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USE OF *Eucalyptus urophylla* WASTE AS RAW MATERIAL IN COMPOSITE PARTICLEBOARDS

Matheus Viana de Souza[1,♣]

https://orcid.org/0000-0003-1867-3249

Pedro Henrique da Silva Cazella[1]

https://orcid.org/0000-0002-9323-808X

Rodrigo Andraus Bispo[1]

https://orcid.org/0000-0001-8320-6490

Marjorie Perosso Herradon[1,4]

https://orcid.org/0000-0001-9284-1023

Antonio José Santos Junior[1,4]

https://orcid.org/0000-0002-9868-4900

Maria De Lourdes Xavier De França Neta Alves[2]

https://orcid.org/0000-0002-4736-857X

Denise Luisa Chotolli[1]

https://orcid.org/0000-0003-3195-9946

Márcia Regina de Moura Aouada[3]

https://orcid.org/0000-0002-2534-5553

André Luis Christoforo[4]

https://orcid.org/0000-0002-4066-080X

Sérgio Augusto Mello da Silva[1]

https://orcid.org/0000-0001-6114-0283

ABSTRACT

Eucalyptus urophylla (ampupu) is one of the most commonly cultivated species in Brazil for industrial scale particleboard production. This study investigates the reuse of *Eucalyptus urophylla* sawmill waste as a raw material for particleboard manufacturing, addressing the growing need for sustainable material solutions. Without prior particle homogenization, two manufacturing approaches were tested: single-layer and three-layer boards. Using a castor-oil-based polyurethane resin (10 % for single-layer and 12 % for three-layer boards), the panels were pressed at 5 MPa for 10 minutes at 100 °C. Performance evaluation under standards revealed that multilayer panels demonstrated superior mechanical and physical properties, while single-layer boards did not meet classification standards, highlighting the benefits of optimizing wood waste in multilayer compositions.

[1]São Paulo State University (Unesp). Department of Civil Engineering. Ilha Solteira, Brazil.

[2]Federal University of Rio Grande do Norte. Department of Civil and Environmental Engineering. Natal, Brasil.

[3]São Paulo State University (Unesp). Department of Physics and Chemistry. Ilha Solteira, Brazil.

[4]Federal University of São Carlos. Department of Civil Engineering. São Carlos, Brazil.

♣Corresponding author: mv.souza@unesp.br

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INTRODUCTION

The circular economy is driven by the need for more sustainable material use, promoting alternatives like agricultural waste and recycled wood for particleboard production (Lee *et al*. 2022). Inevitably, waste is generated during wood processing, but the demand for post-processed wood has grown, aligning with the expanding wood industry and its derived products (Eshun *et al*. 2012, Mirski *et al*. 2020).

Shavings and sawdust, both by-products from the wood and furniture sectors, are often overlooked in their economic potential, with incomplete combustion being a common fate, especially in the wood sector (Top *et al*. 2018). This contributes to environmental degradation, as wood waste not only depletes natural resources but also generates significant environmental impacts (Eshun *et al*. 2012).

It is evident that micro-sized enterprises generate specific types of wood waste, primarily sawdust and shavings, depending on whether they produce timber or furniture. This waste is often underutilized but holds economic value, especially in the timber sector (Top *et al*. 2018). From a technological and economic standpoint, using primary wood residues like chips or sawdust makes sense, as these materials are not reprocessed and are commonly used in the energy sector, though underutilized in the wood sector (Mirski *et al*. 2020).

Particleboard is an alternative to utilizing these low-value residual materials, offering advantages through its uniform properties, with Pine and Eucalyptus species being the most commonly used raw materials (IBÁ 2022, Astari *et al*. 2019). In Brazil, ampupu (*Eucalyptus urophylla* (S.T.Blake)), native to Indonesia, is the most planted exotic species, covering approximately 4,75 million hectares. Known for its medium density and pink-to-brown heartwood, is predominantly used in panels, pulp, poles, fibers, charcoal, and sleepers (Paludzyszyn-Filho and Santos 2011, Moura 2004).

Studies have found that ampupu (*Eucalyptus urophylla* (S.T.Blake)) exhibits a basic density greater than 510 kg/m³ across different regions of São Paulo (Assis Ribeiro and Zani Filho 1993), with densities of 516 kg/m³ to 534 kg/m³ at ages 7 to 8 years in Rio Claro (Ferreira *et al*. 1979). Additional research using ampupu (*Eucalyptus urophylla* (S.T.Blake)) clones for low-density particleboard production reported wood densities ranging from 520 kg/m³ to 650 kg/m³ (Mendes *et al*. 2014).

