↑

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Authorship contribution statement

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Competing interests

The authors declare that they have no known financial conflicts of interest or personal relationships that could have influenced the work reported in this article.

Statement on the use of Artificial Intelligence

Not applicable.

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