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Articles

Homogeneous *Tachigali vulgaris* wood particleboard agglomerated with organic resins

Painel de partícula homogênea da madeira *Tachigali vulgaris* aglomerado com resinas orgânicas

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ABSTRACT

In recent decades, the establishment of reforestation areas with native species has been driven by a new consumer market aware of environmental issues, *Tachigali vulgaris* wood has been investigated for this purpose. This study aimed to evaluate the potential of *T. vulgaris* wood as a raw material for homogeneous particleboards agglomerated with castor oil-based polyurethane resin (PU-Castor) and urea-formaldehyde (UF). The chemical composition, basic density (D_b), and pH of the wood's total soluble extractives were determined. Static bending and perpendicular tensile tests were carried out to determine the modulus of rupture (MOR), modulus of elasticity (MOE), and internal bond (IB). X-ray densitometry, bulk density (BD), thickness swelling (TS), and scanning electron microscopy (SEM) before and after accelerated weathering (AW) tests were carried out. The physical and chemical results of the wood (lignin: 23.8%; holocellulose: 76.3%; total extractives: 4.2%; ash: 0.6%; D_b; 525.5 $kg.m^{-3}$; pH: 5.5-5.8) corroborate those in the literature. The physical and mechanical results were compared to the ANSI A208.1:2016 and ISO 16893:2016 standards. The performance of the PU-Castor panel (TS: 29.2%; MOR: 6.0 MPa; MOE: 514.7 MPa; IB: 1.9 MPa; BD: 473 $kg.m^{-3}$) was superior to that of UF (TS: 21.5%; MOR: 2.4 MPa; MOE: 215.7 MPa; IB: 0.8 MPa; BD: 461 $kg.m^{-3}$), being classified as an LD-2 type panel according to ANSI A208.1:2016. The SEM images show the degradation of the panels after cycles of humidity and temperature variation. The characteristics of *T. vulgaris* wood make it suitable for producing homogeneous particleboards.

Keywords: White taxi; Particleboard; Urea-formaldehyde; Castor oil-based bicomponent resin; Homogeneous forest plantation

RESUMO

Nas últimas décadas, a implantação de áreas de reflorestamento com espécies nativas tem sido impulsionada por um novo mercado consumidor consciente das questões ambientais, e a madeira de *Tachigali vulgaris* vem sendo investigada com este propósito. Este estudo teve como objetivo avaliar o potencial da madeira *T. vulgaris* como matéria prima de painéis de partículas homogêneas aglomeradas com resina poliuretana à base de óleo de mamona (PU-Castor) e ureia-formaldeído (UF). A composição química, densidade básica (D_b) e pH de extrativos solúveis totais da madeira foram determinados. Os ensaios de flexão estática e tração perpendicular foram realizados para determinação de módulo de ruptura (MOR), módulo de elasticidade (MOE) e adesão interna (IB). Foram realizados ensaios de densitometria de raios-X, densidade aparente (BD), inchamento em espessura (TS) e microscopia eletrônica de varredura (SEM) antes e após ensaio de intemperismo acelerado (AW). Os resultados físicos e químicos da madeira (lignina: 23,8%; holocelulose: 76,3%; extrativos totais: 4,2%; cinzas: 0,6%; D_b: 525,5 kg.m^{-3}; pH: 5,5-5,8) corroboram com os da literatura. Os resultados físicos e mecânicos foram comparados às normativas ANSI A208.1:2016 e ISO 16893:2016. O desempenho do painel PU-Castor (TS: 29,2%; MOR: 6,0 MPa; MOE: 514,7 MPa; IB: 1,9 MPa; BD: 473 kg.m^{-3}) foi superior ao de UF (TS: 21,5%; MOR: 2,4 MPa; MOE: 215,7 MPa; IB: 0,8 MPa; BD: 461 kg.m^{-3}), sendo classificado como painel tipo LD-2 de acordo com a ANSI A208.1:2016. As imagens de MEV demonstram a degradação dos painéis após ciclos de variação de umidade e temperatura. As características da madeira de *T. vulgaris* habilitam sua utilização para produção de painéis de partículas homogêneas.

Palavras-chave: Taxi-branco; Painel aglomerado; Ureia-formaldeído; Resina bicomponente à base de óleo de mamona; Plantio de florestas homogêneas

1 INTRODUCTION

Homogeneous particleboards (HPB) are made from fragmented lignocellulosic raw material, agglutinated with synthetic organic resin, and agglomerated by applying temperature and pressure. The panels are then used to make furniture, aviaries, doors etc. (Cravo; Sartori; Fiorelli, 2017).