Several studies have successfully incorporated shavings into particleboards, demonstrating that sawmill waste can add value, with panel strength depending on the balance between the core and outer layers, as well as the type of resin used (Mirski *et al*. 2020, Silva *et al*. 2021). Common adhesives for wood panel production include urea-formaldehyde, which represents approximately 90 % of adhesives used, along with phenol-formaldehyde (Maloney 1993, Pizzi 1994).

However, polyurethane resin derived from castor oil offers a sustainable, non-polluting alternative that is biodegradable and biomass-based. This resin is produced from *Ricinus communis*, a tropical evergreen shrub cultivated in over 15 countries, known for its oil-producing seeds (Araújo 1992, Silva *et al*. 2005).

Various studies incorporating residues and alternative resins into panels have been documented (Lee *et al*. 2017, Lubis *et al*. 2018, Fiorelli *et al*. 2019, Akinyemi *et al*. 2019, Faria *et al*. 2020, Pędzik *et al*. 2021, Martins *et al*. 2021, Laksono *et al*. 2022, Oliveira-Junior *et al*. 2023). While the use of alternative lignocellulosic materials has been proven feasible, most panels remain categorized for furniture applications (P2) and seldom meet the criteria for structural purposes (Pędzik *et al*. 2021). This research aims to produce and evaluate particleboards using ampupu (*Eucalyptus urophylla* (S.T.Blake)) waste, with the goal of achieving higher strength than those specified by minimum normative standards.

MATERIALS AND METHODS

Material collection and preparation

The ampupu (*Eucalyptus urophylla* (S.T.Blake)) used in this study was harvested at 11 years of age from the UNESP Teaching Farm in Ilha Solteira, São Paulo, Brazil (Figure 1). The polyurethane adhesive, AGT 1315, donated by IMPERVEG® Polímeros Indústria e Comércio Ltda, consisted of a 1:1 polyol and pre-polymer mixture, following previous studies (Rodrigues *et al.* 2023, Gilio *et al.* 2021, Buzo *et al.* 2020).

The polyol, derived from castor oil, was a light-colored viscous liquid, while the pre-polymer, derived from petroleum, had a darker hue. This composition adhered to Brazilian standards ABNT NBR 14810-1 (2013) and ABNT NBR 14810-2 (2018), as well as the European standard CEN EN 312 (2003).

Figure 1: Ampupu (*Eucalyptus urophylla* (S.T.Blake)) donated by the UNESP farm, (a) Wooden log; (b) Cross section.

Exploratory study

Initially, an exploratory phase assessed whether panel production was viable using untreated, unclassified, and unprocessed material directly collected from the processing laboratory of wood. As detailed by Silva *et al.* (2021) and Faria *et al.* (2020), 10 % adhesive was applied relative to the dry mass of particles, achieving a panel density of 0,550 g/cm³, with dimensions of 35 cm x 35 cm x 1,2 cm. The total panel mass reached 810 g, aligning with methodologies reported by Gilio *et al.* (2021) and Bispo *et al.* (2022).

Further investigations and particle classification

Based on the positive results from the initial mixture, subsequent investigations proposed continuing panel production using particles collected after log thinning, further classified by particle size. The material was processed using a granulation method, separating particles based on size, in accordance with previous classifications (Souza *et al.* 2023, Souza *et al.* 2022a, Souza *et al.* 2022b).

To improve the mechanical properties of the panels, the resin content was increased to 12%, as supported by prior studies (Dias 2020, Archangelo 2019). The Eucalyptus logs, sourced from Madeireira Paraíso in Ilha Solteira, São Paulo, had a saturated moisture content. After processing into shavings, the particles were oven-dried at 70 °C. Moisture content was monitored daily, reaching a final moisture level of 3 % (Borysiuk et al. 2019, Klímek et al. 2016).

Particle grinding and separation

For the production of the outer layers of the multilayer panels, fine particles (4,75 mm to 1,19 mm) were produced by grinding the shavings using a knife mill with an 8 mm sieve. The inner layer, however, remained unprocessed, using the particles in their original form without further grinding or refinement. These fine materials were then separated using mechanical sieving, obtaining the particles required for panel production. Figure 2 and Figure 3 illustrate the grinding and resulting particle separation processes.

