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MATERIALS TECHNOLOGY - ORIGINAL ARTICLE

Surface properties of tropical woods produced in an Agroforestry System in Amazonia

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ABSTRACT

Agroforestry systems (AFS) are an alternative for combining environmental services and food production with tree cultivation, but there is a lack of published studies on their wood quality. This study aimed to evaluate the surface properties of African mahogany, Freijó, Paricá, and Teak woods produced in AFS in the Amazonia. Anatomical characteristics, FTIR spectroscopy, colorimetry, roughness, contact angle, and wettability in the longitudinal-radial and tangential planes were evaluated. The woods presented non-uniform diffuse porosity, with solitary and multiple vessels, except for Teak, which showed semi-porous ring porosity. Woods rays were multiseriate and heterogeneous, except for Teak, whose rays were homogeneous. The largest average vessel diameter was observed in Teak (~180 µm) and the smallest in A. mahogany (~98 µm). The frequency of vessels was higher in A. mahogany (~12 vessels mm^{-1}) and lower in Paricá (~5.5 vessels mm^{-1}). In FTIR, A. mahogany showed intense peaks at 1,193 cm^{-1} (triterpenoids), while Teak had peaks at 1,700 and 1,145 cm^{-1} (tectoquinone). A. mahogany and Teak presented pinkish and yellowish-olive colors, respectively, while Paricá and Freijó had pinkish-grey tones. Teak presented the lowest roughness and A. mahogany the highest, while Freijó and Paricá exhibited intermediate values. The highest contact angle was recorded in A. mahogany (~115° for urea-formaldehyde and ~70° for varnish), while the lowest was observed in Paricá. The evaluated woods have surface properties suitable for furniture and boards, and fine sandpaper is recommended for higher-quality finishes.

KEYWORDS: African mahogany; teak; tropical wood; wood anatomy; wood roughness

Propriedades da superfície de madeiras tropicais produzidas em Sistema Agroflorestal na Amazônia

RESUMO

Os sistemas agroflorestais (SAFs) configuram-se como alternativa para combinar serviços ambientais e produção de alimentos com o cultivo de árvores, no entanto, estudos relativos às características da madeira são escassos na literatura. Este estudo teve como objetivo avaliar as propriedades de superfície das madeiras de mogno africano, freijó, paricá e teca produzidas em SAFs na Amazônia. Foram avaliadas as características anatômicas, a espectroscopia FTIR, a colorimetria, a rugosidade, o ângulo de contato e a molhabilidade nos planos longitudinal-radial e tangencial. As madeiras apresentaram porosidade difusa não uniforme, com vasos solitários e múltiplos, exceto a teca, que apresentou porosidade anelar semiporosa. Nas madeiras, os raios foram multisseriados e heterogêneos, com exceção da teca, cujos raios foram homogêneos. O maior diâmetro médio de vaso foi observado na teca (~180 µm) e o menor no mogno africano (~98 µm). A frequência de vasos foi maior no mogno africano (~12 vasos/mm) e menor no paricá (~5,5 vasos/mm). No FTIR, o mogno apresentou picos intensos a 1193 cm^{-1} (triterpenóides), enquanto a teca apresentou picos a 1700 e 1145 cm^{-1} (tectoquinona). O mogno e a teca apresentaram cores rosadas e amarelo-oliva, respectivamente, enquanto o paricá e o freijó apresentaram tons cinza-rosados. A teca apresentou a menor rugosidade e o mogno africano a maior, enquanto o freijó e o paricá apresentaram valores intermediários. O maior ângulo de contato foi registrado em mogno africano (~115° para ureia-formaldeído e ~70° para verniz), enquanto o menor foi observado em paricá. As madeiras avaliadas têm propriedades de superfície adequadas para móveis e tábuas, e recomenda-se o uso de lixa fina para acabamentos de maior qualidade.

PALAVRAS-CHAVE: mogno africano; teca; madeira tropical; anatomia da madeira; rugosidade da madeira

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INTRODUCTION

Traditional agricultural practices, combined with illegal logging and the reduction of natural forests, have generated significant environmental impacts, including river silting and threats to biodiversity. This situation has intensified discussions among governments and the scientific community seeking alternatives to conventional production systems. Among the most promising solutions are agroforestry systems (AFS), which integrate forest and agricultural species, enabling carbon capture, income diversification, food security, and sustainable wood production under conservation-oriented management (Mascarenhas 2015).

This highlights the need to intensify research in this area, especially on the forestry component of AFS, which has been the subject of limited studies, particularly regarding the technological properties of tropical woods. In addition, Minini et al. (2024) reported that, although studies are still limited, some research has highlighted the potential of tropical species for cultivation in AFS, including African mahogany (*Khaya senegalensis*), Freijó (*Cordia goeldiana*), Paricá (*Schizolobium amazonicum*), and Teak (*Tectona grandis*).

With an estimated 37,000 hectares planted in Brazil and notable adaptability (Reis et al. 2019), A. mahogany has attracted attention for its suitability in furniture manufacturing and both light and heavy construction. Its plantation potential also makes it a viable substitute for Amazonian mahogany (*Swietenia macrophylla*), whose exploitation is legally restricted and affected by *Hypsipyla grandella* (Mascarenhas et al. 2021a). At 20 years, A. mahogany can yield nearly 250 m^3 ha^{-1}, with sawn wood valued at about 270 US\$ m^{-3}. Freijó, widely used in furniture and construction, can reach 297 m^3 ha^{-1} at 19 years in AFS, with sawn wood worth roughly 140 US\$ m^{-3} (Mascarenhas et al. 2021b). Regarding Paricá, it is a fast-growing Amazonian species used in plantations for restoring degraded areas and supplying wood to the laminated panel industry, whose products can be marketed at around 553 US\$ m^{-3} (ITTO 2025). With a planted area in Brazil exceeding 90,000 hectares (IBÁ 2025), Paricá can reach, at 6 years old, volumes of about 161 m^3 ha^{-1} in monocultures and 135 m^3 ha^{-1} in crop-livestock-forest integration systems (Silva and Sales 2018). As for Teak, the planted area in Brazil exceeds 80,000 hectares, and the species has garnered interest due to its fast growth and the high value of its wood (IBÁ 2025). Studies report that teak at 25 years old can reach volumes of around 350 m^3 ha^{-1}, with blockwood market value around 500 US\$ m^{-3} (Reis et al. 2023).

The information presented highlights the strong potential for cultivating these species in AFS in the Amazonia, contributing to income generation and production diversification, particularly for small rural producers who aim to supply high-value raw materials to the timber industry. Studying wood properties is essential because it supports the technical feasibility of AFS and guides management practices according to the intended uses of the wood produced, such as furniture and interior finishing. In AFS, tree growth dynamics differ from monocultures, since species vary in size, age, spacing, successional status, and resource requirements. Despite this, no studies have examined how AFS conditions influence wood surface properties, which depend on anatomical structure, chemical composition, roughness, liquid spreading, and colorimetric characteristics (Laina et al. 2017). These attributes affect how liquids such as varnishes interact with the wood and influence finishing processes, including sanding and coating, as well as workability, adhesion in glued components, and panel production (Iwakiri and Trianoski 2020). Despite the growing interest in cultivating A. mahogany, Freijó, Paricá, and Teak in agroforestry systems, information on how this environment affects their surface properties remains limited.