In 2020-2021, the compulsory remote work imposed by the coronavirus pandemic led to a 14.6% increase in Brazilian particleboard production from 7.1 to 8.2 million m^3 (IBÁ, 2022), reaching around 3.47 million m^3 of particleboard (FAO, 2022) in 2022. *Pinus* and *Eucalyptus* forests are the main raw material sources to produce these panels (Iwakiri *et al*., 2019).

Although *Pinus* and *Eucalyptus* forests prevail, this scenario is going through changes driven by a new consumer market aware of environmental issues in the face of the recent reduction in wood supply from native forests caused by the increasing strictness of legislation and control by regulatory agencies (Oliveira *et al.*, 2018; Martins *et al.*, 2020).

In addition, planting native species in degraded areas can mitigate the adverse impacts of native forest deforestation (Silva; Schmidt; Mantau, 2020). For example, planting native *carvoeiro* or white-taxi in degraded soil in the state of Mato Grosso showed a higher survival rate (52%) than two varieties of *Eucalyptus* (38%) (Farias *et al*., 2016).

The tree species known as white-taxi (*Tachigali vulgaris* L. G. Silva & H. C. Lima; synonym *Sclerolobium paniculatum* Vogel) is a *Fabaceae* and has a geographical distribution in the Cerrado and Amazon in South America, from the Guianas to Peru and central Brazil. It is a fast-growing pioneer tree suitable for reforestation and recovering degraded areas (Orellana, 2015).

The following attributes of *T. vulgaris* wood are favorable for energy forests: 1) higher calorific value between 4,390 and 4,849 kcal.kg^{-1} (Silva *et al.*, 2021); 2) growth rate: 2.2 - 2.5 m.year^{-1}; diameter growth rate: 2.05-3.40 cm.year^{-1}); and 3) wood density (470 - 780 kg.m^{-3}) (Barros-Junior *et al*., 2022).

The energy potential of *T. vulgaris* wood is well described in the literature for firewood and charcoal, which release greenhouse gases (SO_x, NO_x, CO_x, etc.) upon combustion (Silva *et al*., 2021). However, its technological potential remains little investigated since only one application focuses on plywood (Lisboa *et al.*, 2016).

The two-component organic polyurethane adhesive based on castor oil (PU-Castor) has been used as an alternative to other formaldehyde-based resins (e.g. urea formaldehyde (UF)). Castor oil is a renewable resource and mixing it with methylene diphenyl diisocyanate (MDI) does not produce volatile compounds harmful to health in the workplace, and since it is insoluble in water, PU-Castor resin is ideal for applications in humid environments, such as the Amazon (Gama; Ferreira; Barros-Timmons, 2019).

The HPB and PU-Castor from Amazonian species have been investigated: 1) *Schizolobium amazonicum* (*paricá*) (PU-Castor: 15%; 789 kg.m^{-3}; MOR: 24 MPa; MOE: 2133 MPa; IB: 2.27 MPa) (Amstalden *et al*., 2013); 2) *Hevea brasiliensis* (rubber tree) (PU-Castor: 12%; 789 kg.m^{-3}; MOR: 13.21 MPa; MOE: 1893.55 MPa; IB: 2.68 MPa) (Gava *et al*., 2015).

The mechanical performance of high-density HPB from *Pinus spp.* exposed to temperature and humidity variations was investigated using an accelerated weathering (AW) test, and the results showed no significant difference in the modulus of rupture compared to reference panels (Bertolini *et al.*, 2013). While the mechanical performance of low-density *Pinus spp.* HPB (PU-Castor: 12%; 500 kg.m^{-3}) met international standard requirements after the AW test (Cabral *et al.*, 2017).

Thus, this study aimed to evaluate the wood chemical composition and physical and mechanical performance of panels made from homogeneous low-density *T. vulgaris* particles agglutinated with PU-Castor and UF resins before and after accelerated weathering.

