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Chemical, physical, and mechanical wood properties of *Rhizophora mangle* L., *Avicennia germinans* (L.) L., and *Laguncularia racemosa* (L.) C.F. Gaertn. on the Brazilian Amazon coast

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Abstract

Key message Wood of *Laguncularia racemosa* (L.) C.F. Gaertn. and *Avicennia germinans* (L.) L trees have similar chemical properties, while *Rhizophora mangle* L. is superior in physical-mechanical properties. It is highly suitable for charcoal production and civil construction.

Context Wood from mangrove tree species has been widely used by traditional communities on the Amazon coast, although its chemical and physical-mechanical properties are unknown.

Aims This study intends to assess the chemical and physical–mechanical properties of wood from mangrove trees and compare data obtained from the three most dominant species: *R. mangle*, *A. germinans*, and *L. racemosa*.

Methods Chemical and physical-mechanical properties of wood were analyzed in five trees of each mangrove species, using standards ASTM D1107-21, ASTM D1106-21, ASTM D1102-84, ASTM D2395-17, and ASTM D143/2014.

Results Among the chemical properties, *A. germinans* presented the highest values for ash, *R. mangle* for lignin and holocellulose, and *L. racemosa* for total extractives. Of the physical properties, *R. mangle* presents high values of basic density, tangential contraction, volumetric variation, and anisotropy coefficient, while *A. germinans* high values of radial contraction.

Conclusion Higher-quality chemical properties present advantages in natural durability and resistance to xylophagous for *A. germinans* and *L. racemosa*, while higher lignin has better mechanical resistance for *R. mangle* and holocellulose and better charcoal production for *L. racemosa*. Such information is the basis for management in mangroves due to the multiple uses of mangrove wood and deforestation intensity in mangrove forests.

Keywords Amazonian mangroves, Anisotropy coefficient, Radial and tangential contraction, Volumetric contraction, Wood density

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1 Introduction

Mangrove forests are made up of trees and shrubs adapted to intertidal areas on all tropical and subtropical coasts around the world (Tomlinson 2016). These forests represent about 8% of the entire global coastline and 25% of the tropical coast, covering a total of 181,077 km^2 (Spalding et al. 2010). It should be noted that Indonesia, Australia, Brazil, and Nigeria have around 43% of the planet's mangrove forests (Alongi 2002). Indonesia has the largest mangrove area in the world, with 42,550 km^2 distributed throughout its archipelagos. Brazil is the country with the second-largest mangrove area with ~ 9900 km^2, which extends from the north, in Amapá, to the south in the State of Santa Catarina (Spalding et al. 2010; Diniz et al. 2019). The coastal region of the Brazilian Amazon extends from Cape Orange, in the State of Amapá, to the State of Maranhão and has the largest mangrove area in the country, representing more than 80% of this ecosystem in the national territory. In this region between the bay of Marajó (48° W; 0° 30` S), in the State of Pará, to the bay of São José (44° 15` W; 2° S), in the State of Maranhão, there is the largest continuous extension of this ecosystem on the planet, covering an area of 7591 km^2, accounting for around 57% of Brazil's mangroves (Souza Filho 2005; Diniz et al. 2019).

The mangroves in the State of Pará are formed by six tree species: *Avicennia germinans* (L.) L; *Avicennia schaueriana* Stapf & Leechman ex Moldenk; *Rhizophora mangle* L.; *Rhizophora racemosa* G. F. W. Meyer; *Rhizophora harrisonii* Leechman; and *Laguncularia racemosa* (L.) C.F. Gaertn. The species *R. mangle* is the most dominant both on the coast of Pará and on the entire Brazilian Amazon coast (Abreu et al. 2016). This species dominates brackish environments, areas of low salinity, and hence those areas with greater frequency of flooding (Menezes et al. 2008). On the other hand, *A. germinans* is the second most dominant species, developing in areas with higher topography, greater salinity, and hypersaline regions, where they form monospecific forests with shrubby characteristics and short individuals (Medina et al. 2001; Virgulino-Júnior et al. 2020). The third most dominant species in the Amazonian mangroves is *L. racemosa*, which is most common on the margins of mangrove forests and in natural and anthropogenic clearings (Abreu et al. 2016).

In the State of Pará, traditional coastal communities live in or around mangroves. These communities depend on the exploitation of mangrove forests (Fernandes et al. 2018; Galvão et al. 2024), with wooden products being used for the most varied applications, such as in civil construction, fishing pens, fences for pig and cattle farming, boats, fuel (firewood) for manufacturing cassava flour, and charcoal production for domestic and commercial use (Voigt 2011; Galvão et al. 2024). In addition, this extractive activity of mangrove wood for multiple uses is of great relevance and represents a vital source for the subsistence of these communities (FAO 2023).

For a better understanding of the use of wood resources from mangrove forests, it is still necessary to assess the quality of wood typical of this ecosystem, since knowledge of wood properties is an important factor for the development of silvicultural practices, management, and forest improvement; this knowledge influences the transformation process and determines the most appropriate conditions for the rational exploitation of these forest resources (Rodríguez-Anda et al. 2018; Chambi-Legoas et al. 2021). Therefore, knowing the chemical and physical–mechanical properties of wood is essential to support various investigations, enhance its different uses, and reduce excessive logging and waste, in addition to adding value to products resulting from the use of this wood (Medeiros et al. 2021). Considering the importance of the mangrove wood as a multi-purpose resource for people who live in the estuarine-coastal zone, this work aims to assess whether there is a similarity between the chemical and physical–mechanical properties of the wood of the three dominant species of mangrove trees (*R. mangle*, *A. germinans*, and *L. racemosa*) on the Brazilian Amazon coast. It also investigates whether such properties are similar to those presented by the dominant tree species in mangroves on other continents since these species are also multi-purpose resources used by people who depend on these ecosystems.