Considering the hypothesis, supported by information from literature, that wood produced in AFS is suitable for uses equivalent to that from monocultures or natural forests, and that, depending on the anatomical plan, variations in surface parameters may occur, it is essential to conduct studies that provide data in this context. The objective of this work was to evaluate the physical, chemical, anatomical, colorimetric, and liquid spreading properties of the surface of A. mahogany, Freijó, Paricá, and Teak wood produced in AFS.

MATERIAL AND METHODS

Characterization of the study site and tree selection

The trees of the species A. mahogany, Freijó, Paricá, and Teak were cultivated in double rows at a spacing of 5.0 × 2.5 m (800 trees ha^{-1}) in an AFS with an area of 1 ha (80 × 125 m), implemented in 1996 using seedlings. The AFS is located on the premises of the experimental station of the Executive Commission of the Cocoa Farming Plan in Ouro Preto do Oeste, central-western region of the state of Rondônia, northern Brazil (altitude 249 m, latitude 10°43'6.36" S and longitude 62°13'22.17" W). The climate in the region is classified as tropical monsoon (Am – Köppen-Geiger), with an average annual temperature of ~27 °C, annual rainfall of ~2,150 mm, and relative humidity around ~85%.

The 19-year-old trees of the four species were harvested, and sampling was performed following the guidelines established in ASTM D 5536 (ASTM 2017). The phytosanitary conditions of the trees were also considered, verifying the absence of defects, bifurcations, tortuosity, or inclination. Logs measuring 1.5 m in length were removed from each tree from the base of the trunk, which was sent to a sawmill for splitting to make the test specimens.

For each species evaluated, three trees were harvested, and four samples were obtained from each tree, totaling twelve test specimens composed exclusively of heartwood, with sapwood and pith excluded. For all tests, the longitudinal-radial and longitudinal-tangential planes of the test specimens were regularized with 50-grit sandpaper. Studies carried out by Mascarenhas et al. (2021a), Mascarenhas et al. (2021b), Mascarenhas et al. (2021c), and Mascarenhas et al. (2021d) provide information on the chemical components of wood. Table 1 presents basic information on the trees used in this study.

Anatomical characterization of species

Prismatic wood specimens (10 × 10 × 10 mm) were saturated in water for 7 days and then sectioned (15 µm thick) using a sliding microtome in the transverse, longitudinal-radial, and longitudinal-tangential planes. Permanent slides were then prepared according to Mady (2007). Four slides per plane were prepared, mounted with coverslips, and examined under a light microscope (4–40×) to quantify vessel features (diameter, frequency, grouping) and parenchyma traits (IAWA 1989). Microphotographs were converted to 8-bit in ImageJ 13.0.6 to measure vessel area.

Fourier transform infrared spectroscopy - FTIR

The analysis was performed to identify the functional groups present in the extractives and structural molecules of the woods studied in different anatomical planes, with the aim of clarifying how these chemical compounds influence the behavior of the surface in contact with liquids, such as adhesives and varnishes, as well as contributing to the understanding of color variations.

Two sets of 10 × 10 × 5 mm specimens were prepared, one exposing the longitudinal-radial plane and the other the longitudinal-tangential plane. FTIR analyses were performed using a Varian 600-IR spectrometer (California, USA) with a GladiATR accessory from Pike Technologies (Wisconsin, USA) for ATR measurements at 45° with a zinc selenide crystal. Spectra were collected from 500 to 4,000 cm^{-1}, at 4 cm^{-1} resolution, with 64 scans per measurement.

Table 1. Means and standard deviations of diameter at breast height (DBH), total height (Ht), basic density (ρb), and apparent density (ρa) of A. mahogany, Freijó, Paricá, and Teak woods produced in an agroforestry system in the Amazonia.

Species	DBH (cm)	Ht (m)	ρb (kg m^{-3})	ρa (kg m^{-3})
A. mahogany	30.0 ± 3.3	17.0 ± 3.4	522.5 ± 49.6	727.4 ± 46.4
Freijó	17.2 ± 6.1	12.8 ± 4.3	444.3 ± 17.3	582.6 ± 41.4
Paricá	41.2 ± 17.2	23.4 ± 7.3	280.3 ± 38.1	354.3 ± 54.6
Teak	40.3 ± 12.7	20.0 ± 2.2	432.9 ± 33.7	575.1 ± 46.8

Colorimetric evaluation

Three specimens from each species were used to conduct this test. Four readings were taken for each specimen in both longitudinal-radial and longitudinal-tangential planes to obtain the color parameters according to the CIELab system. The parameters evaluated were luminosity (L*), the green–red colorimetric coordinate (a*), the blue–yellow colorimetric coordinate (b*), color saturation (C), and hue angle (h*). A Konica Minolta CM-5 colorimeter from Osaka, Japan, was used for the measurements, with a viewing angle set to 10° and illuminant D65 (daylight). Next, the parameters obtained from the CIELab system were converted to the RGB scale (0-255) using the online tool EasyRGB (https://www.easyrgb.com).

Surface roughness

Strictly oriented wood samples measuring 20 × 20 × 50 mm were used to obtain the average roughness (Ra), root average square deviation of the roughness (Rq), maximum height of the roughness profile (Rz), and total height of the roughness profile (Rt). The roughness parameters were obtained using the Surtronic 3+ Taylor Hobson rugosimeter (Leicester, United Kingdom) according to the procedures presented in NBR ISO 4287-2002 (ABNT 2002). Four specimens from each species were evaluated, with six readings taken for each anatomical plane (radial and tangential) on every specimen. In each plane, two readings were collected at the extreme ends and two at the middle of the specimen. The roughness meter needle was moved parallel to the fibers during the readings, using a cut-off of 0.8 mm, a measurement length of 4 mm, and an amplitude of 100 µm.

Contact angle and wettability

The contact angle and wettability were assessed following TAPPI T 458 cm-04 (TAPPI 2004) using a Krüss DSA30 goniometer (Hamburg, Germany). Four specimens per species (20 × 20 × 50 mm) were positioned on the image acquisition base. Tests used Suvinil varnish (110 cP, 30% solids, pH = 8.0) and urea-formaldehyde adhesive (645 cP, 52% solids, pH = 7.6). For each specimen, five measurements were taken in both anatomical planes to characterize liquid–wood interaction.

Experimental design and data analysis

The experiment was conducted using a completely randomized design. The analyses of contact angle, wettability, colorimetry, and roughness followed a factorial arrangement with four species and two anatomical planes. Quantitative anatomical characterization considered only the species factor. The data underwent analysis of variance and Tukey's test ($p<0.05$). The FTIR spectral signatures were normalized and presented in graphs with peaks of the absorption bands of the chemical groups. All statistical analyses were performed using SISVAR software.

RESULTS

Anatomical characterization of species

In the transverse plane of A. mahogany wood (Figure 1a), indistinct growth layers and pores arranged diffusely and non-uniformly were observed. Pores showed a radial pattern, primarily in groups of 2-3, with some solitary pores obstructed by inclusions. The axial parenchyma appeared as vasicentric and aliform paratracheal types, being scarce, with the presence of marginal apotracheal parenchyma. In the longitudinal-tangential plane (Figure 1b), alternate oval intervessel pits and multiseriate rays, along with uniseriate rays, were identified. In the longitudinal-radial plane (Figure 1c), heterogeneous stratified rays consisted of procumbent, erect, and square cells.