2 MATERIALS AND METHODS

2.1 Physico-chemical characterization of the wood

The 9-year-old white-taxi wood (*T. vulgaris*) (SISGEN AA58FCF) was supplied by the Brazilian Agricultural Research Corporation (EMBRAPA-AP) from a homogeneous forest, and evaluated with the following tests: 1) physical: sampling and preparation of the wood under NBR 14660 (ABNT, 2004), basic density (D_b) by NBR 11941 (ABNT, 2003), and 2) chemical: total extractives by NBR 14853 (ABNT, 2010b), ash by NBR 13999 (ABNT, 2017), insoluble lignin by NBR 7989 (ABNT, 2010a), and holocellulose (Browning, 1963). The pH of the solutions with soluble extractives in cold/hot water was determined using a digital pH meter (PG2000, GEHAKA) (Geffert; Geffertova; Dudiak, 2019).

2.2 Panel production

T. vulgaris HPBs were produced by adapting the methodology of Fiorelli, Bueno and Cabral (2019). The particles were obtained with a thickness planer (DW733, DEWALT) and classified through stainless steel sieves (4 mm and 6.3 mm). The HPB's estimated nominal density was 500 kg.m^{-3}. The particles were dried at 103 ± 2ºC in a forced air circulation oven until reaching a dry base moisture content of 4%. Then, the resin was applied manually to the particles and homogenized for 3 min. in a planetary mixer (BP12RP, GPANIZ).

We used 12% castor oil-based two-component polyurethane adhesive (Imperveg® AGT 1315) and 12% Cascamite urea-formaldehyde regarding the particle's dry mass (Table 1) to make the HPBs.

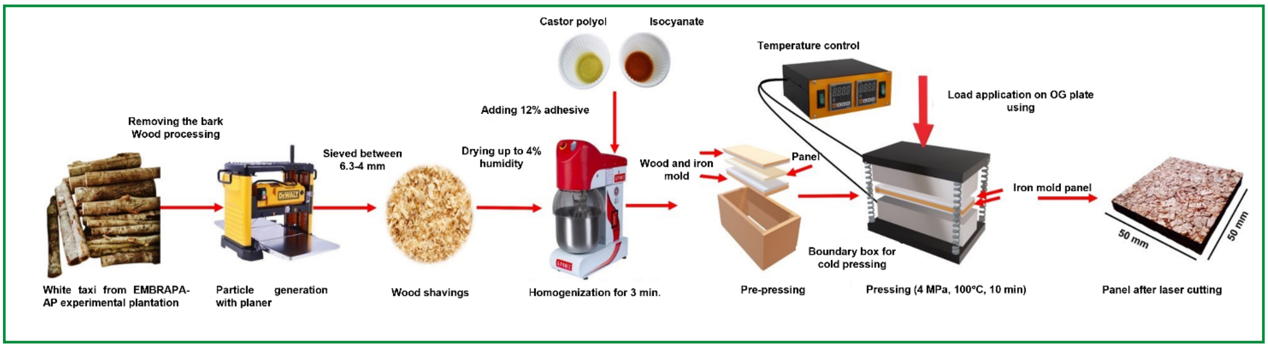
Table 1 – Treatments with different types of resin

Treatments	Biomass	Adhesive
UF	*T. vulgaris*	12% UF
PU-Castor	*T. vulgaris*	12% PU

Source: Authors (2024)

The homogenized particles were pre-pressed in an iron mold (190 mm x 60 mm x 6.2 mm) and formed under 4 MPa in a hydraulic press of 15 t hydraulic press (MPH-15D, MARCON) with a heating system (Plate OG, OVERGROW) at a temperature of 100°C (PU-Castor) and 140 °C (UF) for 10 min. The HPB produced were laser-cut into specimens of nominal dimensions (124 mm x 50 mm x 6.2 mm and 50 mm x 50 x 6.2 mm) (Figure 1).

Figure 1 – Illustration of the HPB production stages



Source: Authors (2024)

2.3 Physical and mechanical characterization

The performance of the HPB was determined using physical and mechanical tests under ISO 16893 (ISO, 2016). The HPB bulk density (BD) was calculated by measuring the mass and volume on an analytical balance and caliper (±0.1%), respectively. The HPB mechanical properties were assessed on an EMIC DL-30.000 Universal Mechanical Testing Machine. In the static bending test, the load was applied to the center of the 124 mm x 50 mm specimen until it broke to determine the modulus of rupture (MOR) and modulus of elasticity (MOE), under ISO 16978 (ISO, 2003a).