2 Materials and methods

2.1 Study area

The study area is located within the Caeté-Taperaçu MER in the northeast of the State of Pará (Fig. 1). The Chico Mendes Institute for Biodiversity Conservation (ICMBio) manages the protected area. The climate in this region is hot and humid, and according to a 40-year data series, the average annual temperature is 26.5 °C, with annual precipitation of 2348.5 mm and average relative humidity of 85% (INMET 2022). The dry period is from July to November, while the rainy period occurs from December to June (Moraes et al. 2005).

2.2 Collection and characterization of wood properties

The criterion for choosing trees for wood collection was the median of the structural variable diameter at breast height (DBH) of *R. mangle*, *A. germinans*, and *L. racemosa* with DBH around 20 cm, 23 cm, and 19 cm, respectively. Five trees of each species were collected (License MMA/ICMBIO/SISBIO no.: 77770–1) and taken to the Mangrove Ecology Laboratory—Federal University of Pará, Bragança Campus—for preparation of the test

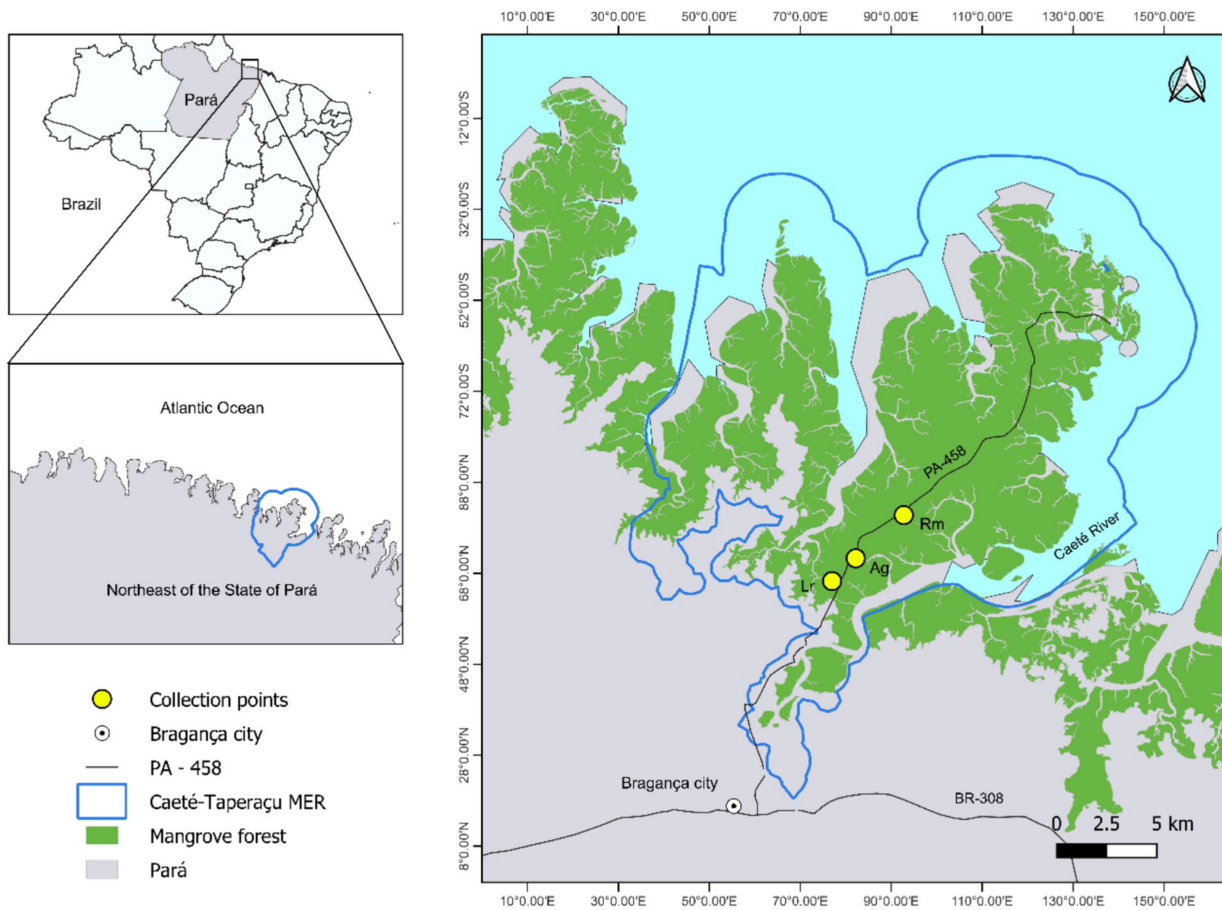

Fig. 1 Location of the Caeté-Taperaçu Marine Extractive Reserve (MER), municipality of Bragança, State of Pará, Brazilian Amazon coast. Rm, *Rhizophora mangle*; Ag, *Avicennia germinans*; Lr, *Laguncularia racemosa*

specimens. After preparation, test specimens were taken to the Multi-User Forestry Engineering Laboratory – State University of Pará, Paragominas Campus and Laboratory of Mechanical Testing of Wood and Derivatives (LEMMAD), at the "Luiz de Queiroz" College of Agriculture (ESALQ), University of São Paulo (USP) for chemical and physical-mechanical analyses.