Freijó wood (Figure 1d) displayed distinct growth rings with irregular diffuse porosity, containing solitary pores and 2–4 pore multiples, often occluded and radially arranged, along with vasicentric paratracheal axial parenchyma and sparse marginal apotracheal bands. Longitudinal sections showed simple perforation plates (Figure 1e), alternate oval intervessel pits, and heterogeneous rays with procumbent and erect cells (Figure 1f). Paricá wood (Figure 1g) showed well-defined growth rings with fibrous zones and irregular porosity, with radial or diagonal solitary pores and obstructed 2–4 pore multiples. The axial parenchyma was aliform and vasicentric paratracheal. In the longitudinal-tangential plane (Figure 1h), simple perforation plates, alternate oval pits, and multiseriate radial parenchyma were observed. Rays were heterogeneous, with procumbent, erect, and square cells (Figure 1i).

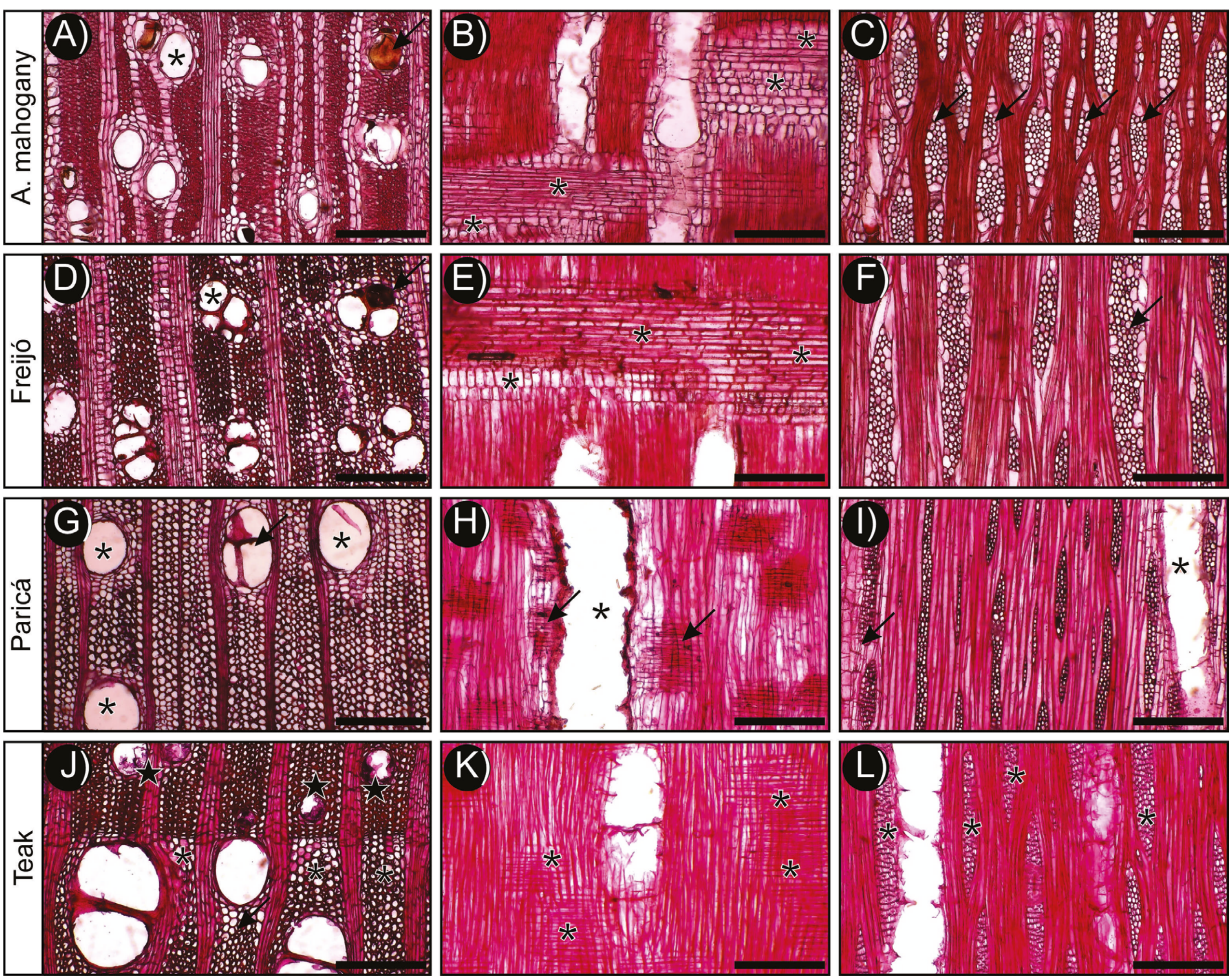

Figure 1. Light microphotographs of the anatomical planes: **A**) transverse – vessel element (*), tyloses (arrow); **B**) longitudinal-radial – radial parenchyma (*); **C**) longitudinal-tangential – multiseriate stratified rays (arrow) in the wood of A. mahogany; **D**) transverse – multiple vessel elements (*); **E**) longitudinal-radial – radial parenchyma (*); **F**) longitudinal-tangential – multiseriate rays (arrow) in the wood of Freijó; **G**) transverse – solitary (*) and multiple vessels (arrow); **H**) longitudinal-radial – vessel elements (*) and heterogeneous rays (arrow); **I**) longitudinal-tangential – vessel element (*) and multiseriate rays (arrow) in Paricá wood; and **J**) transversal – axial parenchyma (*), vasicentric parenchyma (arrow), and vessels obstructed by tyloses (★); **K**) longitudinal-radial – radial parenchyma (*); **L**) longitudinal-tangential – multiseriate rays (*) in Teak wood produced in an agroforestry system in the Amazonia. All scale bars correspond to 300 µm.

Teak wood (Figure 1j) exhibited distinct rings demarcated by marginal parenchyma bands and semi-porous zones. Pores showed tangential/radial arrangement in multiples of 2-3 and obstructed solitary pores. The axial parenchyma was scarce, vasicentric paratracheal with marginal apotracheal. In the longitudinal-tangential plane (Figure 1k), alternate oval intervessel pits and multiseriate rays with uniseriate rays were identified, with rays being homogeneous and composed of procumbent cells (Figure 1l).

Quantitative characterization indicated that A. mahogany wood exhibited the lowest average values for both the average diameter and the tangential diameter of vessel elements (Figure 2). In contrast, Freijó and Paricá woods showed average diameters and tangential diameters ranging from approximately 100 μm to 150 μm (Figure 2a,b). The highest values for these parameters were observed in Teak wood, with average diameters around 180 μm and tangential diameters around 160 μm.

Regarding vessel frequency, the largest ones were observed for A. mahogany wood (Figure 2c), a trend opposite to that observed for the average and tangential diameter of vessel elements. Another result that drew attention was the second highest vessel frequency for Freijó wood (~8 vessels mm^{-2}), which had the second smallest average diameter for vessel elements. Although Teak and Paricá woods presented a difference in density of around ~150 kg m^{-3} (Table 1), the vessel frequency values were very similar, ranging from 5 to 6 vessels mm^{-2} (Figure 2c).

The most significant variations in the area occupied by vessel elements were observed in A. mahogany wood (Figure 2d). This can be attributed to the random sampling conducted along the pith-bark direction. As a result, the values obtained for A. mahogany were like those for Teak wood, which was approximately 7.5%. The highest average area occupied by vessel elements was found in Freijó wood, at around 8.0%, while Paricá wood had the lowest average at approximately 4.5%. Additionally, Paricá wood exhibited the lowest standard deviation among the samples.