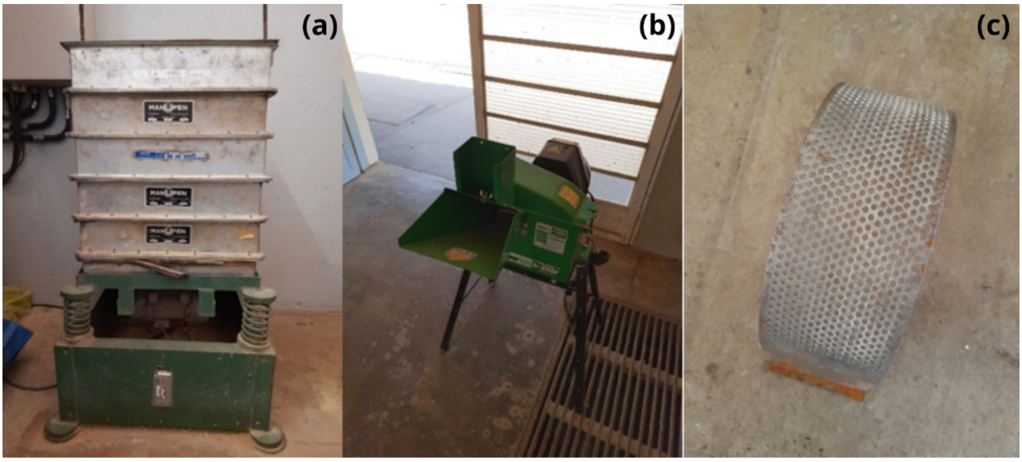

Figure 2: Equipment used for separating and reducing particle sizes for multilayer particleboard, (a) Mechanical sieve; (b) Knife mill; (c) Sieves (#10 mm with round holes).

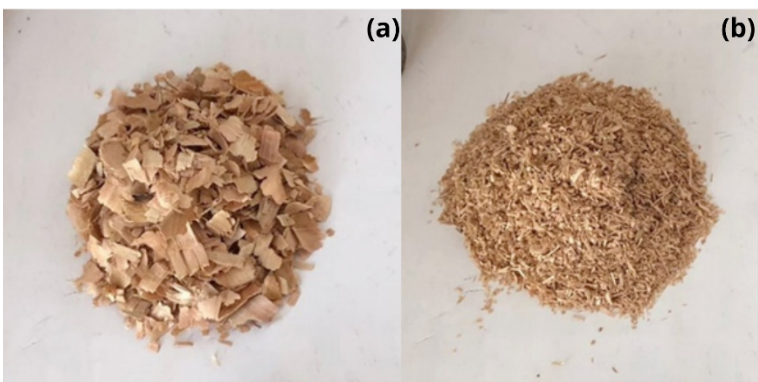

Figure 3: Ampupu (*Eucalyptus urophylla* (S.T.Blake)) particles, (a) Without processing; (b) Processed.

The granulometric composition of the particles followed standard ABNT NBR 17054 (2022), with adaptations based on Trevisan (2021) and Bispo (2021), using 35 g of particle mass for testing. For the production of single-layer panels (E1), particles were used in their entirety. The particles were selected using sieves with mesh openings in descending order: 19,1 mm, 12,7 mm, 9,52 mm, 6,35 mm, 4,75 mm, 2,38 mm, 1,19 mm, and finer. For three-layer particleboard (E2), the core particles were selected for homogeneity, while the outer layers were composed of particles ranging from 6,35 mm to 0,84 mm, as shown in Figure 4.