2.3 Chemical properties

Wedges from all collected discs for the three examined species were used for the chemical characterization of wood from mangrove species, always using two opposing wedges. The wedges were reduced to chips and then crushed in a knife mill to obtain sawdust. The material obtained was sieved, and only the fraction retained between the 40 and 60 mesh sieves (=opening of 0.420 mm and 0.250 mm, respectively) was used.

The wood's total extractive content was analyzed following the adapted Standard ASTM D1107-96 (ASTM 2021a), in which the samples were extracted in toluene, alcohol, and hot water. The insoluble lignin content was determined according to the procedures described by Standard ASTM D1106-21 (ASTM 2021b) and the soluble lignin by the procedure presented by Goldschmid (1971). The total lignin content was determined by the sum of soluble and insoluble lignin. In contrast, the holocellulose content was determined by the difference between the initial mass and the amount of extractives and total lignin. After extraction, the samples were stored in an oven at 103 ± 2 °C to evaporate the solvents, and the dry material was weighed to determine the extractive content by mass difference.

The soluble, insoluble, and total lignin were determined by the difference between the initial mass and the quantities of extractives, lignin, and ash, that is, 100 − (Extractives + Lignin + Ash). The ash content was determined following Standard ASTM D1102-84 (ASTM 2021c).

2.4 Physical-mechanical properties

To characterize the basic density of wood, a 6-cm-thick disc was removed from each tree at 1.30 m above ground level (Fig. 2). Four radial positions were taken

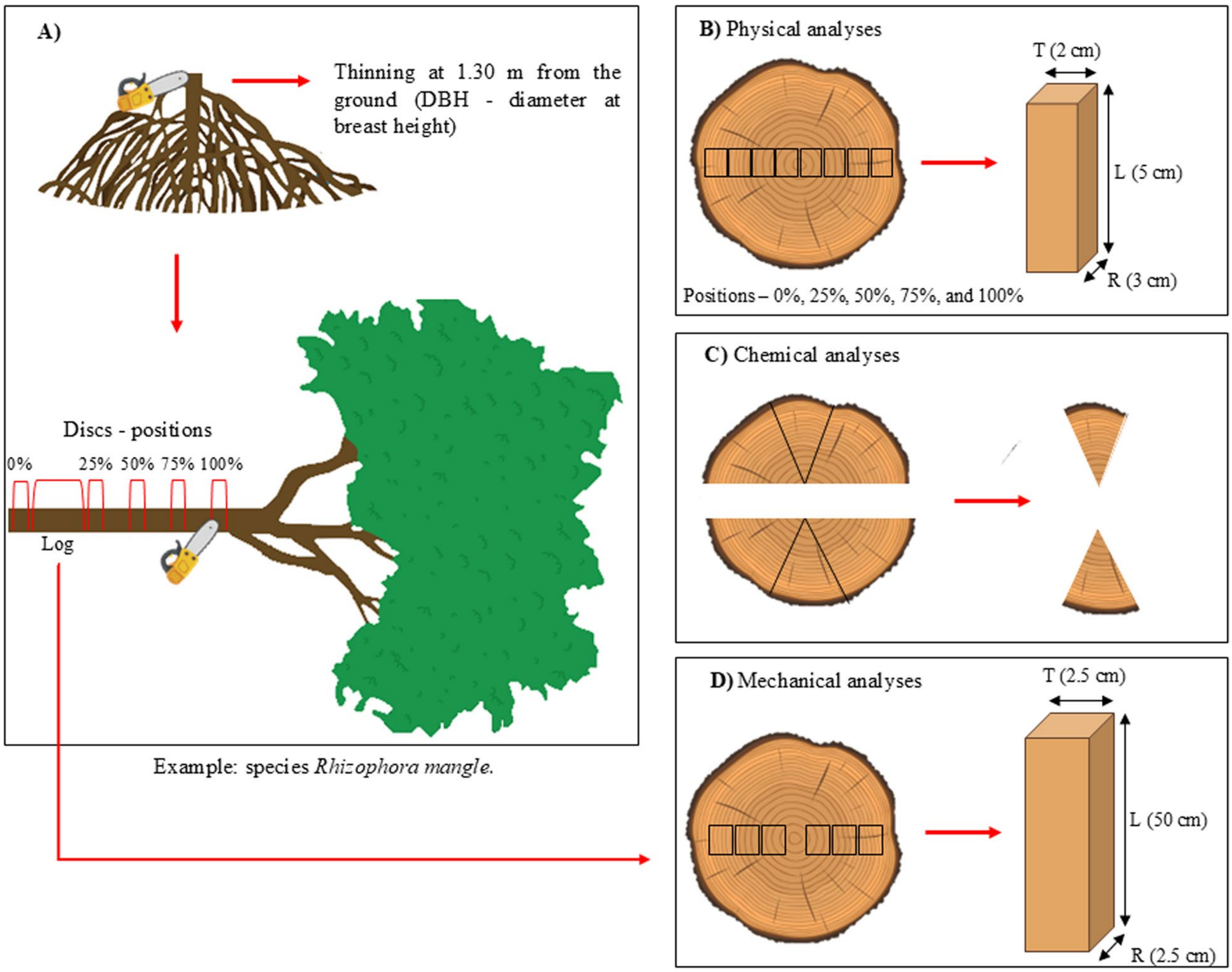

Fig. 2 Schematic diagram of the specimen collection and preparation process. **A** Process of collecting samples and selecting discs. **B** Preparation of samples for physical analysis. **C** Preparation of samples for chemical analysis. **D** Preparation of samples for mechanical analysis; R, radial; T, tangential; L, longitudinal