For the perpendicular tensile test, the faces of the 50 mm x 50 mm specimens were glued to two wooden molds with epoxy resin for 24 hours. The molds were then placed in two metal jaws connected to the load cell of the Universal Testing Machine. The vertical speed of the jaws was 7 $mm.min^{-1}$, ensuring that the specimens broke between 30 and 90 seconds. Internal bond (IB) was calculated using the maximum load per side section area of the panel according to ISO 16984 (ISO, 2003c). Thickness swelling (TS) was determined according to the recommendations of ISO 16983 (ISO, 2003b).

2.3.1 X-ray densitometry (DA-X)

The X-ray densitometry was carried out to assess the density profile of the HPBs. Samples of 50 mm x 50 mm were prepared for each treatment and the density values were determined for each 50 μm thickness. An IMAL DPX 300-LTE X-ray densitometer was used (33kV, 0-1mA, 11° radiation, initial and final beam positions of 100 and 50 μm) (Belini *et al*., 2014) to determine the average, maximum, and minimum values along the HPB thickness.

2.4 Accelerated weathering

The accelerated weathering (AW) test evaluated 20 specimens (124 mm x 50 mm) coated with acrylic paste on their edges. The specimens were subjected to 8 cycles of 12 hours (8 hours of UVB at 0.49 $W.m^{-2}$ at 60°C and 4 hours of condensation at 50°C) in a UV accelerated weathering test chamber (EQUV, EQUILAN) following APA PRP 108 (APA, 1994). Later, the HPBs' weathered sides were upwards and subjected to the static bending test to determine the MOR and MOE values.

2.5 Scanning electron microscopy (SEM)

The SEM analyses were carried out in triplicate (15 mm × 15 mm) on a microscope (TM300, HITACHI). Images were taken at magnifications of 100 and 500 times. These analyses were carried out on the HPB before and after the accelerated weathering test to identify differences in particle morphology and agglomeration.

2.6 Analysis of the results

The mechanical results were evaluated by Analysis of Variance (ANOVA) applied to the entire HPB data set (before and after AW). A 5% Tukey test was carried out to determine significant differences in the mechanical properties of the treatments (PU-Castor and UF).

3 RESULTS AND DISCUSSIONS

3.1 Chemical composition and physical and chemical properties of wood

Table 2 shows the results of the physical and chemical analysis of 9-year-old *T. vulgaris* wood. The values found were like those described in the literature, with higher levels of holocellulose and lower levels of lignin and extractives (Carneiro *et al.*, 2017). The lignin, holocellulose, extractives and ash contents of *T. vulgaris* corroborate those obtained by Orellana (2015). The lignin and holocellulose content are like those reported for *Pinus spp*. and *Pinus oocarpa* (Fiorelli *et al.*, 2014; Narciso et al., 2021).

Table 2 – Mean values and coefficient of variation of chemical components and physical and chemical properties of *T. vulgaris* wood

Treatment	L (%)	H (%)	TE (%)	TA (%)	D_b (kg.m^{-3})	pH CW	pH HW
T. vulgaris	23.87 (1.03)	76.36 (0.89)	4.20 (2.03)	0.68 (0.18)	525.50 (12.98)	5.88 (1.19)	5.52 (1.44)

Source: Authors (2024)

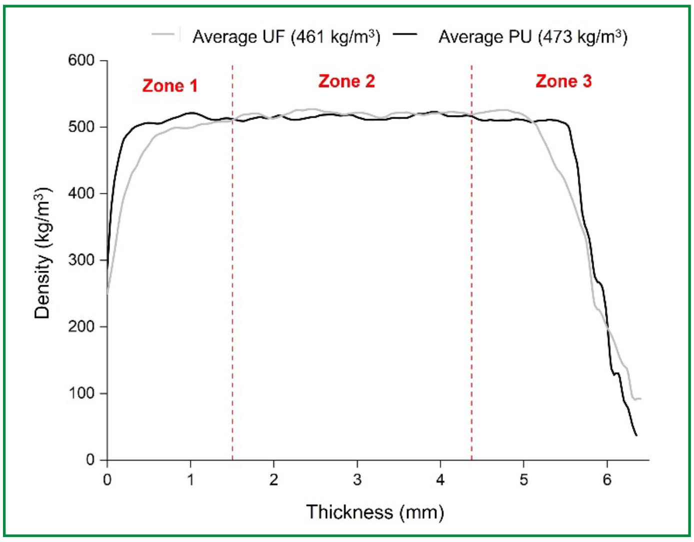
In where: L: Lignin content; H: Holocellulose content; TE: Total extractives content; TA: Ash content; D_B: Basic density; pH CW: Soluble extractives in cold water; pH HW: Soluble extractives in hot water.

