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Evaluation of conventional and microwave drying of tropical Amazonian wood indicated for the manufacture of EGP (Edge Glued Panels)

Avaliação da secagem convencional e por micro-ondas de madeiras tropicais amazônicas indicadas para fabricação de painéis EGP (*Edge Glued Panels*)

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Wood drying is an important process in the forestry industry since the quality of manufactured products is directly related to the moisture content of the raw material. In the Amazon region, the complexity of the drying process is accentuated by the vast diversity of species, each with distinct technological profiles. This study focused on the evaluation of oven and microwave drying of five species of tropical Amazonian wood: Angelim-pedra (*Hymenolobium pulcherrimum*), Angelim-vermelho (*Dinizia excelsa*), Breu-vermelho (*Protium puncticulatum*), Murici (*Byrsonima crispa*) and *Piaozinho* (*Micrandropsis scleroxylon*), recommended for the production of laterally glued panels (EGP). Samples of these species were collected in areas of terra-firme forest in Amazonas, Brazil, and subjected to oven-dry for 25 days and in semi-industrial microwaves for 120 minutes (100 ± 3 °C). Additionally, analyses of the wood properties were carried out. The results indicate that microwave drying surpassed the efficiency of oven-dry. Specifically, Breu-vermelho and Murici wood presented the best results in terms of moisture content. This drying method not only significantly reduced the drying time but also resulted in defect-free wood. Furthermore, the energy consumption was lower compared to conventional drying. The physical-mechanical properties of wood showed a significant correlation with heat-treatment. In particular, microwave drying proved to be effective in obtaining standard moisture for manufacturing EGP panels and could be an advantageous alternative for the region.
Keywords: Amazonian woods, microwave, technological properties.

A secagem da madeira é um processo crucial na indústria florestal, uma vez que a qualidade dos produtos manufaturados está diretamente relacionada ao teor de umidade da matéria-prima. Na região amazônica, a complexidade do processo de secagem é acentuada pela vasta diversidade de espécies, cada uma com perfis tecnológicos distintos. Este estudo concentrou-se na avaliação da secagem em estufa e em micro-ondas de cinco espécies de madeiras tropicais amazônicas: Angelim-pedra (*Hymenolobium pulcherrimum*), Angelim-vermelho (*Dinizia excelsa*), breu-vermelho (*Protium puncticulatum*), Muricy (*Byrsonima crispa*) e Piãozinho (*Micrandropsis scleroxylon*), recomendadas para a produção de painéis colados lateralmente (EGP). As amostras dessas espécies foram coletadas em áreas de floresta secundária de terra firme no Amazonas, Brasil, e submetidas à secagem em estufa por 25 dias e em micro-ondas semi-industrial por 120 minutos a 100 ± 3 °C. Adicionalmente, foram realizadas análises das propriedades das madeiras. Os resultados indicam que a secagem por micro-ondas superou a eficiência da secagem em estufa. Especificamente, as madeiras de Breu-vermelho e Murici apresentaram os melhores resultados em termos de teor de umidade. Este método de secagem não apenas reduziu significativamente o tempo de secagem, mas também resultou em madeira livre de defeitos. Além disso, o consumo de energia foi menor em comparação com a secagem convencional. As propriedades físico-mecânicas das madeiras mostraram uma correlação significativa com o tratamento térmico. Em particular, a secagem por micro-ondas demonstrou ser eficaz na obtenção de umidade padrão para a fabricação de painéis EGP, destacando-se como uma alternativa vantajosa para a região.
Palavras-chave: madeiras amazônicas, micro-ondas, propriedades tecnológicas.

1. INTRODUCTION

Amazon is renowned for harboring the world's greatest stretch of tropical forest. Cardoso et al. [1] recorded in the region 14,003 species, 1,788 genera, and 188 botanical families. Among the most frequent taxon's identified are Fabaceae, Myrtaceae, Lauraceae, Annonaceae, and Euphorbiaceae. The lack of technological knowledge of forest species with timber potential in the Amazon makes it difficult to indicate new woods on the market, which could generate a real scarcity of traditional species in the near future [2].

