Eco-friendly Particleboard Production: Integrating Recycled PET and Bio-based Pine Resin Adhesives

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Particleboards constitute an important solution addressing two current demands: Improving the use of exploited resources and implementing adequate waste management. In this study, panels were produced from recycled polyethylene terephthalate (PET), rosin (adhesive derived from natural pine resin or colophony), and particles of *Pinus* sp. wood (pinewood). Rosin resin was used at a 20% ratio for all panels, and recycled PET was incorporated at varying proportions (75%, 50%, and 25%) as a wood substitute. Physical tests assessed included density (D), moisture content (MC), 24 h thickness swelling after 24 h (TS-24h), and water absorption after 24 h (WA-24h). All tests were carried out in accordance with NBR 14810-2 (ABNT 2018). The findings revealed commendable physical performance across all mixtures, with mixture M4 demonstrating the most favorable results among the four evaluated. Although further investigation is warranted, the integration of wood, rosin resin, and PET in particleboard production represents a sustainable and efficient alternative.

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INTRODUCTION

As part of its 2030 agenda, the United Nations (UN) has set goals to promote sustainable forest management and ensure the efficient utilization of natural resources. Timber, despite being one of the most extensively harvested natural resources, remains significantly underutilized in industrial applications. Current data reveals that only 35% of processed logs are transformed into sawn timber, with the remaining 65% categorized as waste. This material, often diverted to low-value uses, such as biomass energy production, underscores the pressing need for innovative strategies to enhance the value recovery of wood residues (Feitosa 2012).

Within this context, engineered wood panels, particularly particleboards, represent a highly efficient solution for optimizing wood utilization by incorporating smaller particles as raw materials. In Brazil, the particleboard industry primarily relies on reforested timber, with pinewood species serving as a significant resource due to their widespread availability and adaptability to industrial applications (Iwakiri and Trianoski 2020).

Global forests cover 4 billion hectares, with planted forests representing only 7% (294 million hectares) (FAO 2020). Expanding forest plantations and prioritizing reforested timber can reduce pressure on native forests. In Brazil, pinewood, covering 1.93 million hectares, is widely used in construction, paper, cellulose, and panel industries (IPEF 2024). In 2021, global particleboard production reached 104 million m^3 (FAO 2023), highlighting pinewood's significance. Additionally, particleboards can incorporate other materials that contribute to reducing raw material consumption, such as plastic waste, thereby enhancing sustainability (Iždinský *et al.* 2013; Cazella *et al.* 2024).

The 12th Sustainable Development Goal (SDG) also emphasizes a substantial reduction in waste generation through recycling initiatives. In this context, particleboards stand out for their ability to incorporate various materials, including plastics, during the manufacturing process (Gonçalves *et al.* 2018). This approach not only facilitates the appropriate disposal of recyclable materials, but it also enhances their economic value, transforming waste into a resource with added utility.

In 2019, Brazil generated 13.35 million tons of plastic waste, which constituted 16.8% of total urban solid waste (ABRELPE 2020). PET, widely used in packaging, is 100% recyclable, yet only 56.4% of discarded PET packaging was recycled in 2021 (ABIPET 2022). Most recycled PET is used in packaging and polyester fiber production, but studies show its integration into wood panels improves waste management and panel performance. Research by Iždinský *et al.* (2013), Campos *et al.* (2023), and Cazella *et al.* (2024) highlights PET's role in enhancing water-related properties, reducing moisture content and swelling.

In pursuit of innovative products aligned with sustainability goals, this study assessed the technical feasibility of incorporating recycled PET into particleboards bonded with rosin resin, a bio-based adhesive derived from pine resin. Colophony, commonly referred to as rosin, is a natural gum obtained from conifer resin, consists primarily of abietic- and pimaric-type resin acids, which provide excellent film-forming properties and hydrophobic characteristics (Kugler *et al.* 2019). Characterized by its solid, brittle, transparent, and glassy appearance, rosin is widely applied in the manufacturing of adhesives, paints, paper glue, and synthetic rubber (Phun *et al.* 2017).

Several studies have explored the potential of rosin-based materials in various composite applications. Patel and Rawat (2017) investigated the use of gum rosin in wood-polymer composites, demonstrating its ability to enhance mechanical properties. Similarly, Tao *et al.* (2020) developed rosin-based epoxy composites reinforced with carbon nanotubes and cork powders, highlighting improvements in thermal stability, mechanical resistance, and flame retardance.