from the discs, from bark to bark, namely close to the pith 0%, 33%, and 66% of the radius, and on the periphery of the stem close to the bark 100%, with 5 cm edges in the longitudinal direction (L), 3 cm in the radial direction (R), and 2 cm in the tangential direction (T), all free of defects and perfectly oriented, following the test procedure specified by Standard ASTM D2395-17 (ASTM 2022).

The basic density (ρ_{basic}; g cm^{-3}) of mangrove wood was calculated using Eq. 1, using the ratio between the oven-dried mass (M_s; g) and the saturated volume (V_{sat}; cm^3).

$$\rho_{basic} = \frac{M_S}{V_{sat}} \tag{1}$$

To characterize the dimensional variation (linear contractions) of mangrove wood, Radial and Tangential contraction calculations were performed using Eq. 2, where ε_r = swelling index (%), L_{sat} = saturated dimension (cm), L_{dry} = dry dimension (cm).

$$\varepsilon_r = \left(\frac{L_{sat} - L_{dry}}{L_{sat}}\right) * 100 \tag{2}$$

The volumetric contraction (ΔV; cm^3) of mangrove wood was calculated using Eq. 3, where V_{sat} = saturated volume (cm^3), V_{dry} = dry volume (cm^3).

$$\Delta V = \left(\frac{V_{sat} - V_{dry}}{V_{dry}}\right) * 100 \tag{3}$$

The anisotropy coefficient (θ; %) or anisotropic factor of mangrove wood is the result of tangential and radial variations and was calculated by Eq. 4, where Ct = tangential contraction (%), Cr = radial contraction (%)

$$\theta = \frac{Ct}{Cr} \quad (4)$$

To assess the mechanical properties, the standard ASTM D143-14 (ASTM 2014) was used with dimension adaptations mentioned previously. The tests were conducted on a Universal Testing Machine with a capacity of 300 KN.

2.5 Data analysis

The raw data regarding wood's chemical and physical–mechanical properties were tested for normality using the Shapiro–Wilk test and homoscedasticity using the Levene test. ANOVA analysis of variance was used to verify the differences between the mean values of the chemical and physical–mechanical properties of the three species of mangrove trees (*R. mangle*, *A. germinans*, and *L. racemosa*). When the data did not meet the assumptions of normality or homoscedasticity, the Kruskal–Wallis (H) non-parametric analysis of variance was used; when significant, Dunn's post hoc tests were applied to the results. These analyses were performed using the BioEstat 5.0 statistical package (Ayres et al. 2007).

3 Results

3.1 Chemical features

The chemical characterization of wood from the three mangrove species is described in Table 1. The contents of ash, lignin, holocellulose, and total extractives were presented in different proportions. In the results obtained for ash content, *A. germinans* presented the highest values, followed by *L. racemosa* and *R. mangle*, with a significant difference found between the three species ($H=27.9$; df = 2; $p<0.05$). *R. mangle* presented the highest values for lignin content compared to the other two species (*L. racemosa* and *A. germinans*), with no significant difference between the three species. The same trend of significance was recorded for holocellulose, although the highest values were recorded for *R. mangle*, followed by *A. germinans* and *L. racemosa*. The total extractive content was highest for *L. racemosa*, followed by *A. germinans* and *R. mangle*, but varying significantly between the three species ($H=17.3$; df = 2; $p<0.05$).

Table 1 Mean ± standard deviation for the contents of ash (%), lignin (%), holocellulose (%), and total extractives (%) of wood from the three dominant tree species in Amazonian mangroves. Rm: *Rhizophora mangle*; Ag: *Avicennia germinans*; Lr: *Laguncularia racemosa*; *p*: significance level; n.s.: not significant

Species	Ash	Lignin	Holocellulose	Total Extractives
Lr	1.7 ± 0.3	23.7 ± 2.4	60.2 ± 3.3	14.5 ± 2.1
Ag	2.3 ± 0.5	20.7 ± 4.4	62.7 ± 9.5	14.4 ± 2.1
Rm	0.8 ± 0.1	24.9 ± 3.3	70.0 ± 2.4	4.3 ± 1.8
P	< 0.05	n.s	n.s	< 0.05

3.2 Physical-mechanical features

The basic density, contraction, and anisotropy presented different values for the physical characterization of wood from the three mangrove species (Table 2). In the observed results, *R. mangle* presented the highest values, followed by *A. germinans* and *L. racemosa*, varying significantly between the three species ($H=95.1$; df = 2; $p<0.05$). For linear contraction, the species *A. germinans* presented the highest radial contraction, followed by *R. mangle* and *L. racemosa*, varying significantly between the three species ($H=36.7$; df = 2; $p<0.05$). For tangential contraction, the species *R. mangle* presented the highest values, followed by *A. germinans* and *L. racemosa*, varying significantly between the three species ($H=94.0$; df = 2; $p<0.05$). In volumetric variation, the species *R. mangle* presented the highest values, followed by *A. germinans* and *L. racemosa*, varying significantly between the three species ($H=104$; df = 2; $p<0.05$). For anisotropy, the species *R. mangle* presented the highest values, followed by *A. germinans* and *L. racemosa*, varying significantly between the three species ($H=46.9$; df = 2; $p<0.05$).

