

Recycled Polyethylene Terephthalate Powder in Particleboard Production: Epoxy as a Formaldehyde-Free Adhesive Alternative

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This study investigated the production of particleboards by incorporating recycled polyethylene terephthalate (PET) powder into *Pinus spp.* particles, using epoxy resin as an adhesive at 5% and 10% levels. The panels were manufactured and tested in accordance with ABNT NBR 14810-2 (2024) and further evaluated under EN 312 (2003) and ANSI A208.1 (2016) standards. The results demonstrated that both the increase in adhesive content and the incorporation of PET powder contributed to significant improvements. Compared with literature data on panels without PET, the addition of recycled PET reduced moisture content (MC), thickness swelling (TS), and water absorption (WA) by about 29% and promoted mechanical gains of up to 33% in modulus of elasticity (MOE), 31% in modulus of rupture (MOR), and 133% in internal bond strength (IB). Increasing epoxy from 5% to 10% further enhanced performance, with reductions of 46.3% in TS and 49% in WA after 24 h, and increments of 57.1% in MOR, 68% in MOE, and 104.3% in IB. Scanning electron microscopy confirmed improved encapsulation of wood and PET particles with 10% adhesive. These findings point to a viable circular-economy route by upcycling plastic waste and wood residues into higher-value particleboards while avoiding added formaldehyde.

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INTRODUCTION

Wood is a natural resource of great relevance to contemporary society, notable for its versatility and broad potential applications. Wood is biodegradable, renewable, recyclable, and cost-effective. It differs from materials such as steel, cement, and plastic

by requiring less energy in its production. In addition to acting as a carbon sink in forests, wood enables the storage of this element in long-life products. Reducing waste throughout the processing chain contributes to greater efficiency in material use and strengthens strategies aimed at achieving low environmental impact (Wang and Haller 2024). This prominence occurs in a scenario of increasing global demand for raw materials. According to UNEP (2024), between 1970 and 2020, global consumption of natural resources is more than tripled, rising from 30.9 to 95.1 billion tons per year, with projections to reach 106.6 billion tons in 2024. In this context, it becomes essential to reduce the pressure on virgin resources and to expand the use of recyclable alternatives throughout the production chain.

The use of wood residues in particleboard production has been consolidated as an efficient alternative. These engineered materials are widely applied in the construction, furniture, and packaging industries, due to their versatility and cost-effectiveness (Iswanto *et al.* 2025). In 2023, global production reached 116 million m³, representing a 6.5 % increase compared to the previous year (FAO 2025). These panels are produced by pressing wood particles with synthetic adhesives under high temperatures and pressures (Masuanchik *et al.* 2023), constituting an efficient solution for the reuse of lignocellulosic residues (Saal *et al.* 2017).

However, the predominant use of formaldehyde-based adhesives, which account for 90% to 92% of the European market, raises concerns regarding volatile compound emissions (Mantanis *et al.* 2018). Such limitations drive the search for alternatives that combine performance, lower environmental impact, and health safety. Bio-adhesives formulated with soy flour, lignin, tannin, vegetable oils, and epoxy resins have emerged as promising options (Yin *et al.* 2021; de Souza *et al.* 2022; Baharuddin *et al.* 2023; Cazella *et al.* 2024; Santos Junior *et al.* 2025).

In addition to innovations in adhesives, the incorporation of alternative raw materials such as agro-industrial residues, natural fibers, and recycled wood enhances process sustainability, reduces pressure on virgin timber, and adds value to waste. The potential of these inputs depends on their physical and chemical properties, availability, feasibility of acquisition, and integration into the production process (Pędzik *et al.* 2021). In this context, plastics represent a global challenge: In 2019, about 353 million tons of waste were generated, of which only 9% were recycled (Global Plastics Outlook 2022). Among them, polyethylene terephthalate (PET) stands out, which is widely used in packaging due to its low cost, high chemical resistance, thermal stability, and high strength-to-weight ratio (Velásquez *et al.* 2019; Bałazińska *et al.* 2021). Although studies have already investigated the addition of recycled PET in particleboards (Rahman *et al.* 2013; Campos *et al.* 2023; Cazella *et al.* 2024), a gap remains regarding its association with high-performance alternative adhesives such as epoxy resin.