These findings underscore the versatility of rosin as a renewable resource for bio-based composites. However, its potential as a bonding agent in wood panels remains underexplored. This study investigated this application to promote and enhance the value of non-timber forest resources.

EXPERIMENTAL

The panel manufacturing process utilized pinewood particles, recycled PET, and colophony (rosin) as raw materials. Figure 1 illustrates the materials employed in the process.

(a) (b) (c)

Fig. 1. Pinewood (a), recycled PET (b), and rosin (c)

Initially, all materials underwent a preparatory process. Pinewood particles were obtained by processing boards, with particles of optimal size selected through sieving and subsequently dried in an oven until achieving a moisture content of approximately 3%, as described by De Souza *et al.* (2022). Recycled PET, sourced from plastic bottles, was supplied by Global PET (São Carlos, SP) in a pre-shredded format. Rosin, originally presenting a rocky texture and yellow coloration, was manually ground into a fine white powder.

Table 1. Particle Size Distribution

Type	Hole (mm)	Average Retained Mass (g)	Cumulative Retained Mass (g)	Retained Material (%)	Cumulative Retained Material (%)
1/4"	6.36	0.63	0.63	1.3	1.3
4	4.75	3.09	3.72	6.2	7.4
8	2.36	16.34	20.06	32.7	40.1
16	1.19	24.07	44.13	48.1	88.3
30	0.60	5.75	49.88	11.5	99.8
50	0.30	0.00	49.88	0.0	99.8
100	0.15	0.00	49.88	0.0	99.8
Pan fraction		0.02	49.90	49.90	100.0
Total Sample Mass (g)		**Losses (g)**	**Losses (%)**	**Fineness Module**	
50,00		0.1	0.2	4,37	

To select wood particles with appropriate dimensions, a sieve shaker equipped with meshes of decreasing aperture sizes 12.5, 9.52, 6.36, 4.36, 2.36, and 1.19 mm was employed. The particles were placed in the equipment and subjected to agitation for 10 minutes. Upon completion of the dimensional separation, oversized and excessively fine particles were discarded. A granulometric composition test was conducted, adapted according to the methodology proposed by Souza *et al.* (2022), to verify the particle size distribution. The selected wood particles intended for panel manufacturing exhibited dimensions ranging from 0.595 to 6.36 mm. The results are presented in Table 1.

This study proposed four distinct mixtures, designated as M1, M2, M3 and M4. The composition of each mixture is detailed in Table 2.

Table 2. Composition of Mixtures

Mixture	Pinewood (%)	PET (%)	Rosin (%)
M1	100	0	20
M2	75	25	20
M3	50	50	20
M4	25	75	20

Initially, a nominal density of 0.40 g/cm³ was adopted. The panels were molded into a square shape with dimensions of 350 × 350 mm, with an initial thickness of 1 cm, which was reduced after the pressing process. The amount of rosin used was determined based on the masses of *Pinus* and PET particles, which were calculated considering the dimensions of the wooden mold, the predefined density, and the pre-established thickness. After homogenizing the wooden particles with the resin, they were ready for the pressing process. As described by Campos *et al.* (2023), the pressing was performed under a pressure of 5 MPa at a temperature of 160 °C for a total duration of 10 min and 30 seconds, including a 30-second relief period to facilitate gas release. Figures 2a and 2b illustrate the panels in the press, before and after pressing, respectively.

(a) (b)

Fig. 2. Pressing stages: Pre-pressing (a); and post-pressing (b)

After the pressing process, the panels were left to rest for a period of 7 days to allow for natural stabilization and drying, the same standardization is applied to other types of adhesives (Campos *et al.*, 2023; Santos Junior *et al.*, 2025). Following this period, the panels underwent a series of physical evaluations. The physical tests included density (D), moisture content (MC), thickness swelling (TS), and water absorption (WA).

Ten specimens measuring 5.0 × 5.0 mm with variable thickness were used for each physical test in each mixture. For the TS-24h and WA-24h physical tests, the specimens were placed in a container filled with deionized water, submerged under a 25 mm water layer, where they remained for 24 hours. After this period, swelling and water absorption of each specimen were assessed based on the test results.

Figure 3 presents the appearance of the specimens from Mixtures M1 and M4 before and after the TS-24h and WA-24h physical tests.