Wood has exceptional properties when compared to other types of materials, e.g., great mechanical strength, minimal energy required for manufacturing, and its status as a renewable resource. Beyond its utilitarian aspects, wood boasts attractive aesthetics, featuring a spectrum of colors and textures. This combination of attributes aroused significant newsworthy in the international market, leading to an increase in studies in the area of wood technology [3, 4]. The drying process is a fundamental step in technological research, given its influence on the production and finished product. Drying improves workability and dimensional stability, increasing mechanical resistance, and is considered the first and most efficient method of wood preservation, which inhibits the action of xylophagous organisms, such as fungi and insects [5, 6].

Drying is a combined heat and mass transfer mechanism. In the oven process (conventional), the removal of free water in the piece of wood (moisture) occurs slowly, where the transport of heat occurs in the external direction to the innermost layers of the wood, requiring a forced ventilation system for process efficiency. In the microwave system, electromagnetism acts in the production of heat waves, which causes the vibration of the polar molecules of water in the wood to be immediately expelled from its interior by the osmotic pressure that the heat entails. In this drying, the process takes less time, consequently lowering energy costs and providing, in general, a more uniform drying with reduced defects in the piece of wood [7, 8].

The quality of wood for the manufacture of certain engineered products (MDL, CLT, EGP panels, among others) needs to combine attributes such as medium density, low concentration of extractives, medium roughness, and mainly low moisture, and for edge glued panels (EGPs), the content acceptable minimum is 12%. Bila et al. (2016) [9] and Araújo et al. (2019) [10] assessed the use of Amazon wood for EGP panels and found similar results regarding the standard of end product, considering that the properties were enhanced by drying the wood.

Studies on new wood drying processes in Brazil are scarce and/or focused on some species, such as Cavalcante et al. (2016) [7], who proposed a drying program for *Nectandra cuspidata* (Louro-preto), and Talgatti et al. (2020) [11], who evaluated different temperature powers in a microwave system to remove water from *Eucalyptus tereticornis* (Eucalipto) and *Hovenia dulcis* (Uva-japonesa).

Drying wood quickly and accurately is essential for the timber sector in the Amazon, mainly in the commercial sense of developing quality products, which considers the low moisture content, generating numerous technological and financial advantages. This research aimed to evaluate oven and microwave drying of tropical Amazonian wood, Angelim-pedra (*Hymenolobium pulcherrimum*), Angelim-vermelho (*Dinizia excelsa*), Breu-vermelho (*Protium puncticulatum*), Murici (*Byrsonima crispa*) and Piaozinho (*Micrandropsis scleroxylon*), which present technological potential for the manufacture of EGP panels.

2. MATERIALS AND METHODS

2.1 Study and sampling area

The surveyed woods were collected in a tropical forest managed at the Experimental Station of Tropical Silviculture/INPA/MCTI at geographic coordinates 2°37' to 2°38' S and 60°09' to 60°11' W (Amazonas/Brazil). The region experiences a Köppen-Geiger Af climate, characterized by temperatures ranging from 19 to 39 °C. The annual precipitation in this area measures 2,407 mm (average) [12, 13].

A total of 15 trees were selected for the study, based on the dendrometric characteristics of the species, from an inventoried plot (subplots of 100 × 4, 25 m) and defined in the INCT Amazonian Woods project (MCTI/CNPq/FAPEAM). Species selection was based on the individuals with the highest frequency in the area (Table 1), and anatomical identification was performed at the Laboratory of Identification and Anatomy of Wood (INPA/Brazil). For the drying tests, specimens were made with dimensions of 600 × 60 × 25 mm, and for physical-mechanical characterization, specimens were made with dimensions of 30 × 20 × 20 mm (density) and 300 × 20 × 20 mm (modulus of elasticity and rupture). Finally, 60 mesh sawdust was obtained for chemical analysis (Figure 1).

Table 1: Selected forest species from the managed area.