In view of this gap, the present study analyzes the effect of using recycled PET powder incorporated into wood particles, combined with epoxy resin as an adhesive. The study evaluates the partial substitution of wood with PET powder at two adhesive proportions (5% and 10%), seeking combinations that provide improved physical-mechanical performances through standardized tests and scanning electron microscopic (SEM) analysis, in compliance with current standards. This approach expands knowledge on the potential of epoxy resin as an alternative to conventional adhesives, while also promoting the use of recycled PET powder, thus contributing to the development of more durable, efficient, and sustainable particleboards.

EXPERIMENTAL

Methodology

Pinus spp. used in the study was obtained from the processing of boards purchased from local suppliers in Ilha Solteira, São Paulo. The initial preparation employed a thickness planer (LMS 400, Rocco, Limeira, Brazil), resulting in wood shavings that were transformed into particles using a knife mill (Model 500, Metalúrgica Trapp, Jaraguá do Sul, Brazil), with dimensions ranging from 1.19 mm to 6.30 mm and moisture content below 5%, using a moisture analyzer (Model i-Thermo G, BEL, Monza, Italy) (Campos *et al.* 2023; de Carvalho *et al.* 2025; Santos Junior *et al.* 2025). The epoxy adhesive, commercially named Epoxy Resin 2004, was supplied by Redelease Redecenter, São Paulo. This adhesive is a two-component system, consisting of Resin 2004 (1120 kg/m³ density and viscosity from 600 to 900 cPs) and Hardener 3154 (1005 kg/m³ density and 200 cPs max viscosity). The PET used originated from discarded beverage bottles, supplied by Global PET SA, São Carlos, São Paulo. The material was supplied in powder form and used as received, without pre-processing or additional treatment. Sieve verification indicated a maximum aperture of 0.250 mm (60 mesh).

Two mixtures were defined, composed of 70% wood particles and 30% PET powder, with variations of 5% and 10% epoxy adhesive relative to the dry mass of the particles and PET powder. Considering a nominal density of 0.5 g/cm³ and a wooden form with dimensions of 350 x 350 x 20 mm, the total mass was 1225 g per panel, of which 857.5 g corresponded to *Pinus spp.* particles and 367.5 g to PET powder. The epoxy adhesive was applied at a 2:1 resin-to-hardener ratio, following the manufacturer's specifications. All parameters were established based on literature references, where panels were pressed at 110 °C, under a pressure of 5 MPa, for 10 min, in accordance with previous research (Herradon *et al.* 2023; Santos Junior *et al.* 2025).