(a) (b)

Fig. 3. Physical tests: M1 Mixture (a); M4 Mixture (b)

All physical tests were performed in accordance with the recommendations outlined in NBR 14810-2 (ABNT 2018), which establishes performance-based classifications for panels ranging from P2 to P7. Table 3 details the minimum requirements for panels with a thickness of 4 mm to 6 mm to meet the standards specified by the Brazilian normative standard.

Table 3. Minimum Requirements for Panels with Thicknesses between 4 mm and 6 mm

Class	D (kg/m³)	MC (%)	TS-24h (%)
P2 (NBR 14810)	550 to 750	5 to 13	25

Density (D), moisture contents (MC), thickness swelling (TS)

A sample measuring 5.0 × 5.0 × 5.0 mm was extracted from the M3 mixture, composed of 50 % pinewood, 50 % PET, and 20 % rosin, for analysis *via* scanning electron microscopy (SEM). The analysis was conducted using an EVO-LS15 microscope (ZEISS). This equipment provided high-resolution images, allowing for a detailed investigation of the material interactions within the panel.

RESULTS AND DISCUSSION

Table 4 details the results of the physical tests, along with the statistical analysis performed on the measured values.

Table 4. Results of Physical Properties of Panels Manufactured with 20% Rosin Resin Content

Mixture	Estat.	*D* (kg/m³)	MC (%)	TS-24h (%)	WA-24h (%)
M1	X_m	1050.04 (B)	5.62 (A)	98.58 (A)	84.55 (A)
	CV (%)	2,43	3,38	14.44	12.13
M2	X_m	1083.00 (A)	3.97 (B)	38.33 (B)	39.70 (B)
	CV (%)	1.93	9.08	21.27	13.33
M3	X_m	1093.69 (A)	2.73 (C)	17.75 (C)	16.38 (C)
	CV (%)	2.39	7.47	30.74	20.87
M4	X_m	1099.58 (A)	1.58 (D)	6.42 (D)	6.17 (D)
	CV (%)	4.96	7.84	36.19	25.60

Density (D), moisture contents (MC), thickness swelling (TS), water absorption (WA)

According to Table 4, the incorporation of PET influenced the densification of the panels, with Mixture 4 (M4) yielding the highest average density values. While the average density of the panels increased with higher PET content, the results of the Tukey test at a 5 % significance level indicated that the observed variations among the mixtures were not statistically significant. Additionally, in compliance with NBR 14810-2 (ABNT 2018), all panels were classified as high-density panels, as their densities exceeded the threshold of 750 kg/m³.

The moisture content (MC) of the panels decreased significantly with the incorporation of plastic, with M4 exhibiting the best performance. The results of the Tukey test confirmed that the variations among mixtures were statistically significant, highlighting the positive impact of increasing plastic residue on MC reduction. Additionally, all panel mixtures outperformed the requirements specified by Brazilian standards for this property.

Regarding the 24-hour thickness swelling (TS-24h) and water absorption (WA-24h) properties, a behavior similar to that observed for MC was noted. A higher PET content enhanced the panel’s resistance to water percolation, effectively increasing particle impermeability and, as a result, leading to a reduction in TS-24h and WA-24h values. Conversely, the increased proportion of pinewood particles in M1 contributed to its higher TS-24h and WA-24h values. This outcome can be attributed to the hygroscopic nature of wood, which absorbs moisture more readily than plastic, causing greater dimensional changes when exposed to water. Consequently, mixtures M1 and M2, with 100 and 75% pinewood, were the only formulations to exceed the maximum swelling limit of 25% specified in NBR 14810-2 (ABNT 2018), further reinforcing the importance of plastic incorporation in enhancing panel dimensional stability.

According to the PET and wood sample, a Scanning Electron Microscopy (SEM) analysis was conducted. This analysis focused on the use of wood and PET, agglutinated with rosin resin, which is derived from *Pinus* wood. Figure 4(a) corresponds to the mixture of wood and rosin (M1), while Fig. 4(b) represents the mixture of wood, rosin and an additional amount of PET (M3).