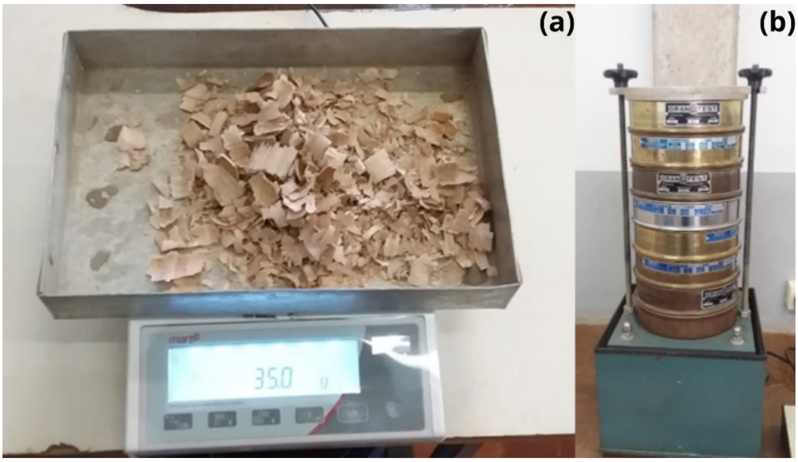

Figure 4: Wood particles, (a) Weighing of material for sieving; (b) Granulometric testing.

The particle size composition test followed the methods outlined by Trevisan (2021) and Gilio (2020). A total sieving time of 15 minutes was used, with the equipment set to level 4. After mechanical sieving, manual sieving was conducted until the mass loss through the sieve was less than 1 %. The retained material was then weighed, and the mass recorded to calculate the granulometric composition of the particles.

Particle density determination

The particle density was measured using the volumetric flask method, following ABNT NBR 6457 (2016) and ABNT NBR 6458 (2017) standards. A calibrated 500 ml pycnometer was used with 99,3 % anhydrous ethyl alcohol at a temperature of 3 % moisture, following studies by Trevisan (2021) and Bispo (2021). For both single-layer and three-layer panels, the pressing parameters were identical: 5 MPa pressure, 10 minutes pressing time, and 30 seconds degassing (Rodrigues *et al.* 2023). A castor oil-based polyurethane (PUR) binder was used in line with previous research (Gilio *et al.* 2021, Bispo *et al.* 2022).

Mono-layer and three-layer panel composition

For the three-layer particleboard, 60 % of the total mass of particles was allocated to the outer layers (4,75 mm to 1,19 mm), and 40 % for the core, which used the same particles as the single-layer panels (Iwakiri *et al.* 2003). The adhesive was divided into three equal parts: 8 % for the fine particles and 4 % for the larger core particles, based on the dry weight of the particles (Souza *et al.* 2023, Souza *et al.* 2022a, Souza *et al.* 2022b). Curing and Panel Testing After pressing, the panels underwent a 7-day curing period for PUR stabilization (Cazella *et al.* 2024). Post-curing, the panels were cut into 10 specimens per test for the evaluation of static flexion (MOR and MOE), perpendicular traction, density, thickness swelling, water absorption, and moisture content. The specimen dimensions were 50 mm x 50 mm x 12 mm, except for static flexion tests (350 mm x 50 mm x 12 mm).

Statistical analysis and normative evaluation

A Tukey’s mean contrast test at a 5 % significance level was used to assess the influence of panel type on physical and mechanical properties. Different letter groupings (A, B, C) indicate statistical equivalence between treatments with similar means. The physical and mechanical evaluations were conducted according to international (CEN EN 312 (2003)) and national (ABNT NBR 14810-2 (2018)) standards, as summarized in Table 1.

Table 1: Normative references for evaluatng panel properties thickness ranging between 11 and 13 mm.

Standards	Classification	D (kg/m³)	MC (%)	TS 24 h (%)	MOR (MPa)	MOE (MPa)	IB (MPa)
ABNT NBR 14810-2 (2018)	P2	550 – 750	5-13	22	11	1800	0,40
ABNT NBR 14810-2 (2018)	P3	550 – 750	5-13	17	15	2050	0,45
ABNT NBR 14810-2 (2018)	P4	550 - 750	5-13	16	16	2300	0,40
CEN EN 312 (2003)	P2	-	-	-	13	1800	0,45
CEN EN 312 (2003)	P3	-	-	14	15	2050	0,45
CEN EN 312 (2003)	P4	-	-	16	16	2300	0,40

Density (D), moisture contents (MC), thickness swelling (TS), modulus of rupture (MOR), modulus of elasticity (MOE) and internal bonding (IB).

Microscopic imaging for material behavior analysis

To gain a deeper understanding of the material's behavior based on its physical and mechanical properties, zoom images were captured using a specimen measuring 50 mm x 50 mm. An 8x magnification was applied through a camera magnifying glass connected to the Leica EZ4W system, utilizing the Las EZ software (Souza *et al.* 2022a, Souza *et al.* 2022b). This imaging approach provided detailed visual insights into the structure of the material, aiding in the interpretation of test results.