The largest and widest rays were found in Freijó wood (Figure 3a, b), which also showed the greatest variation around the mean values for height and width (~40%). In comparison, the lowest was obtained for Paricá wood (~20%). The lowest ratio between height and radius width was obtained for A. mahogany wood (~4.4). For Freijó, Paricá, and Teak woods,

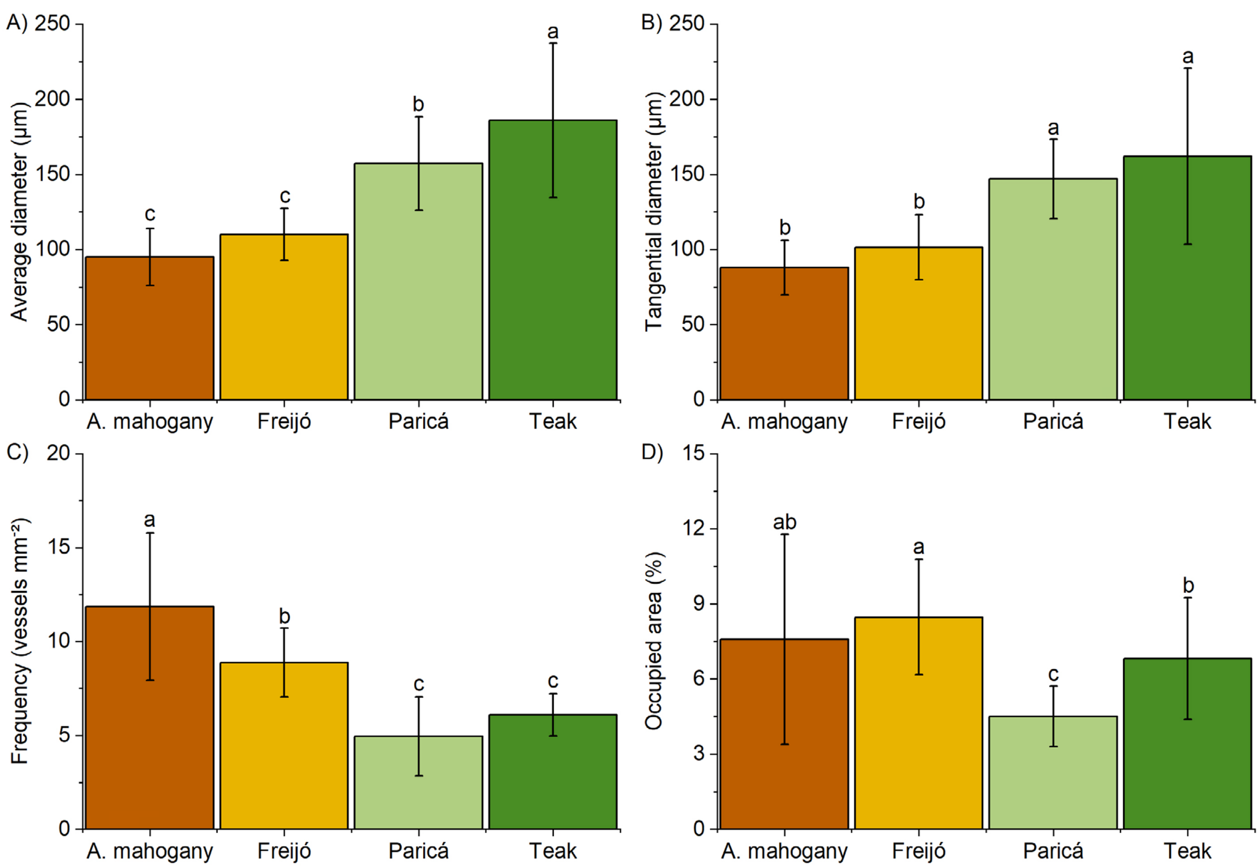

Figure 2. A) Average vessel diameter, **B**) tangential vessel diameter, **C**) vessel frequency and **D**) area occupied by vessels of A. mahogany, Freijó, Paricá, and Teak woods. Averages followed by the same lowercase letter do not differ from each other across species, considering Tukey's test ($p<0.05$).

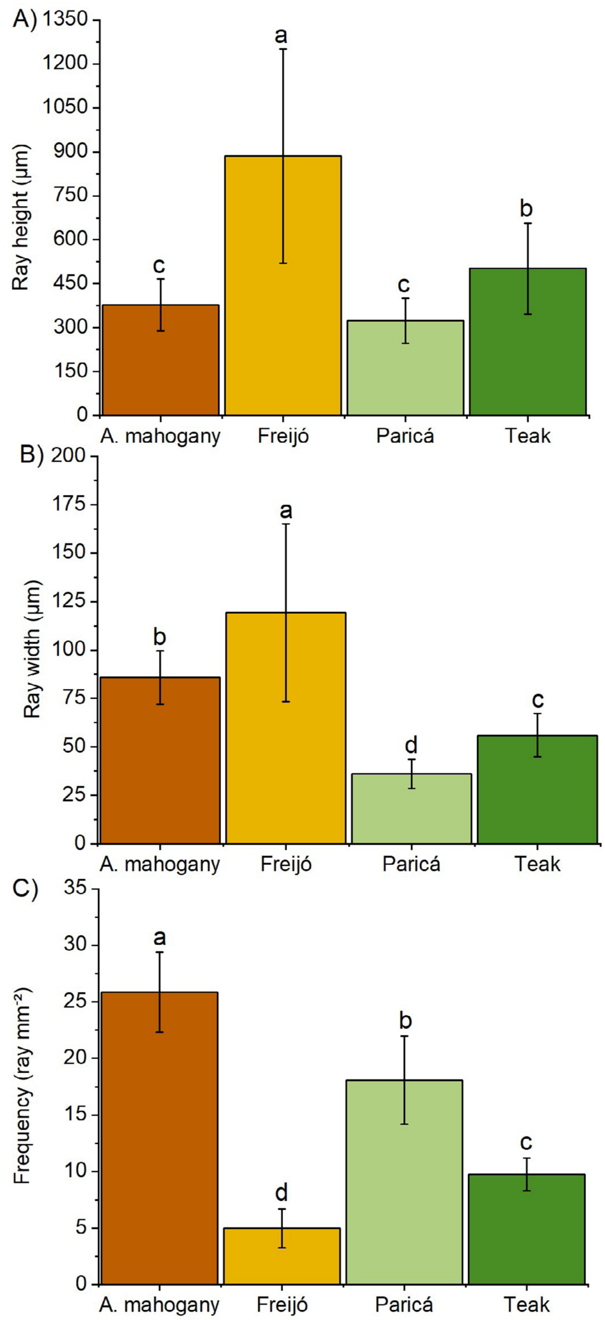

Figure 3. A) Ray length, **B**) ray width of the woods, and **C**) ray frequency of the woods of A. mahogany, Freijó, Paricá, and Teak. Averages followed by the same lowercase letter do not differ from each other across species, considering Tukey's test ($p<0.05$).

the ratios were ~7.4, ~8.9, and ~9, respectively. Furthermore, A. mahogany wood presented the highest frequency of rays (~26 rays mm^{-2}) (Figure 3c), which is explained by stratification (see Figure 1c). The second highest frequency was observed for Paricá wood (~18 rays mm^{-2}), followed by Teak (~10 rays mm^{-2}) and Freijó (5 rays mm^{-2}). These results suggest that rays with more uniform proportions, as is the case with A. mahogany, lead to an increase in frequency.