Scientific name (Family)	**Popular name**	**No. trees**	**General observations of the trunk and wood**
Byrsonima crispa A. Juss (Malpighiaceae)	**Murici**	3	Straight trunk indistinct heartwood/sapwood with light brown coloration and distinct growth rings.
Dinizia excelsa Ducke (Fabaceae)	**Angelim-vermelho**	3	Straight, cylindrical trunk, slightly distinct heartwood/sapwood with reddish-brown coloring, distinct growth rings.
Hymenolobium pulcherrimum Ducke (Fabaceae)	**Angelim-pedra**	3	Straight trunk, distinct heartwood/sapwood, yellowish brown color with dark brown (heartwood) and cream (sapwood) spots. Distinct growth layers, individualized by darker tangential fibrous zones.
Micrandropsis scleroxylon W. Roch, (Euphorbiaceae)	**Piaozinho**	4	Straight trunk, distinct heartwood/sapwood with a larger portion of heartwood, where the presence of a hollow can be observed, the color of the sapwood is light brown and heartwood dark brown, growth rings difficult to visualize.
Protium puncticulatum J. F. Macbr (Burseraceae)	**Breu-vermelho**	2	Straight trunk, distinct heartwood/sapwood, light brown (sapwood) to dark brown (heartwood) coloration, little distinct growth rings and portion of oil-resin stains.

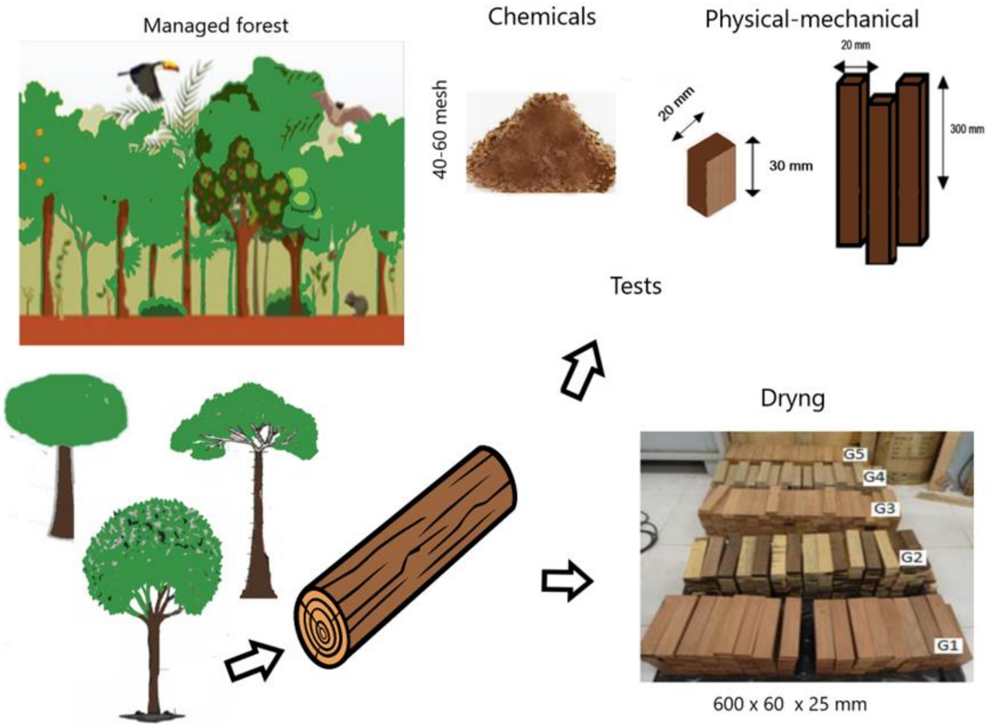

Figure 1. Scheme of the sampling and preparation of specimens.