The D_b of *T. vulgaris* is within the expected values of 470 - 780 kg.m^{-3} (Tonini *et al*., 2018). The soluble extractives in cold water were 1 unit higher than that observed for *Pinus spp.* while in hot water they remained between 3 and 6 as observed for Amazonian woods (Barros-Junior *et al*., 2022).

3.2 Physical and mechanical properties of the panel

Figure 02 illustrates the results of the HPB density profile, and it is possible to observe a typical behavior for this type of material, with a constant density throughout the thickness.

Figure 2 – Density profile of *T. vulgaris* HPB



Source: Authors (2024)

The HPB of the UF and PU-Castor treatments were classified as low density (<640 kg.m^{-3}) according to ANSI A208.1:2016 and met the requirements for a maximum variation of ±10% of the average BD according to ISO 16893:2016.

On the surface, the HPB adhesion with PU-Castor resin was higher than that observed for HPB with UF resin (Zone 1 and Zone 3). The density inside the panel (Zone 2) was similar for all treatments. No defects were observed on the surfaces of the HPB in terms of particle size and geometry that could be attributed to the raw material or processing (Wang *et al*., 2023).

Table 03 shows the average values and coefficients of variation of thickness swelling of HPB produced with UF resin and PU-Castor.

Table 3 – Mean values and coefficient of variation of *T. vulgaris* HPB's thickness swelling (TS)

Treatments	**TS (%)**
UF	21.53 (16.32)
PU-Castor	29.29 (46.67)

Source: Authors (2024)

Compared to HPB made from *Eucalyptus spp*., *Neolamarckia cadamba* and a hybrid of *E. spp.* and sorghum bagasse (Tinti, 2015; Junior *et al*., 2016), the UF panel showed a 10% lower TS for low-density panels. However, the PU-Castor panel had a higher TS than HPB made from peanut shells (TS: 18.92%; 15% PU-Castor; 542 kg.m^{-3}), *Dendrocalamus giganteus* composites (TS: 15.29%; 12% PU-Castor; 641 kg.m^{-3}) and piassava fiber (TS: 7.31%; 15% PU-Castor; 606 kg.m^{-3}) (Varanda *et al*., 2014; Cravo *et al*., 2015; Lima, 2019). Only the UF panel met the maximum thickness variation requirement of 1.5 mm (TS < 24.19%), established by the ISO 16893:2016 standard.

The average values and their respective coefficients of variation for MOR, MOE, and IB are shown in Table 4.

Table 4 – Average values and coefficient of variation of the mechanical properties of *T. vulgaris* HPB before and after accelerated weathering

Treatments		MOR (MPa)	MOE (MPa)	IB (MPa)
UF		2.40 (10.29) a	215.74 (17.09) a	0.85 (83.68) a
PU-castor		6.01(12.29) b	514.79 (20.81) b	1.91 (42.09) b
UF AW		0.44 (70.13) c	36.42 (59.73) c	-
PU-castor AW		3.51(8.22) d	260.20 (12.65) a	-
Normative requirements for panels between 6-13 mm thick				
ANSI A208.1:2016	LD-1	2.80	500.00	0.10
	LD-2	2.80	500.00	0.14
ISO 16893:2016	P-GP REG	10.50	-	0.28
	P-FN REG	11.00	1,800.00	0.40

Source: Authors (2024)

In where: Averages followed by the same letter in the same column showed no significant difference in the Tukey test at 5% significance (N = 6).

The MOR and MOE values observed for HPB produced with UF resin did not meet the regulatory requirements and showed lower performance than those observed in studies evaluating *E. grandis* HPB (6-8% UF; MOR: 3.27-7.27 MPa; MOE: 385-932 MPa; 618-624 kg.m^{-3}) (Faria *et al*., 2020). Similar results are found in the literature for HPB of *E. spp*. (10% UF; MOR: 2.52 MPa; MOE: 330.31 MPa; 466 kg.m^{-3}) and *D. giganteus* (6% UF; MOR: 2.43 MPa; MOE: 677.74; 610 kg.m^{-3}) (Valarelli *et al*., 2014a; Tinti, 2015). The lower performance may be related to the type of raw material, production process, equipment, and materials used in this study.