Fourier transform infrared spectroscopy - FTIR

Peaks of similar intensity were observed in the bands at 1,602, 2,929, 2,852 and 3,340 cm^{-1} across all anatomical planes of the woods studied, indicating slight variations in the chemical structure of these spectral regions (Figure 4). Notably, peaks at 2,364 cm^{-1} were detected in all planes except for the tangential plane of Freijó wood. In contrast, Teak wood exhibited more intense peaks at 600, 659, 1,700 and 1,145 cm^{-1}, while A. mahogany wood was characterized by prominent peaks in the spectral region of 1,193 cm^{-1}. Regardless of the anatomical plane, except for Freijó, the most intense peak was consistently observed at 1,727 cm^{-1}. Paricá wood, on the other hand, presented stronger peaks in the bands between 1,241 and 1,025 cm^{-1}.

Colorimetric evaluation

The wood colorimetric parameters showed uniformity between the radial and tangential planes (Table 2).

The studied woods presented wide variation in the basic colorimetric parameters: luminosity (L*) between 58.15 and 86.66; green-red colorimetric coordinate (a*) between 4.01 and 12.22; blue-yellow colorimetric coordinate (b*) between 21.22 and 28.04; color saturation (C) between 22.26 and 29.22; and hue angle (h*) between 65.62 and 82.10. Paricá wood obtained the highest values for L*, b*, and h*, while A. mahogany reached high values in the parameters a* and C, and the other species exhibited intermediate results (Table 2). The colors of the wood samples evaluated in the longitudinal-tangential and longitudinal-radial planes, as well as the conversion of the data to the RGB scale (0-255), are illustrated in Figure 5.

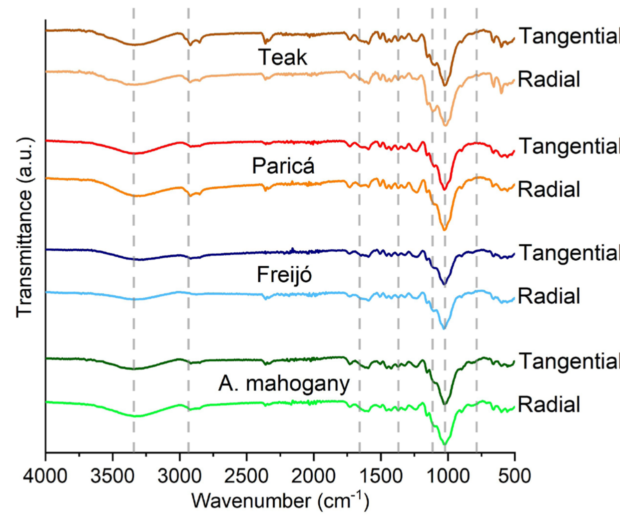

Figure 4. FTIR-ATR bands of the longitudinal-radial and longitudinal-tangential anatomical planes of A. mahogany, Freijó, Paricá, and Teak woods produced in an agroforestry system in the Amazonia.

Table 2. Means and standard deviations of the colorimetric parameters lightness (L*), green–red colorimetric coordinate (a*), blue–yellow colorimetric coordinate (b*), color saturation (C), and hue angle (h*), obtained in the CIELab system for the anatomical planes of A. mahogany, Freijó, Paricá, and Teak woods produced in an agroforestry system in the Amazonia.

Species	Anatomical plane	L*	a*	b*	C	h*
A. mahogany	Radial	62.92 ± 8.62bc	12.22 ± 3.55a	26.42 ± 2.50a	29.22 ± 3.44a	65.62 ± 5.45d
	Tangential	63.49 ± 8.67b	11.61 ± 3.10a	25.38 ± 2.84b	27.98 ± 3.60a	65.78 ± 4.67d
	Average	63.20 ± 8.46	11.91 ± 3.28	25.90 ± 2.67	28.60 ± 3.50	65.70 ± 4.97
Freijó	Radial	65.65 ± 5.80b	5.24 ± 1.93b	23.47 ± 3.57b	24.05 ± 3.90b	77.77 ± 3.02b
	Tangential	62.69 ± 7.36b	5.16 ± 1.47b	21.83 ± 2.68c	22.47 ± 2.76b	76.77 ± 3.45b
	Average	64.17 ± 6.65	5.2 ± 1.68	22.65 ± 3.20	23.26 ± 3.40	77.27 ± 3.21
Paricá	Radial	86.66 ± 3.15a	4.01 ± 1.46b	27.77 ± 1.32a	28.09 ± 1.45a	81.85 ± 2.63a
	Tangential	86.23 ± 3.69a	6.04 ± 7.07b	28.04 ± 1.24a	26.51 ± 6.74a	82.10 ± 3,00a
	Average	86.45 ± 3.36	5.02 ± 5.10	27.90 ± 1.26	27.30 ± 4.84	81.97 ± 2.76
Teak	Radial	58.15 ± 6.82c	6.64 ± 0.79b	21.22 ± 2.38b	22.26 ± 2.25b	72.45 ± 2.93c
	Tangential	60.04 ± 5.23b	6.85 ± 1.07b	22.14 ± 2.03c	23.19 ± 2.07b	72.78 ± 2.44c
	Average	59.09 ± 6.02	6.74 ± 0.92	21.68 ± 2.21	22.73 ± 2.17	72.62 ± 2.64

Averages followed by the same lowercase letter in the column do not differ from each other with respect to species, according to the Tukey's test (p<0.05).

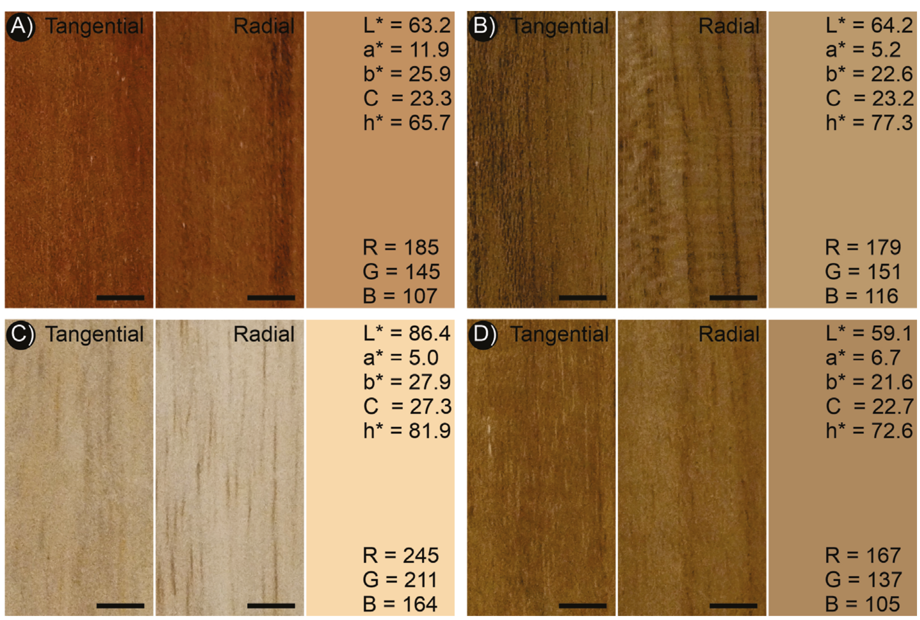

Figure 5. Colors converted from the CIELab system to RGB (0–255), based on the colorimetric parameters lightness (L*), green–red coordinate (a*), blue–yellow coordinate (b*), color saturation (C), and hue angle (h*), for the anatomical planes of **A**) A. mahogany, **B**) Freijó, **C**) Paricá, and **D**) Teak woods. All scale bars correspond to 5 mm.