2.2 Drying test

Conventional drying was carried out in an electric oven (105 ± 2 °C) for a period of 25 days, and all samples were dried in a single load. In the EasyDry microwave system (Wu-M-Gobler, frequency 915 MHz; potency 50 kW), each species was dried separately, given the need to insert the basic density value of the species in the operating software. A total of 250 samples divided into 50 replications per species were used in the tests, and the moisture % of the tested samples was measured using an electrical sensor (Digisystem-DUC 2050). After drying, the wood was stored in a climatic chamber (20 ± 2 °C and relative humidity of 65 ± 5%), and at the end, the moisture % was tabulated, and a visual analysis was performed on the samples.

2.3 Technological characterization

The tested woods have the potential to indicate the manufacture of EGP panels; however, there is information regarding the physical-mechanical and chemical properties. Therefore, for a complete evaluation, the following variables were determined.

2.3.1 Apparent density (AD)

The AD was assessed by the stoichiometry method [14], and a total of 50 samples (10 replicates per species) were evaluated:

$$AD = m/V$$

m = weight (g) and V = volume (cm^3).

2.3.2 Basic density (WD)

The WD is the ratio between the dry weight of the wood and the saturated volume [14]. The samples (n=50) were saturated in water to determine the volume, then the dry mass was obtained, and the calculation proceeded:

$$WD = W_d/Vs$$

Wd = dry mass (g) and Vs = volume saturated (cm^3).

2.3.3 Extractives (TE)

The 60-mesh sample was extracted with ethanol-toluene (1:2) in Soxhlet for approximately 8 hours [15]. In the end, the following calculations were performed:

$$TE\% = (W_f - W_i)/W_d \times 100$$

W_i = starting mass of the dry flask (g), W_f = mass of the flask with extractives (g) and W_d = dry mass of sample (g).

2.3.4 Klason lignin

The extractive-free sample was treated with H_2SO_4 (72%) for 6 hours, and at the end, the material was washed, dried, and weighed [15]. The insoluble lignin % was determined as follows:

$$\text{Klason lignin } \% = W_2/W_1 \times 100$$

W_1 = starting sample mass (g), and W_2 = dry mass of lignin obtained (g).

2.3.5 Ash

The 60-mesh sample was carbonized in a muffle furnace at 580-600 °C [15]. The ash % was assessed by the equation:

$$\text{Ash\%} = (W_{ash}/W_d) \times 100$$

W_{ash} = ash mass (g), and W_d = dry sawdust mass (g).

2.3.6 Dynamic modulus of elasticity (MOED)

In the method used, the voltage wave variables are extracted from the stress wave timer device [10] and calculated by the following equation:

$$\text{MOED} = (L/t)2 \times D/g \times 10^{-5}$$

L = sample length (m), t = wave propagation time (s), D = sample density (kg/m^3) and g = gravity acceleration (m/s^2).

2.3.7 Modulus of elasticity (MOE) and rupture (MOR)

Static flexion tests were performed with three repetitions (specimens 20 × 20 × 300 mm) for each individual [16]. Chemometric models [17] were constructed employing traditional methodologies (MOE and MOR) alongside NIR spectra, with the outcomes expressed in megapascals (MPa).

2.4 Data analysis

The raw drying data and properties underwent statistical analysis to ensure compliance with the assumptions of normality, homogeneity, and independence of residues. Analysis of variance (ANOVA) and Tukey's test at a 5% significance level were employed to compare treatments and evaluate the impact of both species and drying methods. In the final, a Pearson correlation matrix was estimated between drying types/properties using the PAST 4.08 program.

3. RESULTS AND DISCUSSION

3.1 Amazonian wood drying

The artificial drying of wood in the Amazon region requires knowledge of the raw material, given the variability of species with different technological profiles. The drying process plays a key role in the issue of wood quality, which improves certain properties of the material. The woods of *Byrsonima crispa*, *Dinizia excelsa*, *Hymenolobium pulcherrimum*, *Micrandropsis scleroxylon* and *Protium puncticulatum*, which occur in the Amazonian tropical forest, were submitted to a drying treatment in an oven (forced air circulation) and industrial microwave until they reached constant moisture, and the results are shown in Figure 2. In conventional drying (oven), the moisture content ranged from 17.58 (*B. crispa*) to 18.48% (*D. excelsa*), showing less efficiency in relation to microwave drying, which presented a moisture of 12.72 (*B. crispa*) at 14.08% (*P. puncticulatum*), and in microwaves, the moisture determined was 25.47% (average) lower, and the average drying time was approximately 120 minutes.