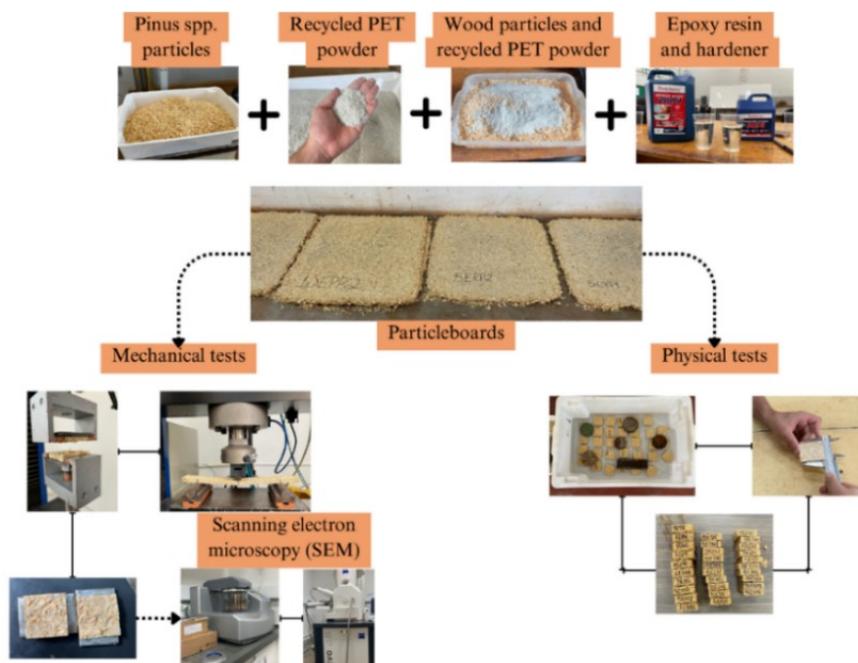


Fig. 1. Production process of the particleboards

For particleboard production (Fig. 1), the adhesive was initially prepared by manually mixing the resin with the hardener for 5 min. Subsequently, the adhesive solution was applied onto the *Pinus spp.* particles and PET powder, promoting the first homogenization. The mixture was then subjected to a rotary drum (Model 120L cv, CSM, Jaraguá do Sul, Brazil) for an additional 5 min to ensure complete adhesion between particles, powder, and adhesive. After this step, the mixture was placed in a wooden mold with dimensions of 350 × 350 × 20 mm and then transferred to the hydraulic press for the pressing process.

Following pressing, the panels were conditioned for up to seven days, according to the adhesive manufacturer's recommendations, before cutting the test specimens, following the dimensions prescribed by Brazilian Association of Technical Standards (ABNT) NBR 14810-2 (2024) for the experiments.

The physical tests performed were moisture content (MC), density (D), thickness swelling after 24 h (TS-24h), and water absorption after 24 h (WA-24h). For each test, 10 specimens with dimensions of 5 × 5 cm were used. The mechanical tests were conducted using a universal testing machine (GR048, EMIC, São José dos Pinhais, Brazil) and comprised modulus of rupture (MOR), modulus of elasticity (MOE), and perpendicular internal bond strength (IB). The static bending test for MOR and MOE determinations used specimens of 35 × 5 cm in both mixtures, adopting a span of 27 cm for the panels with 5 % adhesive and 28 cm for the panels with 10 % adhesive.

The SEM was used to evaluate the interaction between epoxy adhesive and wood particles under pressing conditions and varying adhesive contents. Fragments ($\approx 1 \times 1 \times 0.4$ cm) from the rupture region were mounted on metallic stubs, gold-coated, and analyzed using a ZEISS EVO LS15 microscope with EDS (Oxford Instruments, INCAx-act model, Oberkochen, Germany). The standards used for the evaluation of the results were ABNT NBR 14810-2 (2024), European Standard (EN) 312 (2003) and American National Standard (ANSI) A208.1 (2016).

RESULTS AND DISCUSSION

Table 1 presents the mean values (X_m), coefficients of variation (CV), and the results of Tukey's mean contrast test (5 % significance) regarding the influence of adhesive content (5 % and 10 %) on the physical (D; WA-24h; TS-24h; MC) and mechanical (MOE; MOR; IB) properties of the manufactured panels. The p-values obtained from the Anderson-Darling normality test [0.084; 0.522 – 5% significance level] and from the multiple comparison test [0.241; 0.826 – 5% significance level], were used to assess the homogeneity of variances in the residuals of the analysis of variance (ANOVA, 5% significance level) for the physical and mechanical properties of the panels. The tests showed which differences were higher than the adopted significance thresholds. These results therefore validate the application of ANOVA and Tukey's test. Statistical analyses were performed using Minitab® software, version 18.

For all tests, the best values were obtained with the increase in adhesive content. A statistically significant reduction of 46.3% in TS-24h and 49% in WA-24h was observed. In the mechanical tests, there was an increase of 57.1% in MOR, 68.1% in MOE, and 104.3% in IB, all with significant differences between adhesive contents. For density and moisture content, although increases were observed, no statistically significant differences were found.

Table 1. Experimental and Statistical Results Compared with Standards

Prop.	70/30		70/30		NBR 14810	EN 312	ANSI A208.1				
	5 %		10 %		P2	P2	M-S	M-3	PBU	H-2	D-2
	X _m	CV (%)	X _m	CV (%)							
D (g/cm ³)	0.87 A	11.9	0.90 A	5.2	-	-	-	-	-	-	-
WA-24h (%)	77.3 A	15.4	38.5 B	21.6	-	-	-	-	-	-	-
TS-24h (%)	40.5 A	17.1	21.7 B	14.6	22	-	-	-	-	-	-
MC (%)	5.4 A	9.13	5.5 A	5.71	-	-	-	-	-	-	-
MOE (MPa)	1808 B	10.2	3039 A	4.9	1800	1800	1700	2750	1725	2160	2750
MOR (MPa)	11.9 B	9.8	18.7 A	8.9	11	13	11	16.5	11	18.5	16.5
IB (MPa)	0.7 B	40.2	1.43 A	15.9	0.4	0.45	0.36	0.55	0.4	0.81	0.55
Class.	M-S, PBU (ANSI)		P2 (ABNT/EN), M-3, H-2, D-2 (ANSI)								

M-S: Medium density grade S; PBU: Underlayment; M-3: Medium density grade 3; H-2: High density grade 2; D-2: Manufactured Home Decking grade 2; P2: Nonstructural for dry applications. From Tukey's test (5 % significance), mean in the same letters in the same column is not significantly different at p-value < 0.05.