The apparent density, shear strength, compression strength, bending stiffness, and bending strength

Table 2 Mean ± standard deviation of basic density (ρ; g m^{-3}), contractions (%), and anisotropy (%) of wood from the three dominant tree species in Amazonian mangroves. Rm: *Rhizophora mangle*; Ag: *Avicennia germinans*; Lr: *Laguncularia racemosa*; ρ: basic density (kg m^{-3}); R: radial position (%); T: tangential position (%); VV: volumetric variation (%); *p*: significance level

Species	ρ	Contraction			Anisotropy
		R	T	VV	
Lr	0.6 ± 0.1	4.0 ± 4.9	5.1 ± 1.6	9.0 ± 4.9	1.6 ± 0.6
Ag	0.7 ± 0.1	5.1 ± 1.8	8.3 ± 2.3	13.3 ± 3.4	1.7 ± 0.6
Rm	0.8 ± 0.0	4.6 ± 1.4	11.5 ± 2.5	19.5 ± 3.4	2.8 ± 1.2
P	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05

presented different values for the mechanical characterization of wood from the three mangrove species (Table 3). In the observed results, *R. mangle* presented the highest values, followed by *A. germinans* and *L. racemosa*, varying significantly between the three species ($H = 49.78$; df = 2; $p < 0.05$). *Rhizophora mangle* presented the highest values for shear strength, followed by *L. racemosa* and *A. germinans*, varying significantly between the three species ($H = 37.16$; df = 2; $p < 0.05$). *Rhizophora mangle* presented the highest values for compression strength, followed by *A. germinans* and *L. racemosa*, varying significantly between the three species ($H = 49.39$; df = 2; $p < 0.05$). *Rhizophora mangle* presented the highest values for bending stiffness, followed by *A. germinans* and *L. racemosa*, varying significantly among the three species ($H = 53.22$; df = 2; $p < 0.05$). *Rhizophora mangle* presented the highest values for bending strength, followed by *A. germinans* and *L. racemosa*, varying significantly between the three species ($H = 53.20$; df = 2; $p < 0.05$).

4 Discussion

4.1 Chemical wood properties

The wood of mangrove trees from the Amazon coast presented different values regarding the four chemical properties analyzed here. However, only the values for ash and total extractives differed significantly, with the highest levels evident for *A. germinans* and *L. racemosa*. Considering tree species characteristic of mangrove areas on other continents (Table 4), our results for *R. mangle* are close to those found for *Xylocarpus granatum* J. Koenig. (0.9%) in the Bintuni Bay, West Papua, Indonesia (Ramos et al. 2019). Those from *A. germinans* are similar to those found for *Sonneratia apetala* Buch.-Ham. (2.1%) in Keora, Bangladesh (Jahan and Nasima 2009), and *L. racemosa* similar to those found for *Xylocarpus mekongests* Pierre. (1.6%), and *Bruguiera gymnorrhiza* (L.) Savigny ex Lam. (1.7%) in the Bangladesh and Indonesia (Mun et al. 2011; Ramos et al. 2019) (Table 4). The same table presents percentage values for ash, lignin, holocellulose, and total extractive content of wood from other typical trees

Table 3 Mean ± standard deviation of apparent density at 12% ($\rho_{12\%}$; kg m^{-3}), shear strength (f_{v0}; MPa), compression strength (f_{c0}; MPa), bending stiffness (E_{M0}; GPa), and bending strength (f_M; MPa). Rm: *Rhizophora mangle*; Ag: *Avicennia germinans*; Lr: *Laguncularia racemosa*; *p*: significance level

Species	$\rho_{12\%}$	f_{v0}	f_{c0}	E_{M0}	f_M
Lr	726.8 ± 52.4	12.5 ± 2.5	39.1 ± 6.2	5.8 ± 2.1	86.4 ± 25.3
Ag	882.0 ± 88.9	12.1 ± 3.8	45.3 ± 7.6	11.5 ± 2.3	106.6 ± 18.4
Rm	1031.6 ± 39.6	21.8 ± 4.6	79.6 ± 6.5	18.8 ± 2.6	190.0 ± 13.2
P	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05

from inland environments, such as *Manilkara huberi* (Ducke) Standl. (0.2%), *Bowdichia nitida* Spruce ex Benth (0.1%), *Caryocar villosum* (Aubl.) Pers. (1.0%), and *Piptadenia suaveolens* Miq. (0.5%), commonly found in dryland forests in the Amazon region of South America; the values recorded in the present study are still higher (Medeiros et al. 2021) (Table 4). These results may represent a positive consequence regarding natural durability, as wood with a higher ash content generally has higher resistance to xylophagous agents (Paes et al. 2013). On the other hand, wood from *R. mangle* presented the lowest value of chemical and physical wood properties, equivalent to wood from other types of vegetation from dryland forests, such as *Erisma uncinatum* Warm. (0.7%), already studied in Brazil's southern and northern regions (Batista et al. 2021) (Table 4).