The conventional drying results obtained in this research were superior to those of other studies with tropical woods. Klitzke et al. (2008) [5] tested kiln drying methods with wood from *Hymenaea courbaril* (Jatobá) and found 38.48% final moisture. Silveira et al. (2013) [18] reached much higher values of moisture, approximately 45% for *Lecythis poiteaui* (Jarana-amarela) and *Mezilaurus itauba* (Itaúba) woods. Medeiros et al. (2021) [4] found moisture values ranging from 28.48% for *Bowdichia nitida* (Sucupira-amarela) to 35.99% for *Piptadenia suaveolens*

(Timborana). The average moisture content of wood treated in the microwave in the present study was 13.38%, which is similar to those recorded in drying studies. Cavalcanti et al. (2016) [7] obtained a moisture content of 13.99% at the end of drying *Nectandra cuspidata* wood. In another study with Amazonian woods, Cavalcante and Naveiro (2014) [19] found an average value of 14.76% for the species *Dinizia excelsa* (Angelim-vermelho), *Astronium lecointei* (Muiracatiara) and *Cariniana micrantha* (Tauari-vermelho). Talgatti et al. (2020) [11], using the drying of wood from plantations (*Eucalyptus tereticornis* and *Hovenia dulcis*), obtained very efficient results with a moisture of 12.60%.

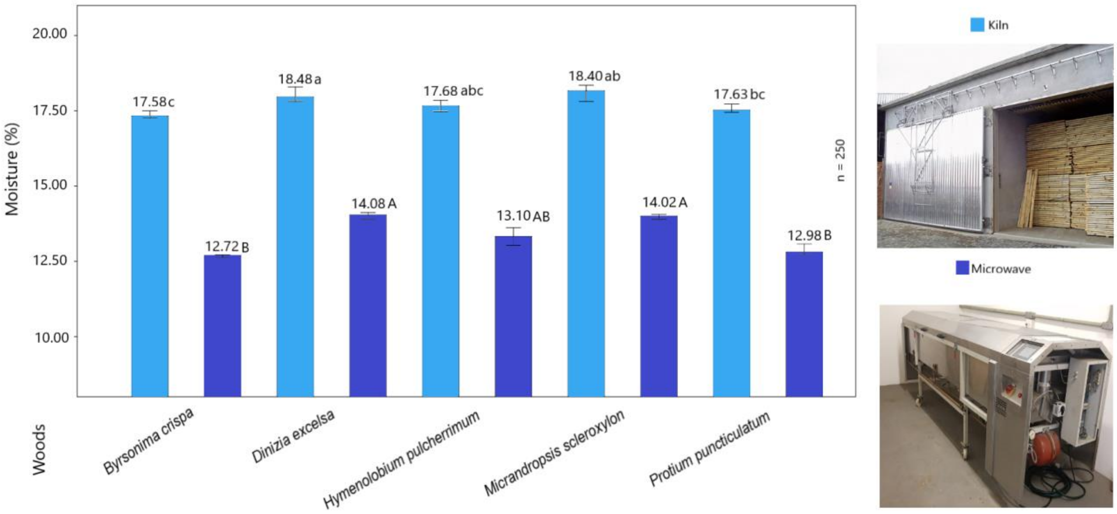

Figure 2. Results of moisture in the woods studied. Bar = standard error ± 1% represents the 99% confidence interval. Groups designated by identical letters within the column exhibit no statistically significant differences according to Tukey's test at the 5% probability level.

Wood, as a raw material for manufacturing panels, must have a maximum moisture of approximately 12%, and higher values can compromise the bonding line as well as the quality of the product [20, 21]. Therefore, the results obtained by the kiln method for the woods studied here were not satisfactory in drying wood for EGP manufacture. However, drying via microwave enabled the wooden pieces to have greater stability in equilibrium moisture (hygroscopic water); finally, the dried samples did not show defects such as collapse, cracks, and even the phenomenon called "overheating" and/or carbonization of the wood according to reports in the literature [19, 22]. This effect can be potentiated mainly by the chemical composition of the wood and the extractives [4, 23].