Concerning the HPB produced from *D. giganteus* (12% PU-Castor, MOR: 5.64 MPa, MOE: 757 MPa; 641.38 kg.m^{-3}), similar MOR and MOE results were observed for *T. vulgaris* HPB, and lower than those verified for HPB from *Pinus spp*. (12% PU-Castor, MOR: 6.6 MPa, MOE: 759 MPa; 550 kg.m^{-3}) (Valarelli *et al*., 2014b; Bertolini; Christoforo; Lahr, 2015).

The PU-Castor specimens that were subjected to AW presented MOR and MOE values 50% lower than the reference HPBs. ANOVA showed that there was a significant difference in MOR between the treatments, however, there was no significant difference between treatments for MOE.

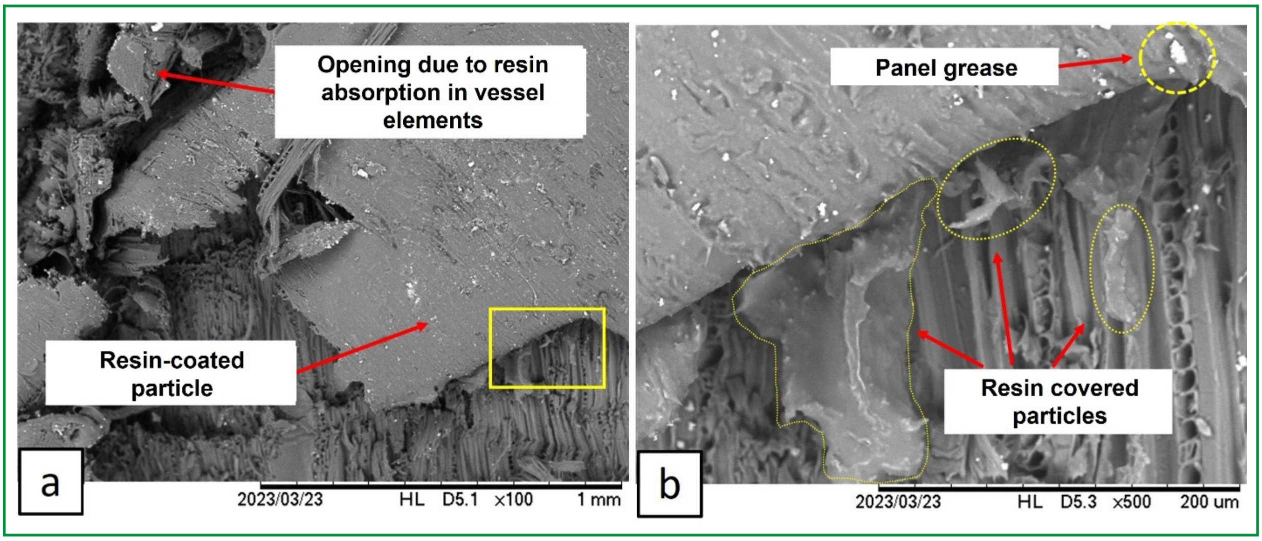
After AW, the mechanical results of PU-Castor HPB were superior to those of UF HPB, however, these materials do not meet the normative recommendations of ANSI A208.1:2016, indicating that their use should be restricted to dry environments.

Low-density HPB from *Dendrocalamus asper* and sugarcane bagasse (PU: 10%; 650 kg.m^{-3}) showed IB of 0.77 and 0.15 MPa, respectively (Brito *et al*., 2020). Better results were observed in low-density HPB from *Cunninghamia lanceolate* (PU:4%; 500 kg.m^{-3}) with IB equal to 0.9 MPa (Chen; Tai, 2018). The results of this study indicated that *T. vulgaris* HPB had AW values above 0.8 MPa, meeting the ANSI A208.1:2016 and ISO 16893:2016 recommendations.

3.3 Scanning electron microscopy

Figures 3-6 show images of the microstructure of HPB with UF and PU-Castor before and after the AW test. The images show the vessel elements at the ends of the particles (Figure 3a) and the adhesion of the resin to the adjacent particles can be seen at the lateral edges of the particles (Figure 3b).