Considering that the total lignin and holocellulose contents did not differ significantly between the three mangrove species, even minor variations in these compounds may be relevant from a technological point of view. The total lignin found here varied between 20.7 and 24.9%, close to the values recorded for other species of mangrove trees, such as *Rhizophora mucronata* Lam. (28.0%) and *Xylocarpus mekongests* Pierre. (21.3%), and *S. apetala* (27.4%) studied in mangroves in Africa (Kenya: Verheyden et al. 2005) and Asia (Bangladesh: Jahan and Nasima 2009; Mun et al. 2011) (Table 3). These lignin values are also similar to those from other types of vegetation originating from dryland forests, such as *Schizolobium parahyba* var. *amazonicum* (Huber ex Ducke) Barneby (range between 25.6 and 29.1%) studied in the forests of the Brazilian Amazon, in South America (Melo et al. 2013; Mascarenhas et al. 2021) (Table 4). Considering that hardwoods have around 24% lignin (Walker 2006), our results may provide an advantage for the use of *R. mangle* wood in the carbonization process (Santos et al. 2016; Islam et al. 2019), because lignin content has a strong correlation with calorific value (White 1987; Gouvêa et al. 2015; Domingos et al. 2020). Another advantage is protection against deteriorating agents, as lignin is responsible for cell wall waterproofing (Vidaurre et al. 2013) and also protects it against the action of degrading agents (Kačík et al. 2015; Medeiros et al. 2021).

Holocellulose varied between 60.2 and 70.0%, with *R. mangle* wood presenting a higher value than the other species. This study found holocellulose close to that recorded for other mangrove species, such as *S. apetala* (between 71.0% and 83.0%) and *Heritiera fomes* (Buch.-Ham) (76.0%) on the Asian continent (Bangladesh: Jahan and Nasima 2009; Mun et al. 2011) (Table 4). On the other hand, our results showed values higher than those found for *R. mucronata* (30%) on the African continent (Kenya: Verheyden et al. 2005). The results found

Table 4 Average values for ash (A; %), lignin (L; %), holocellulose (H; %), and total extractive (TE; %) content of wood from mangrove tree species from other continents and tree species from different tropical forests available in published papers

Mangrove species	A	L	H	TE	Reference
Rhizophora mucronata Lam	-	28.0	30.0	6.0	Verheyden et al. (2005)
Sonneratia apetala Buch.-Ham	2.1	27.4	71.0		Jahan and Nasima (2009)
S. apetala	1.6	31.8	83.0	0.3	Mun et al. (2011)
Excoecaria agallocha L	3.2	23.6	77.8	1.0	
Avicennia alba Blume	1.2	35.0	82.9	0.8	
Heritiera fomes Buch.-Ham	2.6	25.8	76.0	2.2	
Xylocarpus mekongests Pierre	1.6	21.3	81.0	1.1	
Bruguiera gymnorhiza (L.) Lam. ex Savigny	1.0	32.0	76.3	0.6	
A. alba	3.1	-	-	-	Ramos et al. (2019)
Xylocarpus granatum J.Koenig	0.9	-	-	-	
Aegialitis rotundifolia Roxb	1.5	-	-	-	
Ceriops decandra (Griff.) W.Theob	1.8	-	-	-	
B. gymnorrhiza	1,7	-	-	-	
H. fomes	10.4	-	-	-	
S. apetala	1.3	-	-	-	
Avicennia marina (Forssk.) Vierh	1.8	-	-	-	
Rhizophora stylosa Griff	1.1	-	22.7	-	Adebayo et al. (2019)
Rhizophora apiculata Blume	6.3	39.0	33.1	9.1	Irman et al. (2022)
Bruguiera cilindrica (L.) Blume	1.2	28.0	-	-	Sakurai et al. (2023)
R. mucronata	1.1	22.0	-	-	
A. marina	4.3	19.2	-	-	
Non-mangrove species					
Manilkara huberi (Ducke) Standl	0.2	-	-	-	Medeiros et al. (2021)
Bowdichia nitida Spruce ex Benth	0.1	-	-	-	
Caryocar villosum (Aubl.) Pers	1.0	-	-	-	
Piptadenia suaveolens Miq	0.5	-	-	-	
Erisma uncinatum Warm.	0.8	-	-	-	Batista et al. (2021)
Schizolobium parahyba (Vell.) Blake)	-	25.6	-	-	Melo et al. (2013)
S. parahyba	-	29.1	-	-	Mascarenhas et al. (2021)

here also emphasize that *L. racemosa* wood may have an advantage in the carbonization process, considering that wood with low levels of holocellulose presents good yields for the production of charcoal (Vale et al. 2010). In contrast, this is a disadvantage for *R. mangle*, as the wood of this species has the highest holocellulose among those species dominant on the Amazon coast. In addition, wood with higher holocellulose contents has greater rigidity and resistance to mechanical bending. It may be better suited for civil construction, such as a base for house covering, and rural constructions, such as stakes for fences and bridges (Rowell et al. 2005; Nahuz et al. 2013).