RESULTS AND DISCUSSION

Particle evaluation

Granulometric composition

It is well known from the literature that particle size correlates with the final properties of particleboard panels and influences their production methods (Iwakiri and Trianoski 2020). Table 2 shows the percentage of material retained for producing single-layer and three-layer particleboards.

Table 2: Percentage of mass retained in each sieve.

Particles		Panel E1	Panel E2	
Sieve	Diameter (mm)	Single layer % Withheld	Center layer % Withheld	Outer layer % Withheld
3/4"	19,10	0	3,43	–
1/2"	12,50	16,86	18,29	–
3/8"	9,52	15,71	18,57	–
1/4"	6,30	14,29	23,71	0
#4	4,75	13,71	17,43	0
#8	2,36	22,86	15,43	2,29
#16	1,19	100	2	59,43
#20	0,084	-	-	26,57
Bottom	-	6,29	-	11,14

The largest distribution of particles is found in meshes ranging from 12,5 mm to 2,36 mm, accounting for 83,43 % of the material's total weight. This large variation in particle size, when applied to homogeneous panels, poses a problem as smaller particles settle by gravity into the gaps formed by larger particles (Souza *et al.* 2022a), preventing efficient homogenization. Ideally, both sides of the panel should have uniform surfaces (Iwakiri and Trianoski 2020), but the single-layer panel resulted in uneven faces. In contrast, the multilayer panel's external layer showed a more controlled particle size range, preventing surface inconsistencies like those seen in the single-layer panel.

The bulk of the smaller particles was found in the 1,18 mm to 0,084 mm range, with retained values of 59,43 % and 26,57 %, respectively. These smaller particles also acted as levelers, ensuring an even load distribution across the panel. In the multilayer panel's core, coarse shavings, making up around 40 % of the material weight, were used. These ranged between the 12,5 mm and 2,36 mm sieves, with about 96,86 % of the total material retained in these sizes. This improved particle distribution in the panel's assembly led to significant enhancements in the mechanical properties, as will be discussed in subsequent sections.

Density

Table 3 and Table 4 present the specific mass (or density) of the particles, which is crucial for understanding the compaction ratio and properties of the panels. Lower-density woods tend to produce panels with better characteristics (Iwakiri and Trianoski 2020).

Table 3: Result of the ampupu (*Eucalyptus urophylla* (S.T.Blake)) specific mass test.

Espécie	M_1(g)	T(°C)	M_2(g)	M_s(g)	ρ_{al} (kg/m³)	ρ_s (k/m³)
Eucalipto	545,7	29,00	546,63	5,00	789	665

Table 4: Comparison of the ampupu (*Eucalyptus urophylla* (S.T.Blake)) specific mass result with those found in literature.

Reference	Density (kg/m³)
Author	665
Mendes *et al.* (2014)	between 520 and 650
Assis Ribeiro and Zani Filho (1993)	> 510
Ferreira *et al.* (1979)	between 516 and 534

As shown in Table 4, the density value obtained in the test from Table 3 exceeds the typical range found in the literature, which varies from 510 kg/m³ to 650 kg/m³. However, the 11-year-old ampupu (*Eucalyptus urophylla* (S.T.Blake)) species used in this study is still classified as medium density (Silveira *et al.* 2013), making it a suitable material for particleboard production. This species can also be effectively combined with lower-density species. With the measured density of 655 kg/m³, the effective compaction ratio was calculated.

Physical and mechanical properties of the panels

Density and compression ratio

To carry out the density test, the same specimens of the tensile test were used. Factors that influence density - such as pressing time, pressure, temperature and adhesive (Iwakiri and Trianoski 2020) - also influence results regarding internal bonding (IB). To calculate the effective compression ratio, the real density calculated by the average value of the specimens was used, which is the most important parameter for comparison with the literature.

Table 5: Result of real density and compaction ratio.

Proposed panels	Particle density (kg/m³)	Real density (kg/m³)	Effective compression ratio
E1	665	744B (2,88) *	1,12
E2	665	824A (3,09) *	1,24

*Coefficient of variation referring to the sampling used and grouping results by Tukey's mean contrast test (5 % significance). Equal letters imply statistically equivalent means and, being different, A is greater than B.