Surface roughness

Considering the Ra, Rq, Rz, and Rt values, no interactions were detected between the anatomical plane and species factors, except for the Ra parameter, where lower values were found for Freijó in the longitudinal-radial plane (Figure 6a,b,c). Regarding the Rt values, the smallest variations between the anatomical planes evaluated were observed for A. mahogany (Figure 6d). Regardless of the anatomical plane evaluated and the roughness parameter evaluated, Freijó and Paricá woods were the most similar. Among the species assessed, the lowest surface roughness was observed for Teak wood, regardless of the anatomical plane evaluated, especially for Rz and Rq (Figure 6b,c). On the other hand, although it did not differ from the other species, A. mahogany showed a slight tendency to provide a rougher surface, especially when considering the Rq values (Figure 6b).

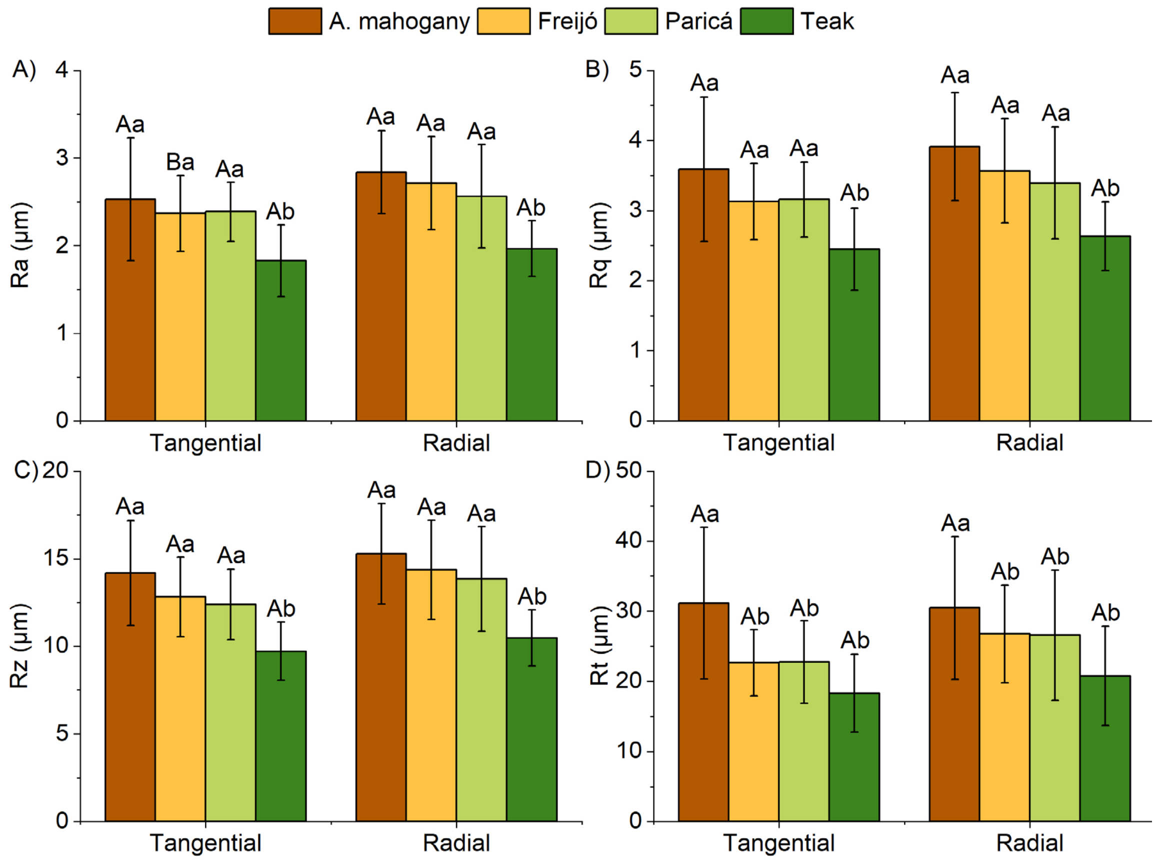

Figure 6. A) Average roughness (Ra), **B**) root average square of the roughness deviation (Rq), **C**) maximum height of the roughness profile (Rz), and **D**) total height of the roughness profile (Rt) for the anatomical planes of the woods. Averages followed by the same uppercase letter do not differ from each other about the anatomical plane, and means followed by the same lowercase letter do not differ from each other across species, considering Tukey's test ($p<0.05$).

Contact angle and wettability

No interaction effects were observed between anatomical planes and species, except for wettability using urea-formaldehyde for Paricá wood (Figure 7c). In A. mahogany wood, a tendency toward higher contact angles was observed, considering urea-formaldehyde or varnish (Figure 7a,b). Paricá showed the greatest variation in contact angles, with varnish producing higher values in the longitudinal-tangential plane. The lowest angles occurred in the longitudinal-tangential plane for urea-formaldehyde and in the longitudinal-radial plane for varnish.

In terms of wettability, the results indicated that Paricá wood, when treated with urea-formaldehyde (Figure 7c), exhibited the highest wettability values in the longitudinal-radial plane and the lowest in the longitudinal-tangential plane. On the other hand, when varnish was used for testing (Figure 7d), A. mahogany wood had the highest wettability values in the longitudinal-radial plane, while Freijó had the lowest values in the same plane. It is also important to note that Freijó wood was unique in recording the highest wettability values in the longitudinal-tangential plane.

DISCUSSION

Anatomical characterization of species

All woods studied, except for Teak, showed similar characteristics, such as diffuse non-uniform porosity, with a predominance of solitary and multiple vessels. Another similarity was the presence of multiseriate rays composed of procumbent, erect, and square cells, indicating heterogeneous rays, except for Teak, which presented homogeneous rays composed only of procumbent cells. In relation to A. mahogany, ray stratification was observed in the longitudinal-tangential plane, a very common characteristic for woods of the Meliaceae family. The heterogeneity of the rays in the wood of the species studied is correlated with workability and surface finishing with sandpaper, given the need to apply different tools and grains for more regular finishes on the wood surface (Bucur 2019).

Another common characteristic was the obstruction of the vessels by inclusions that are associated with the presence of reserve substances or phenolic compounds. Micco et al. (2016) reported that inclusions in the vessels are a frequent characteristic in tropical woods and can influence their