Of the total extractives, the percentages found for the three dominant mangrove species on the Amazon coast varied between 4.3 and 14.5%, with the values for *A. germinans* and *L. racemosa* wood being, on average, higher than those of *R. mangle*. Total extractives are one of the main components of wood, along with cellulose, hemicellulose, and lignin (Vainio-Kaila et al. 2017). Despite being present in a smaller proportion compared to lignin and holocellulose, these secondary components should not be neglected during the wood classification process (Protásio et al. 2021), as total extractives influence natural durability, resistance to fungal degradation, and the organoleptic properties of wood (Menucelli et al. 2019; Zeniya et al. 2019). Overall, our results were close to or superior to those found for other established mangrove species in Africa (Kenya: *R. mucronata* – 6.0%; Verheyden et al. 2005) and Asia (Bangladesh: *H. fomes* – 2.2%; (Mun et al. 2011). The highest percentage of total extractives recorded here for *A. germinans* and *L. racemosa* indicates that the wood of these species has characteristics to preserve the tree's internal tissue against deteriorating attacks (Amusant et al. 2004). However, only a study aimed at understanding the process of natural resistance to rot could provide better information. Additionally, on the Amazon coast and in other places on the planet, communities extract tannin from the bark of trees of the genus *Rhizophora* as raw material for dyeing boat sails and to combat wood-degrading agents (Dewi et al. 2018; Fernandes et al. 2018; Hilmi et al. 2021).

4.2 Physical-mechanical wood properties

Considering the variable basic and apparent wood density, our results showed significant differences between the three species of mangrove trees (*R. mangle*, *A. germinans*, and *L. racemosa*). According to the basic density classification criteria, *R. mangle* wood is classified as heavy wood, with values above 0.8 g m^{-3} (ABNT 2003; IBAMA 2023). In contrast, wood from *A. germinans* and *L. racemosa* were classified as medium, with values between 0.6 and 0.7 g m^{-3} (ABNT 2003; IBAMA 2023). Regarding the classification of apparent density, *R. mangle* e *A. germinans* with heavy wood (Mainieri and Chimelo 1989). In contrast, wood from *L. racemosa* was classified as medium (Mainieri and Chimelo 1989). This high density directly influences the increase in resistance to physical-mechanical damage and to attack by wood-boring invertebrates (Jacobsen et al. 2005; Santini et al. 2012). Values related to wood contraction also varied significantly between the three species, especially in the radial contraction of *A. germinans* wood, which presented the highest value. *Rhizophora mangle* wood presented the highest values in tangential contraction and volumetric variation. Only the tangential and volumetric contraction variables in *R. mangle* were significantly dependent on density, except radial contraction, whose values were lower than expected, largely due to the basic density of *R. mangle* wood. This difference between radial and tangential contraction in *R. mangle* wood is a characteristic of immature trees, whose juvenile wood is abundant (Lorenzo and Muñoz 2018). The effect of wood basic density on dimensional stability, which is the anisotropic factor of wood, was quite notable, particularly in trees of the species *A. germinans* and *L. racemosa*, which were classified with normal dimensional stability (between 1.5 and 2.0), while *R. mangle* was classified as having poor dimensional stability (above 2.0). This poor classification can be attributed to high contraction and volumetric variation values, indicating that this wood has higher tendencies to crack and warp (Motta et al. 2014; Alves et al. 2017). Finally, the influence of age, as in the case of juvenile wood on the anisotropic factor in *R. mangle*, has to be a factor to be observed, as juvenile wood has disorganized growth and has not yet been stabilized, causing this wood to have greater dimensional instability (Lorenzo and Muñoz 2018; Topanotti et al. 2021).

In general, the variables apparent density, shear strength, compressive strength, bending strength, and stiffness were significantly influenced by the difference between the density values of wood (Moreschi 2012; Mokhtar et al. 2018), with *R. mangle* standing out for presenting higher values for all properties studied here. However, this trend was not observed in shear strength for high and medium-density woods, i.e., *A. germinans* and *L. racemosa*. These species presented statistically non-significant values, which may be an effect arising from intrinsic factors such as plant genetics, growth rings (Fiorelli et al. 2009; Sales et al. 2021), presence of juvenile wood (Balboni et al. 2020), length, and cell density (Jakob et al. 2022), tree age, as well as other factors such as growth areas and grain arrangement (Khalid et al. 2010; Vidaurre et al. 2012; Wahab et al. 2017).

A study carried out in Segara Anakan Lagoon, Indonesia, with other species of the genus *Rhizophora* L. showed that *R. apiculata* Blume, *R. mucronata* Lamk., and *R. stylosa* Griff. were the species with the highest values for the mechanical resistance of wood, being classified as high resistance (Hilmi 2018). Comparatively, the same result was found for wood from *R. apiculata* and *R. mucronata* trees, which also presented the highest values for mechanical resistance in studies carried out in Malaysia (Wahab et al. 2020) and Kenya (Manguriu et al. 2013). The same trend was also observed in Indonesia for other species of *Avicennia*, where *A. marina* (Forsk.) Vierh. and *A. alba* Blume. were classified as of moderate strength (Hilmi 2018). Our findings also reveal that *R. mangle* has higher mechanical wood properties than *A. germinans* and *L. racemosa*, indicating that *Rhizophora* is probably the genus with the strongest wood among all mangrove species, even worldwide.