When compared with Santos Junior *et al.* (2025), who produced panels under the same pressing conditions, with the same adhesive content and the same materials, but composed exclusively of *Pinus spp.*, the values obtained in this study were higher. For density, the increase was associated with the addition of PET powder, whose density is 1.36 g/cm³, higher than that of wood (0.630 g/cm³) (Cazella *et al.* 2024). Epoxy also contributed to this result, as its density can reach up to 1.12 g/cm³, according to the manufacturer (Santos Junior *et al.* 2025). Regarding physical results, the incorporation of PET powder promoted an average reduction of approximately 29% in moisture content for both adhesive proportions (5 % and 10 %). For TS-24h and WA-24h, the average reduction was about 25 %. As for mechanical performance, PET powder contributed to a 31% increase in MOR with 5 % epoxy and 13.2% with 10 %. MOE increased by 33% for 5 % epoxy and 13% for 10 %. For IB, the improvements were even more pronounced: 133% for 5 % adhesive and 41% for 10 %.

Compared with the results reported by Rahman *et al.* (2013, 2018), it is evident that the adhesive plays a central role in improving the elastic properties of the material, as it is responsible for filling possible voids and promoting a more homogeneous union between the constituents, allowing the composite to behave as a single material under elastic loading. In their study, although a pressing temperature of 190 °C was applied, close to the PET transition from the glassy to the melting state, the polymer itself did not melt sufficiently to encapsulate the particles and fill the voids. Consequently, the absence of this adhesive action limited the mechanical performance. For TS-24h and WA-24h, the differences observed were mainly related to the manufacturing methodology, where longer pressing cycles contributed to reducing void formation. Figure 2 illustrates the comparison between the mechanical results obtained in this study and those reported in the literature.

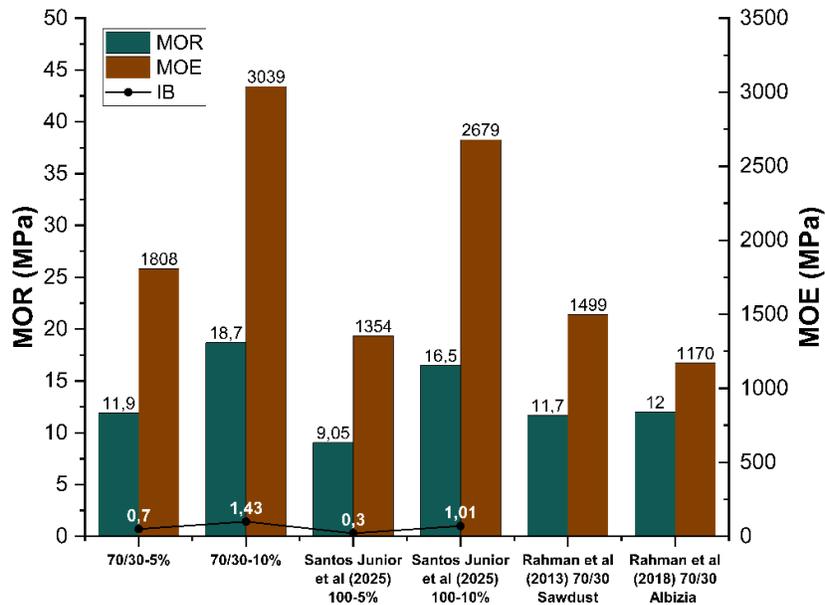


Fig. 2. Mechanical results compared with literature

The panel with 5% adhesive met only the American ANSI A208.1 (2016) standard, whereas the 10% panel complied with all three standards evaluated, being recommended for non-structural indoor applications under dry conditions.