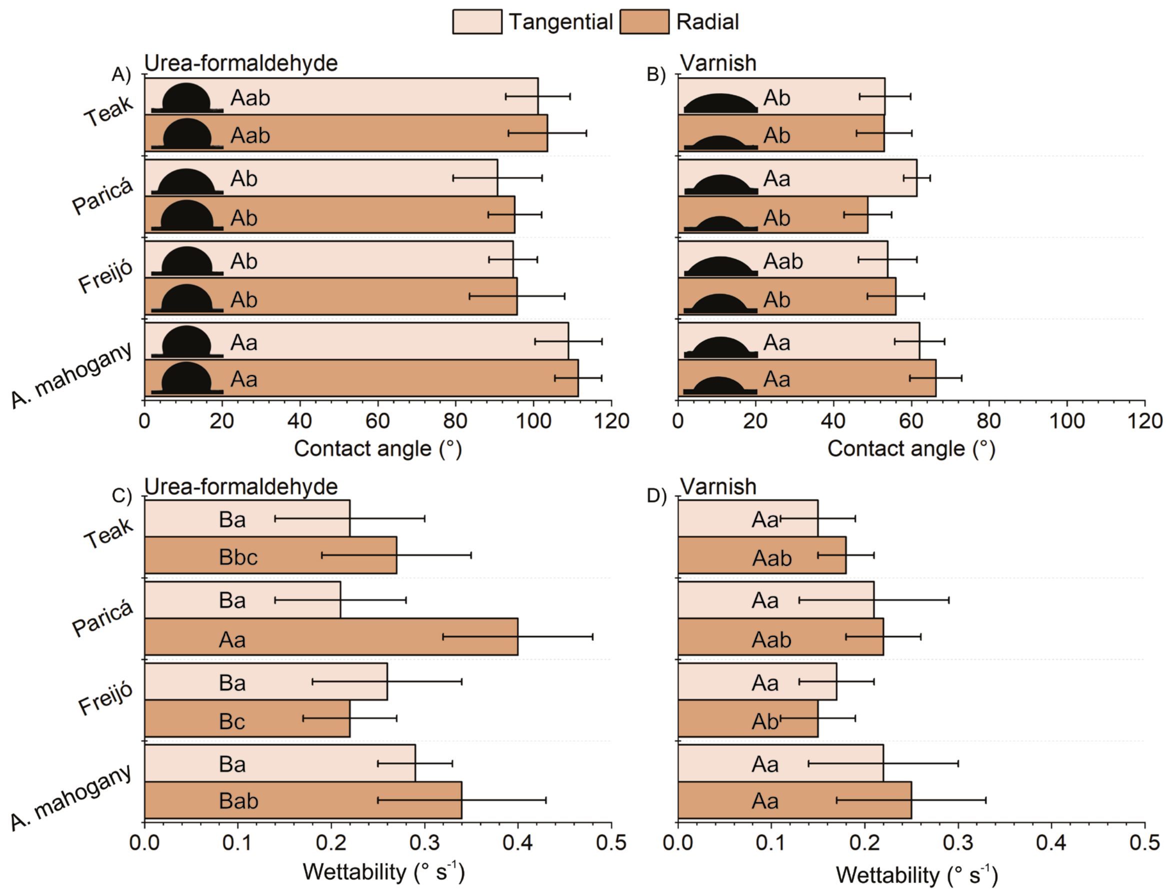

Figure 7. A) Contact angle with urea-formaldehyde, **B**) Contact angle with varnish, **C**) Wettability with urea-formaldehyde, and **D**) Wettability with varnish for the anatomical planes of the species. Averages followed by the same uppercase letter do not differ from each other about the anatomical plane, and means followed by the same lowercase letter do not differ from each other across species, considering Tukey's test ($p<0.05$).

natural durability. The presence of substances in the vessels may also represent difficulties to the absorption of adhesives and the spreading of coatings on the wood. In addition, some extractives contained in these structures may react with varnishes, altering their color and impairing aesthetic parameters for some wood applications.

The presence of paratracheal axial parenchyma, both vasicentric and aliform, was observed in almost all woods, indicating storage of reserve substances. These substances may represent attractions for xylophagous agents for woods with lower extractive content, as is the case with Paricá (Martín and López 2023). The studied woods showed differences in growth rings: A. mahogany and Freijó displayed faint growth rings, while Paricá and Teak exhibited distinct rings with fibrous zones. Furthermore, the higher standard deviations observed in the diameter of Teak wood vessels are justified by the semi-porous nature of the rings, in which a gradual reduction in pores is observed from the beginning of juvenile wood to mature wood (see Figure 1J).

It should be noted that measurements were taken randomly from samples collected at various points in the pith-bark direction. In addition, the trees analyzed were grown from seeds, which naturally causes genetic variability and, consequently, variability in wood characteristics (Kollmann and Côté 1968). This variation affects the absorption of adhesives and varnishes, potentially causing issues like delamination (Iwakiri and Trianoski 2020). Additionally, woods with larger vessels have more cavities, resulting in rougher surfaces. For improved finishing in A. mahogany, Freijó, and Teak, finer sanding is recommended, whereas in Paricá, these cavities enhance adhesion in engineered wood by improving piece-to-piece bonding.

Furthermore, larger vessel dimensions, especially in the longitudinal-tangential plane, contribute to increased roughness. This can be explained by the fact that large vessels affect the dynamics of liquid propagation on the wood surface, resulting from the discontinuity of the fibrous regions and greater exposure of the radial parenchyma diameters (Marbun et al. 2020). Thus, the anatomical characteristics of the woods observed in this study can help in the proper orientation for different applications.

Fourier transform infrared spectroscopy - FTIR

The peaks between 2,929-2,852 cm^{-1} indicate aliphatic chains (C-H) (Cano-Trujillo et al. 2023). The 2,364 cm^{-1} region shows possible nitriles (C≡N) or adsorbed CO_2. The intense peak at 1,727 cm^{-1} (present in all woods except Freijó) confirms carbonyl groups (C=O), characteristic of ketones, esters, and carboxylic acids (Bi and Huang 2021). The 1,602 cm^{-1} peaks may represent either aromatic rings (C=C) or conjugated ketones (C=O in conjugated double-bond systems) (Cogulet et al. 2016).

The most intense peaks in the bands between 1,241 and 1,025 cm^{-1} for Paricá wood are typical of the stretching of C-O bonds in ethers, esters, and alcohols, in addition to skeletal vibrations in aromatic compounds. This fact is probably explained by the lower extractive content that allowed greater exposure of these groups. On the other hand, the most intense peaks in the bands between 659 and 600 cm^{-1} observed for Teak wood represent out-of-plane deformations of C-H bonds in aromatic rings and skeletal vibrations of molecules (Tondi and Petutschnigg 2015).

Peaks at 3,340 cm^{-1} revealed -OH groups in all woods (Herrera-Builes et al. 2022). Teak showed intense peaks (1,700-1,145 cm^{-1}) indicating high lignin (~33%) and tectoquinone content, responsible for its durability (Chávez-Salgado et al. 2022). In A. mahogany, the characteristic 1,193 cm^{-1} band (C-O-C) of limonoids (Mascarenhas et al. 2021a) directly influences adhesion, as nonpolar extractives reduce cell wall permeability. In contrast, woods such as Freijó and Paricá, which contain free hydroxyl groups, show greater affinity for polar compounds, which may enhance the bonding of wood elements in the production of engineered panels.

Colorimetric evaluation

Although it is common to observe color variations between the anatomical planes of wood in native tropical woods from the Amazonia and in cultivated exotic species (Camargos and Gonçalez 2001), in the present study the colorimetric changes were negligible between the longitudinal-radial or tangential planes. This, in turn, may represent an advantage during processing, given that regardless of the plane to be exposed, the woods studied will have homogeneous aesthetic patterns that can align with market requirements.

Furthermore, regarding the peculiarities of each species, it was observed that information on the color parameters of A. mahogany and Freijó is scarce in the literature, which highlights the importance of characterizing tropical woods for technical and scientific knowledge. However, based on the colorimetric analysis of 350 tropical wood species, it was determined that A. mahogany exhibits a predominantly pink coloration, regardless of the anatomical plane, while Freijó appears more pinkish-gray, as indicated by the color classification proposed by Camargos and Gonçalez (2001).