Figure 3 – SEM images of *T. vulgaris* HPB agglomerated with UF resin

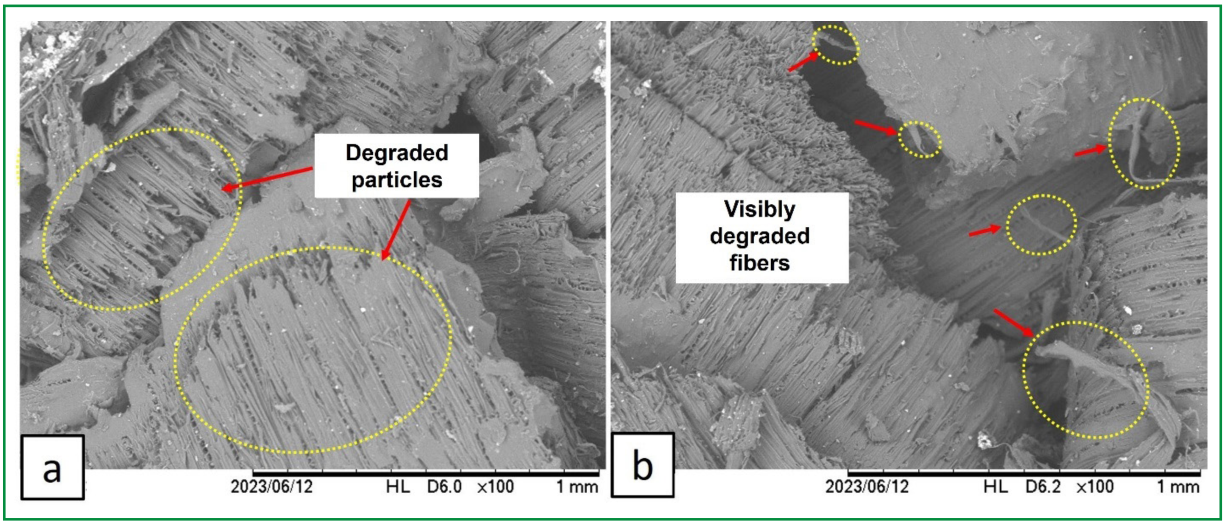


Source: Authors (2024)

In where: (a) magnification (100x); (b) magnification (500x).

Figure 4 shows the degradation of the UF panel, which justifies the MOR and MOE results. However, the reduction in MOE after AW indicates that the degradation of the panel was very severe, as it is not possible to see a layer of surface resin and some libriform fibers have been separated from the particles (Figure 4a-b).

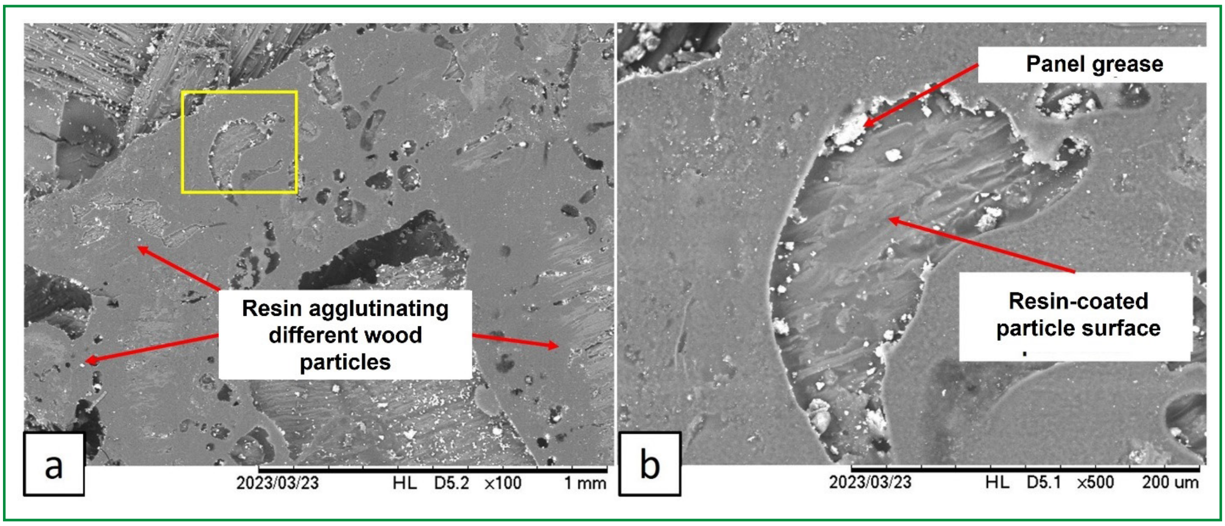
Figure 4 – SEM images of *T. vulgaris* HPB agglomerated with UF resin after accelerated weathering (AW)



Source: Authors (2024)
Where: (a) magnification (100x); (b) magnification (500x).