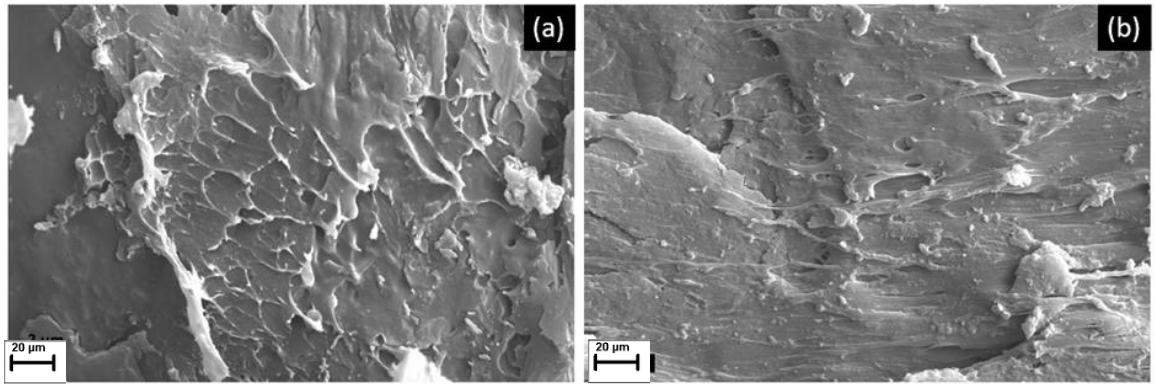

Fig. 4. Scanning electron microscopy (SEM) images of the region: (a) mixture of wood and rosin (M1); and (b) mixture of wood, rosin and an additional amount of PET (M3)

The scanning electron microscopy (SEM) image in Fig. 4a reveals the presence of small voids in the material, which defined the role of rosin. This is a distinctive characteristic of wood, which typically does not form such rounded voids. Another relevant aspect is that rosin exhibited an adhesive-like behavior at high temperatures, which explains its liquid-like appearance upon solidification. Similar findings can be observed in the images obtained by Cazella *et al.* (2024) who reported comparable results; however, their study used only PUR as the adhesive resin, without incorporating rosin. This observation aligns with the MC, TS-24h, and WA-24h results, as the superior performance of the panel in physical tests can be attributed to the adequate resin coverage, which minimizes water percolation within the panel.

In Fig. 4b, PET was added to the sample. However, it is not possible to distinctly identify the PET component in the SEM image, whereas the wood and rosin phases can be distinguished. The wood component, located in the central-left region of the image, exhibits a crack, resembling the typical fracture pattern observed in wood. Rosin, in turn, functions as a binder covering the material, which is particularly noticeable in the central-left area, where elongated and stretched sections are visible— a behavior not observed with any other material used in this study.

Another feature observed in the SEM images is the presence of anatomical structures of wood, such as vessels and pores. As highlighted by Frihart and Hunt (2010), wood porosity significantly influences the mechanical resistance of panels, as it facilitates resin penetration, thereby improving bonding performance. The M4 mixture, which contains a lower proportion of *Pinus* wood particles, reduces resin absorption by the wood and consists of 75% PET, a material with low moisture absorption capacity (Crawford 1998). Additionally, as observed by Iždinský et al. (2013), PET particles contribute to filling voids between wood particles, thereby reducing resin consumption and increasing adhesive availability. The synergy of these factors resulted in the superior performance of the M4 mixture in physical tests involving water exposure.

CONCLUSIONS

This study demonstrated that incorporating recycled PET and colophony resin in the production of particleboards is a viable and sustainable approach for the construction materials industry.

1. The analysis of the results indicated that the partial substitution of wood with recycled polyethylene terephthalate (PET) significantly improved the physical properties of the panels, reducing moisture absorption and thickness swelling, critical characteristics for performance in humid environments.
2. The findings confirmed that a mixture M4, composed of 75% recycled PET and 25% wood particles, exhibited the best performance among the tested formulations. This composition resulted in panels with higher density and lower water absorption, aligning with regulatory requirements for structural and furniture applications. Furthermore, the presence of colophony resin ensured a uniform distribution of the adhesive matrix, enhancing dimensional stability.
3. From an environmental perspective, the partial replacement of wood with recycled PET represents an innovative solution for plastic waste management, contributing to the reduction of the environmental impact associated with improper disposal of this material. This process also adds value to wood residues and natural resins, promoting the efficient utilization of both timber and non-timber forest resources. As a result, this research reinforces the importance of circular economy principles in the construction industry, aligning with the United Nations' 2030 Agenda and Sustainable Development Goal 12, which emphasizes responsible consumption and production.

However, further studies are required to assess the mechanical performance of these panels, as well as their resistance under different environmental conditions and long-term usage. Future investigations could explore the optimization of the adhesive formulation and the application of surface treatments to expand the commercial applications of these materials. In this regard, continued research will contribute to consolidating the use of recycled and bio-based materials in panel manufacturing, fostering advancements in sustainability and technological innovation within the sector.

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