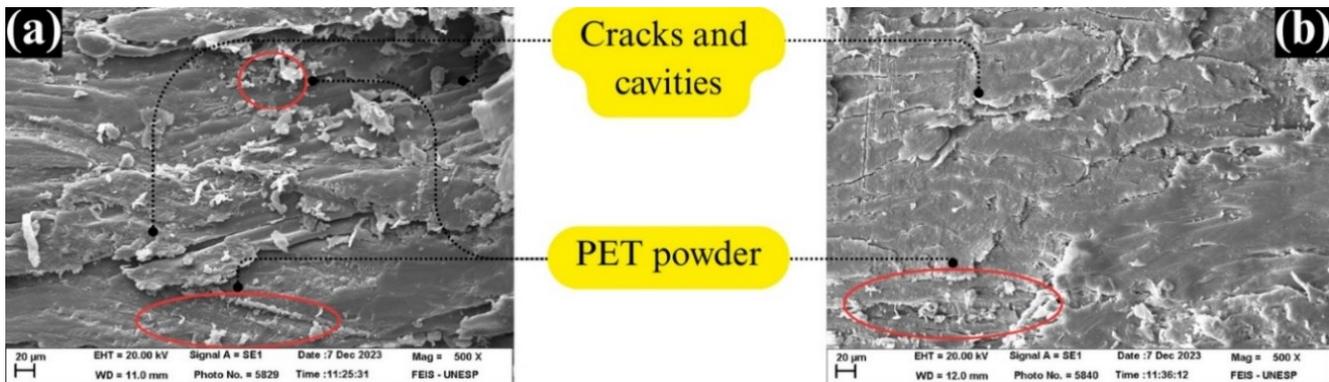


Fig. 3. Scanning electron microscopy (SEM) analysis. (a) 5% epoxy; (b) 10% epoxy

The micrographs obtained by SEM allowed the evaluation of the interaction between wood particles, PET powder, and epoxy adhesive in the rupture regions of the specimens. The images revealed significant differences between the mixtures with 5% and 10% adhesive.

In the 5% epoxy mixture (Fig. 3a), the surface exhibited a greater number of cracks and voids, indicating filling failures and partial adhesion. Wood particles and PET powder remained exposed in some regions, demonstrating limited encapsulation. These discontinuities favored water percolation and explained the higher absorption and swelling values after 24 h. This condition was also associated with lower performance in the mechanical tests, particularly MOR, MOE, and PT. In the 10% epoxy mixture (Fig. 3b), the surface appeared more homogeneous and continuous, with the adhesive more uniformly distributed and capable of filling the gaps between particles. The reduced

porosity and the presence of a denser matrix contributed to higher density and better dimensional stability. This behavior also favored mechanical stress transfer, resulting in significant gains in strength and stiffness.

Overall, the micrographs confirmed that increasing the epoxy content improves particle coating and encapsulation, reducing cracks and voids, and promoting a more compact microstructure. This structural aspect was decisive for the superior performance of the panels with 10 % adhesive, in agreement with the physical and mechanical results obtained.

CONCLUSIONS

The incorporation of recycled polyethylene terephthalate (PET) powder and epoxy resin as adhesive demonstrated significant improvements in the physical and mechanical properties of particleboard panels, reducing porosity and increasing strength and dimensional stability. The results showed that PET powder can be more than just a filler, but an active component in reinforcing the composite. The microscopy analysis (SEM) supported these findings by evidencing better encapsulation of wood particles with 10% epoxy, which was also the only mixture to meet the requirements of the three evaluated standards (ABNT NBR 14810-2, EN 312 and ANSI A208.1).

1. Increasing the adhesive content from 5% to 10% reduced thickness swelling and water absorption after 24 h by approximately 46% and 49%, respectively.
2. Mechanical performance improved with the higher epoxy content and the PET powder, with increments of 57% in modulus of rupture, 68% in modulus of elasticity, and 133% in perpendicular tensile strength.
3. Scanning electron microscopy (SEM) analysis revealed that the panels with 10% epoxy presented a more homogeneous and compact surface, with fewer cracks and voids, leading to superior performance.
4. Only the 10% epoxy panels achieved classification in all three standards evaluated, being suitable for non-structural indoor applications under dry conditions.
5. The results highlight the potential of epoxy resin as an alternative to formaldehyde-based adhesives and reinforce the viability of using recycled PET powder as a raw material for more sustainable particleboard production.

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