The microwave process is not so new, and records indicate the use of this technology in World War II. Drying wood using microwaves is recent in Brazil and lacks technological research to meet the needs of the productive sector. Microwaves allow instant heating of the matrix to be treated, as the beam of electromagnetic energy acts quickly on damp wood. In addition, it has a heating mechanism different from conventional drying, which provides an accelerated drying process, reducing the time to obtain the dry mass and consequent determination of the moisture content [8, 11]. Microwave studies of Amazonian tropical forest species are essential for the technological advancement of the region, combined with sustainable forestry production with low waste production.

3.2 Chemical and physical-mechanical properties of Amazonian woods

In many technological studies on wood, the chemical composition is often overlooked, despite its various correlations with the physic-mechanical characteristics of wood. These correlations have significant implications for industrial processes, including effects on moisture content [3, 4, 23]. The chemical and physical-mechanical properties results are shown below for a complete evaluation of the wood species. In Figure 3, the contents of extractives and lignin are shown, with *D. excelsa* having the highest concentration of extractives (24.14%). *B. crispa* had the lowest extractive content (2.46%) and the highest concentration of fixed mineral residue (ash) (0.51%), while *M. scleroxylon* and *B. crispa* had the highest lignin content (34.30 and 32.52%, respectively). High concentrations of extractives and lignin can indicate high-density wood, which initially takes longer to dry [12, 23], and the presence of minerals (tyloses), waxes, and resins can fill the parenchyma and vessels in the cell wall, making it difficult to leave hygroscopic water. Certain extractives can also influence the wood combustion process, and even when used for panel manufacturing, they can compromise the product's glue line [9, 10, 20].

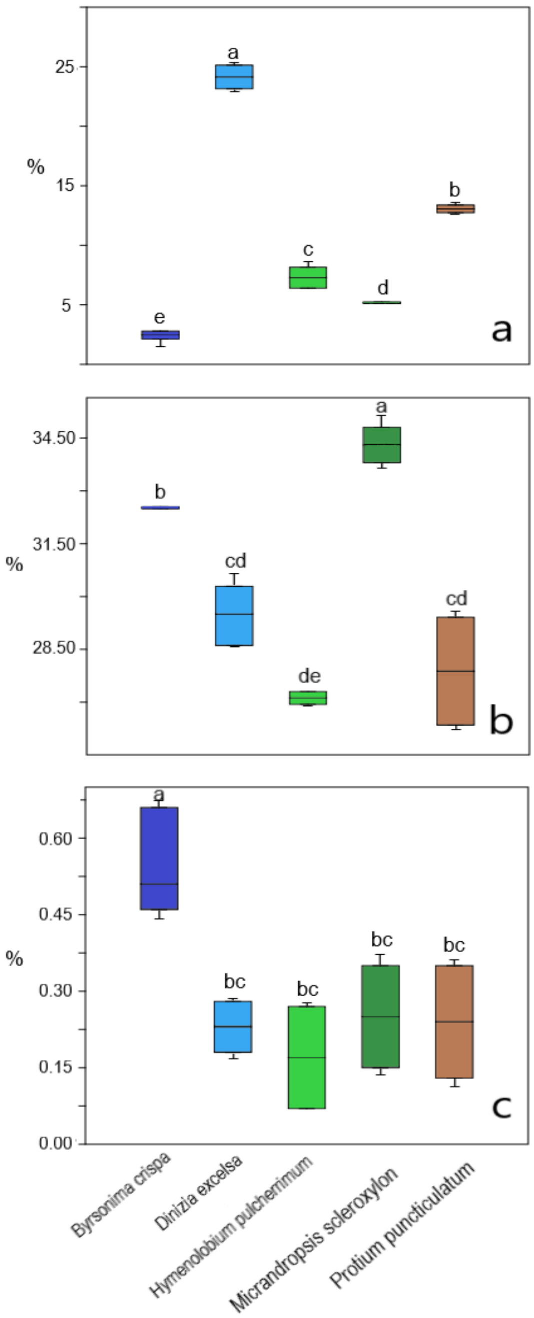

Figure 3. Results of the chemical properties of the studied woods: a – Extractives; b – Lignin; c – Ash. Bar = standard error ± 1% represents the 99% confidence interval. Groups designated by identical letters within the column exhibit no statistically significant differences according to Tukey's test at the 5% probability level.