As shown in Table 5, the restructuring of the particleboard led to an increase in real density, raising the compression ratio from 1,12 to 1,24. According to Araújo *et al.* (2019), a good compression factor typically ranges from 1,3 to 1,6. The low compaction factor in homogeneous panels reflects the significant granulometric dispersion (Souza *et al.* 2022a), which prevents proper particle alignment during pressing. According to ABNT NBR 14810-1 (2013), E1 particleboard, with a density of 744 kg/m³, is classified as medium density, while E2, at 824 kg/m³, qualifies as high-density particleboard.

Physical and mechanical properties

The results of the physical and mechanical tests referring to the ampupu (*Eucalyptus urophylla* (S.T.Blake)) species are described in Table 6 below:

Table 6: Summary of the results of the panels manufactured with wood particles from the ampupu (*Eucalyptus urophylla* (S.T.Blake)) species

Properties	E1		E2	
	X_m	CV (%)	X_m	CV (%)
TS 24h (%)	19,69 A	21,78	14,39 B	15,25
WA 24h (%)	46,64 A	11,53	38,01 B	7,96
MC (%)	4,49 B	8,67	6,97 A	5,62
MOR (MPa)	6,92 B	12,35	17,92 A	16,76
MOE (MPa)	1434 B	12,66	2323 A	16,19
IB (MPa)	0,36 B	18,03	0,81 A	32,65

Thickness swelling (TS), water absorption after 24 h (WA), moisture contents (MC), modulus of rupture (MOR) and modulus of elasticity (MOE), internal bonding (IB). Equal letters imply statistically equivalent means, and being different, A is greater than B.

Analyzing the results in Table 6, the swelling at 24 hours (TS24h) decreased significantly, from 19,69 % in E1 panels to 14,39 % in E2, showing a 27 % reduction. This can be attributed to the polyurethane adhesive from castor oil, which enhances water resistance and particle encapsulation (Gilio *et al.* 2021, Buzo *et al.* 2020). The increased adhesive content (from 10 % to 12 %) also improved the physical properties and compaction ratio.

Similarly, water absorption in E1 panels was 46,64% while E2 panels showed a reduced value of 38,01 % leading to an 18,40 % improvement in water permeability. Moisture content in E2 was 55,23 % higher than in E1, which can be explained by the uncontrolled ambient temperature during panel production and increased resin content, though this did not affect compliance with normative standards.

The mechanical properties also improved, with E2 panels showing a 1,5-fold increase in modulus of rupture (MOR) and a similar increase in modulus of elasticity (MOE), with values of 6,92 MPa and 1434 MPa for E1 and 17,92 MPa and 2323 MPa for E2, respectively. Internal bonding results were significantly better for E2, with values more than double those of E1: 0,81 MPa versus 0,36 MPa. These improvements are attributed to the increased compaction ratio, as cited in the literature (Araújo *et al.* 2019, Brito *et al.* 2020).

Zoom image analysis

When analyzing Figure 5, comparing detail (a) with detail (b), it is evident that the particle arrangement differs between the panels. In detail (a), the 2 mm scale reveals noticeable gaps between larger particles in the single-layer panel, whereas detail (b) shows smaller, better-aligned particles in the multi-layer panel. Similarly, details (c) and (d) reflect this difference. Detail (c) shows smaller particles "falling" due to gravity in the single-layer panel (Souza *et al.* 2022a, Souza *et al.* 2022b), leading to an uneven distribution. In contrast, detail (d) demonstrates a more orderly arrangement in the multi-layer panel.