The basic color parameters of the analyzed woods presented varied values by species, which led to categorizing them into groups of different tones, as reported by Silva et al. (2017). These authors found average colorimetric values collected in the longitudinal-tangential plane of Paricá and Teak woods that differed from this study, with L*= 75.34 and 57.03, a*= 6.68 and 8.04, b*= 19.62 and 20.11, C= 20.89 and 21.66 and h*= 71.67 and 68.15, respectively. This distinction was also found in the color classification of Paricá, which was classified as pinkish-grey and Teak as yellowish-olive (Camargos and Gonçalez 2001).

Studies indicate that wood coloration does not always differ between anatomical planes, as observed by Melo et al. (2019) for tropical species and corroborated by Esteves et al. (2008) for *Pinus pinaster* and *Eucalyptus globulus*. When such differences do occur, they are mainly attributed to variations in extractive composition and anatomical organization. Color diversity is expected among species due to differences in chemical composition, including extractives, tannins, gums, and resins. Wood may range from light beige to dark brown, and even include yellow, orange, red, or purple tones, contributing to the wide variety of options available in the wood market.

Surface roughness

The lower roughness observed for Teak wood is related to moderate width, height, and frequency of rays, frequency and area occupied by vessels. These lower roughness values suggest a more uniform surface, which is highly desirable in industry, especially for products that require refined surface finishing, such as in the manufacture of high-quality furniture, flooring, and laminates. Less rough surfaces imply less waste during the finishing process (Korkut et al. 2008).

The parameters Ra, Rq, Rz, and Rt can all be used to assess the roughness of the four wood species evaluated. However, it is important to note that the Ra parameter is the most used measure for evaluating wood roughness (Melo et al. 2013). This is primarily because, like Rq, the Ra parameter is less affected by isolated peaks and valleys that do not accurately reflect the overall profile (Carpinetti et al. 2020). In contrast to the Rt and Rz parameters, Ra is not influenced by scratches or measurement noise. Thus, the highest roughness values in the longitudinal-radial plane observed for all species can be associated with the perpendicular arrangement of the rays concerning the axial axis of the tree (Kollmann and Côté 1968).

These aspects help explain the greater roughness observed on the surfaces of A. mahogany, likely associated with its anatomical characteristics, such as the larger vessel area and the higher frequencies of rays and stratified rays. The high Rt standard deviation for this species may have caused overlap with others, reflecting variability resulting from sampling different radial positions and from trees grown from seeds, which show broad phenotypic heterogeneity. The roughness observed in Paricá and Freijó is also linked to their anatomy;

Paricá, with larger vessel diameters and a higher frequency of rays, tends to produce rougher surfaces, as reported by Melo et al. (2013).

It is important to note that differences in roughness between anatomical planes were negligible within each species, indicating no need for additional surface-regularization procedures. However, for applications requiring smoother surfaces for varnish applications, such as furniture, finishing elements and musical instruments, woods with higher roughness require sequences with finer grits, since all samples were initially sanded with 50-grit. This information supports better planning for the industrial use of woods produced in the agroforestry system evaluated.

Contact angle and wettability

The increase in wood surface roughness reduces the contact angle, which enhances wettability and improves the bonding performance between liquids and the wood surface (Darmawan et al. 2020). This effect is confirmed by the wettability results obtained for the varnish-based coating, in which A. mahogany, characterized by a rougher surface, showed higher wettability in both the radial (0.25) and tangential (0.22) directions. A similar pattern was observed for the urea-formaldehyde adhesive applied to the tangential section of mahogany wood (0.29). Surface wettability is a complex property influenced by water penetration through capillarity and by interactions with hydroxyl groups of the cell wall components.

These findings support improvements in the application of varnishes and adhesives on wooden surfaces, particularly in furniture manufacturing. When uniformly applied and well adhered, varnish-based coatings enhance and protect wood by adding shine, emphasizing natural grain, and offering resistance to insects, abrasion, and moisture. Adhesives such as urea-formaldehyde resin create strong bonds between wood elements, increasing the structural integrity of manufactured products. The quality of these finishes depends significantly on the condition of the wood surface (Darmawan et al. 2020).

Wood wettability is influenced by anatomical structure, machining, density, moisture content and chemical composition, especially extractives. The higher wettability of A. mahogany may be related to its greater vessel and ray frequency, rougher surface and chemical profile (Mascarenhas et al. 2021a). Although A. mahogany has higher density, this did not prevent the species from showing high wettability and the lowest contact angle. Density, however, can influence this behavior (Melo et al. 2013). Paricá in the longitudinal-radial plane showed high wettability and the lowest contact angle, attributed to its lower density (350 kg m^{-3}) and greater vessel exposure. Freijó and Teak showed similar wettability and contact angles, likely due to their comparable densities, both near 550 kg m^{-3}.

Wettability indicates how easily coatings or adhesives spread over wood surfaces and influences adhesion quality. Varnishes, with their lower viscosity (110 cP), spread uniformly and form smooth films, whereas thermosetting resins like urea-formaldehyde, due to their higher viscosity (645 cP), resist rapid absorption by the wood (Iwakiri and Trianoski 2020). This characteristic is essential for ensuring the formation of resistant glue lines, as it allows the phenomena of flow, transfer, penetration, wetting, and solidification between wood particles to occur properly (Melo et al. 2013). These characteristics, in turn, increase the contact angle and reduce wettability, as observed in the experimental results of this study.

Contact angle measurement is an important indicator of wettability, since values above 90° reflect poor spreading of liquids on wood surfaces (TAPPI 2004). In this study, all species showed varnish contact angles below 90°, while urea-formaldehyde resin produced higher values, indicating reduced spreading capacity. Although A. mahogany exhibited greater wettability, its surface was less hydrophilic than that of the other species, likely due to its higher density and extractive content (Mascarenhas et al. 2021a). Denser woods generally show higher contact angles (Santos and Garcia 2019), and colorimetric parameters also influence this behavior, with more chromatic woods tending to be more hydrophobic and lighter woods more hydrophilic. This trend was confirmed in the present study, as Paricá showed lower contact angles with urea-formaldehyde resin and varnish, indicating better liquid spreading than A. mahogany.

Applications

Teak wood showed the lowest roughness, making it the most suitable species for high-quality finishing. A. mahogany, Freijó and Paricá had roughness more strongly influenced by vessel and ray frequency. Comparisons with published data indicated that cultivation in agroforestry systems did not reduce surface quality when compared to wood from pure plantations or native forests. The absence of color differences between anatomical planes, together with the pink tones of A. mahogany, the yellow-olive tones of teak and the gray-pink hues of Paricá and Freijó, supports the aesthetic stability of these species. FTIR analysis confirmed characteristic compounds that may affect adhesion, durability and coating performance. Contact angle measurements revealed greater hydrophobicity in A. mahogany and lower values in Paricá, reflecting structural and chemical differences that affect wettability and the behavior of adhesives and varnishes. The results show that cultivation in AFS enables these species to develop properties suitable for furniture and panel production, although some may require finer sanding for improved finishing. These findings highlight the importance of integrated characterization to guide technological applications and support the sustainable diversification of Amazonian wood resources.

CONCLUSIONS

The evaluated woods presented desirable characteristics for applications that require high-quality gluing and surface finishing. In other words, the information generated will contribute to filling the gaps in scientific knowledge regarding the surface properties of wood because of tree cultivation in agroforestry systems. In addition, this research can contribute to the better dimensioning of tree cultivation in AFS, aiming at the production of woods with technological parameters that meet the industrial requirements for obtaining products with higher added value (furniture industry, wood boards, residential finishes, among others).

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