Table 2 shows the results of the physics-mechanical determinations for the studied woods. The apparent density (AD) values exhibited a range from 0.76 (*B. crispa*) to 1.18 g/cm^3 (*M. scleroxylon*), while the basic density (WD) varied from 0.43 (*B. crispa*) to 0.98 g/cm^3. Importantly, these values fall within the anticipated range for tropical wood [2, 12]. In general, the results of the determination of AD are greater; this behavior occurs due to the measurement of the mass of the sample obtained in ambient humidity, and at WD, the mass is anhydrous. Ruffinatto et al. (2015) [24] proposed a new classification of hardwood density: low density < 0.40, medium density 0.40–0.75, and high density > 0.75 g/cm^3. Except for *M. scleroxylon* and *D. excelsa*, the other species were classified as medium density, where this attribute is ideal for indicating wood for the manufacture of panels [10, 21]. The wood employed for the fabrication of EGP panels in Brazil currently encompass a range of low to medium densities, e.g., *Pinus elliottii* and *P. taeda* (Pinheiro) with a density of 0.32-0.34 g/cm^3, *Eucalyptus grandis* (Eucalipto) with 0.39-0.51 g/cm^3, *Tectona grandis* (Teca) ranging from 0.48-0.64 g/cm^3, and *Ocotea porosa* (Imbuia) 0.63 g/cm^3 [4, 25].

The mechanical variables of wood MOED (dynamic modulus of elasticity), MOE (modulus of elasticity) and MOR (modulus of rupture) were also evaluated, and *M. scleroxylon* presented elastic resistance (MOED and MOE) > 14,000 MPa. This value was significantly higher than that of the other woods, while for *B. crispa* and *P. puncticulatum*, the strength was < 12,000 MPa. For the MOR, the highest value was also for *M. scleroxylon* (148.90 MPa), and the lowest breaking strength was for *B. crispa* (107.60 MPa) and *H. pulcherrimum* (116.85 MPa). Understanding the physics-mechanical properties of wood facilitates a more informed and efficient utilization of this resource. In studies focusing on wood quality, basic density (WD) is intricately linked to mechanical resistance, positioning it as a reliable predictor of both wood strength and stiffness [3, 18].

Table 2. Results of the physical-mechanical determination of the research species.

Woods	WD*	AD*	MOED**	MOE**	MOR**
Byrsonima crispa	0.43cd	0.76b	11,480b	11,350c	107.60c
Dinizia excelsa	0.98a	1.14ab	14,109a	15,880a	135.34a
Hymenolobium pulcherrimum	0.59c	0.89ab	11,656 b	13,830b	116.85b
Micrandropsis scleroxylon	0.80b	1.18 a	14,070a	15,130a	148.90a
Protium puncticulatum	0.46cd	0.98ab	11,175b	12,470c	122.72b

*g/cm^3; ** MPa; WD = basic density. AD = apparent density; MOED = dynamic modulus of elasticity; MOE = modulus of elasticity and MOR = modulus of rupture in static bending. Groups designated by identical letters within the column exhibit no statistically significant differences according to Tukey's test at the 5% probability level.

Pearson's analysis was used to evaluate the relationship between drying results and the technological properties determined to understand possible correlations (Figure 4). Correlation evaluates both the way and the degree of the linear relationship between quantitative variables. In statistical terms, two variables are considered associated when they show similarities in the distribution of their scores. Specifically, this association can be understood in terms of variance sharing within its frequency distribution [10]. The physical-mechanical variables showed significance ($p > 0.01$ and $p > 0.05$) and high correlation with the drying processes studied, namely, for kiln drying: MOED (0.97) > MOR (0.91) > AD (0.90) > MOE (0.89) > WD (0.84). In the microwave, AD, MOED, and MOR (0.94) > MOE (0.90) > WD (0.85).