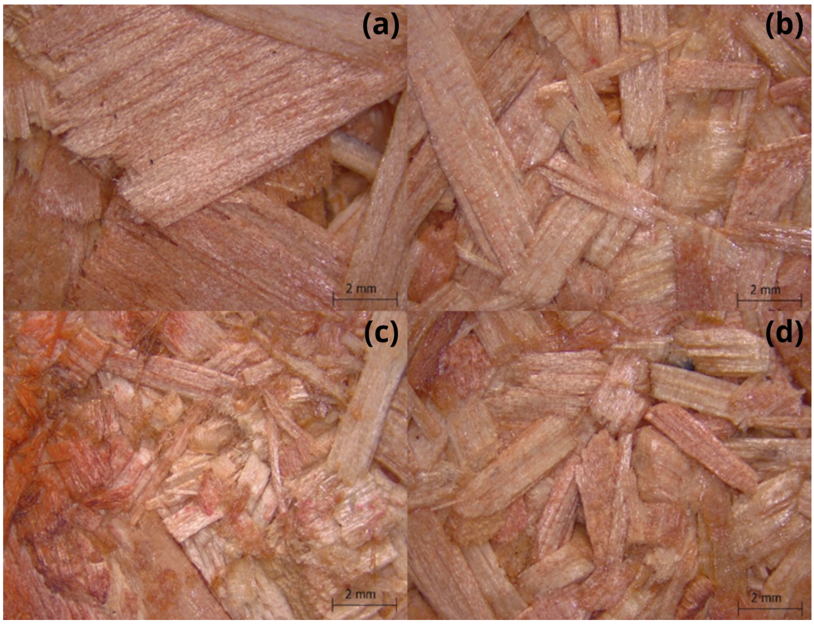

Figure 5: Details of the ampupu (*Eucalyptus urophylla* (S.T.Blake)) specimens, from left to right, (a) Upper surface of single-layer particleboard; (b) Upper surface of three-layer particleboard; (c) Lower surface of single-layer particleboard; (d) Lower surface of three-layer particleboard.

Similarly, Figure 6 reveals the impact of particle organization on compaction. In detail (a), representing the single-layer panel, the cross-section shows inconsistent compaction with both compacted and non-compacted areas. This contrasts sharply with detail (b), where the multi-layer panel displays uniform compaction, making the three layers indistinguishable. The restructuring of particles between treatments resulted in significant improvements in mechanical and physical properties for ampupu (*Eucalyptus urophylla* (S.T.Blake)) panels, as highlighted by Gava *et al.* (2015).

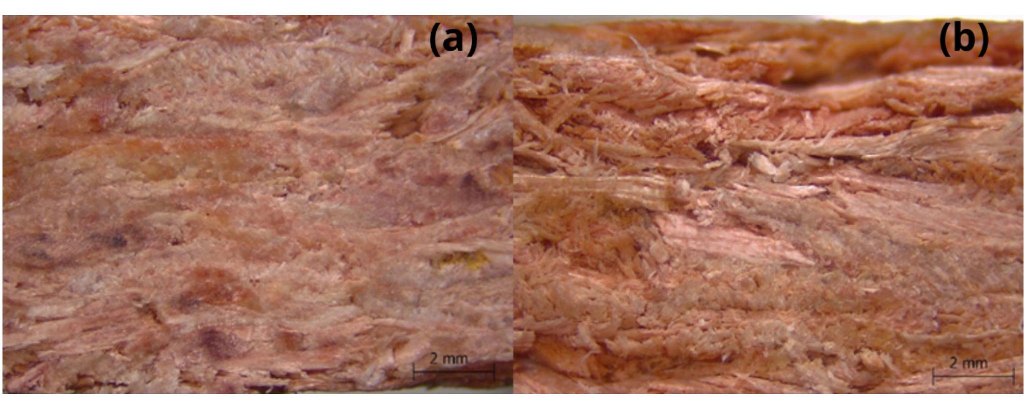

Figure 6: Details of the cross section of the ampupu (*Eucalyptus urophylla* (S.T.Blake)) specimens, from left to right, (a) Single-layer particleboard profile; (b) Three-layer particleboard profile.

CONCLUSIONS

The study concludes that *Eucalyptu urophylla* sawmill waste can be used in particleboard production without prior crushing or sieving, provided it is applied in the core layer, where particle size variation does not significantly affect compaction. Additionally, the integration of polyurethane resin with reconfigured particles enhances physical and mechanical properties. The multilayer panel met the P4 classification for structural panels in dry conditions according to ABNT NBR 14810-2 (2018) and CEN EN 312 (2003), while the single-layer panels did not comply with any Brazilian classification standards.

Authorship contributions

M. V. dS.: Conceptualization, methodology, writing – original draft. P. H. dS. C.: Formal analysis, methodology. R. A. B.: Writing – original draft, writing – review & editing. M. P. H.: Methodology, resources. A. J. S. J.: Methodology, investigation. M. dL. X. dF. N. A.: Conceptualization, writing – review & editing. D. L. C.i: Visualization, investigation. M. R. dM. A.: Project administration, supervision. A. L. C.: Supervision, validation, software. S. A. M. dS.: Conceptualization, Data curation, Project administration.

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