Figure 5 shows that the resin has not been completely absorbed by the particles and curing has taken place on the surface. This type of configuration allows for continuous adhesion throughout a region.

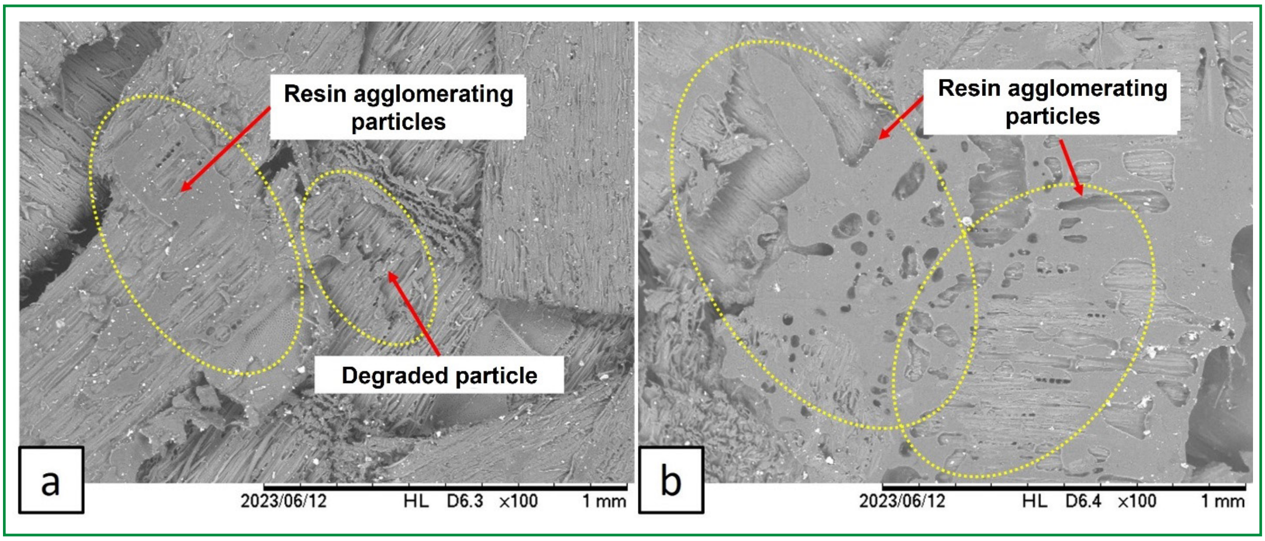
Figure 5 - SEM images of *T. vulgaris* HPB agglomerated with PU-Castor resin



Source: Authors (2024)
Where: (a) magnification (100x); (b) magnification (500x).

Figure 6 displays that the surface of *T. vulgaris* HPB agglomerated with PU-Castor was degraded less intensely than UF HPB and shows the preservation of PU-Castor resin on the particles (6b) after the weathering cycles. This result may explain the less significant variation in the mechanical properties of panels produced with PU-Castor resin compared to ones produced with UF resin.

Figure 6 – SEM of *T. vulgaris* panel agglomerated with PU-Castor resin after accelerated weathering (PU AW)



Source: Authors (2024)

Where: (a) magnification (100x); (b) magnification (500x).

4 CONCLUSIONS

This study evaluated *Tachigali vulgaris* wood's physical and chemical properties and the physical and mechanical properties of homogeneous *T. vulgaris* wood agglomerated with urea-formaldehyde resins (UF) and castor oil-based polyurethane (PU-Castor). The physical and chemical results indicate that the 9-year-old *T. vulgaris* wood can be applied to produce particleboards. Analyses of the physical and mechanical results of the homogeneous *T. vulgaris* low-density wood particleboards indicate their use for internal applications such as door cores.

Analyses of the panels by scanning electron microscopy revealed differences in the resin adhesion to the particles and particle surface degradation after accelerated weathering, illustrating the occurrence of panel degradation after heat and humidity cycles, thus justifying the variations in the mechanical results. *T. vulgaris* wood from reforestation has characteristics that enable it to be used as a raw material to produce homogeneous particleboards.

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