Wood is a complex tissue composed of three types of cells: vessels, fibers, and parenchyma. The distinct structural characteristics and proportions within this matrix directly influence the physics-mechanical properties of the wood. Vessels play an important role in water transport, and species characterized by frequent vessels with large diameters are traces of low-density wood with high moisture content and dimensional instability. Species with a high concentration of cellulose (fibers) generally have the greatest elasticity (MOE). In the parenchyma cells, responsible for storing and transporting nutrients, the cell's influence extends to the extractive content, consequently impacting the moisture content and WD of the wood [12, 26].

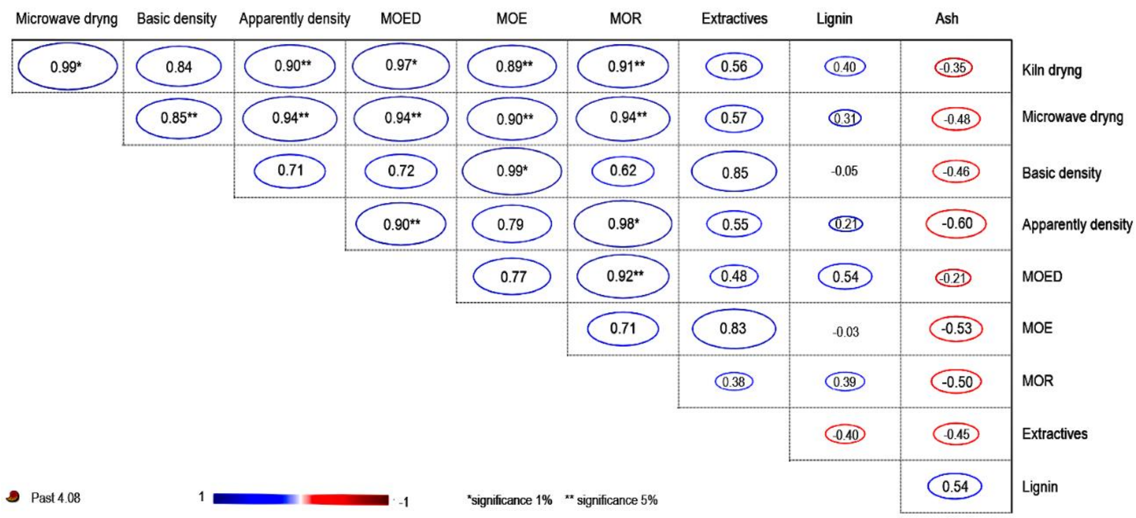

Figure 4: Result of Pearson's analysis based on the correlation between the chemical and physical-mechanical properties of the wood studied. MOED = Dynamic modulus of elasticity; MOE = Modulus of elasticity and MOR = Modulus of rupture in static bending.

One of the most important operations in the wood processing industry is drying. Knowledge about techniques that make it possible to reduce drying time and simultaneously preserve the characteristics of the wood are the keys to reducing energy consumption in the process, leading to cost reductions and leveraging profits [11]. The process of removing free water from the wood and maintaining the moisture balance minimizes the effects of dimensional movement, resulting in a higher-quality material [16].

4. CONCLUSION

The results obtained in conventional drying were less efficient than those obtained in the microwave process. *Byrsonima crispa* (Murici) and *Protium puncticulatum* (Breu-vermelho) wood treated in the microwave showed the best results for moisture. This system significantly reduced the drying time, the wood did not present defects and, in general, its energy consumption was lower. The physical and mechanical properties showed a high correlation with the tested drying conditions. Microwave drying showed satisfactory results for obtaining the ideal moisture content for bonding the EGP panels.

5. ACKNOWLEDGMENTS

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