We also compared the results of physical and mechanical properties with those of commercial species from the Amazon rainforest widely used in civil construction and charcoal production (Table 5). Based on basic density, *R. mangle* wood presents values similar to *Manilkara bidentata*'s (A. DC.) Chev. and *Bowdichia nitida* Spruce ex Benth. On the other hand, *A. germinans* and *L. racemosa* wood have densities similar to those of *Goupia glabra* Aubl. and *Dinizia excelsa* Ducke, respectively. Regarding radial contraction, the data for *R. mangle* are similar to those of *Caryocar villosum* Pers., while those for *A. germinans* and *L. racemosa* are close to those of *Manilkara bidentata* (A. DC.) Chev. and *Bagassa guianensis* Aubl., respectively. Regarding tangential contraction, the data for *R. mangle* are lower than those found for *Lecythis poiteaui* Berg., while those for *A. germinans* and *L. racemosa* are close to those for *Mezilaurus itauba* (Meisn.) Taub. ex Mez. and *B. guianensis*, respectively. Regarding

Table 5 Average values for basic density (ρ; g m^{-3}), contractions radial (R; %), tangential (T; %), volumetric variation (VV; %), anisotropy (A; %), apparent density at 12% ($\rho_{12\%}$; kg m^{-3}), shear strength (f_{v0}; MPa), compression strength (f_{c0}; MPa), bending stiffness (E_{M0}; GPa), and bending strength (f_M; MPa), for commercial species from the Amazonian terra firme forest (Andrade 2015)

Species	Popular name	Physical properties				
		ρ	R	T	VV	A
Hymenolobium excelsum Ducke	Angelim da mata	0.6	4.8	7.4	12.2	1.6
D. excelsa	Angelim vermelho	0.6	4.8	7.4	12.2	1.6
Lecythis pisonis Cambess	Sapucaia	0.9	5.4	7.7	13.1	1.4
Erisma uncinatum Warm	Cedrinho	0.5	4.5	9.1	13.6	2.0
Goupia glabra Aubl	Cupiúba	0.7	4.5	7.8	12.3	1.7
Mezilaurus itauba (Meisn.) Taub. ex Mez	Itauba	0.8	3.2	8.1	11.3	2.6
Lecythis poiteaui Berg	Jarana amarela	0.9	6.8	12.8	19.7	1.9
Manilkara bidentata (A. DC.) Chev	Maparajuba	0.8	5.1	9.1	14.3	1.8
Caryocar villosum Pers	Pequiá	0.7	4.6	8.3	12.9	1.8
Bowdichia nitida Spruce ex Benth	Sucupira preta	0.8	6.0	8.6	14.6	1.4
Tachigali myrmecophila (Ducke) Ducke	Tachi-preto	0.6	4.3	7.3	11.6	1.7
Piptadenia gonoacantha (Mart.) J.F. Macbr	Timborana	0.7	5.1	7.3	12.4	1.4
H. coubaril	Jatobá	0.7	3.4	7.7	11.4	2.3
Bagassa guianensis	Tatajuba	0.7	4.1	5.8	9.5	1.4
Couratari oblongifolia	Tauari	0.5	4.2	6.6	10.9	1.6
		Mechanical properties				
		$\rho_{12\%}$	f_{v0}	f_{c0}	f_M	E_{M0}
B. nitida	Sucupira preta	950	18.8	100.3	182.0	17.5
L. pisonis	Sapucaia	1030	15.0	63.7	129.8	12.9
Dinizia excelsa Ducke	Angelim vermelho	760	21.1	106.9	196.6	19.6
Hymenolobium excelsum	Angelim da mata	760	17.1	83.8	157.8	17.2
Goupia glabra Aubl	Cupiúba	870	15.7	78.6	142.7	14.3
M. itauba	Itauba	910	13.2	77.0	141.6	15.4
Lecythis poiteaui Berg	Jarana amarela	1080	17.7	68.0	128.5	14.2
M. bidentata	Maparajuba	970	13.8	73.2	142.8	14.3
Caryocar villosum Pers	Pequiá	900	16.1	58.6	121.8	12.7
Tachigali myrmecophila (Ducke) Ducke	Tachi-preto	760	19.1	83.2	156.7	16.4
Piptadenia gonoacantha (Mart.) J.F. Macbr	Timborana	860	18.2	89.8	148.3	15.9
D. odorata	Cumaru	1070	15.4	103.6	158.6	15.1
Apuleia leiocarpa (Vogel) J.F.Macbr	Garapeira	880	15.2	74.7	147.5	15.0
Handroanthus serratifolius (Vahl) S.Grose	Ipe roxo	1010	13.8	87.8	174.4	13.2
Manilkara huberi (Ducke)	Maçaranduba	1070	16.3	105.8	171.4	16.6
Astronium lecointei Ducke	Muiracatiara	970	18.0	88.4	146.3	16.1

volumetric variation, the data for *R. mangle* are close to those found for *Lecythis poiteaui* Berg., while those for *A. germinans* and *L. racemosa* are close to those for *Erisma uncinatum* Warm. and *B. guianensis*, respectively. Regarding anisotropy, the data for *R. mangle* are close to those found for *Mezilaurus itauba* (Meisn.) Taub. ex Mez., while those for *A. germinans* and *L. racemosa* are close to those for *G. glabra* and *D. excelsa*, respectively.

Regarding mechanical properties, our bulk density data for *R. mangle* are close to those for *Lecythis pisonis* Cambess. For *A. germinans*, the values are similar to those of *Apuleia leiocarpa* (Vogel) J.F.Macbr., and for *L. racemosa*, the data are close to those found for *Dinizia excelsa* Ducke and *Hymenolobium excelsum* Ducke. For shear strength, *R. mangle* is superior to those of *Tachigali myrmecophila* (Ducke) Ducke, *A. germinans*, and *L. racemosa* are close to those found for *Mezilaurus itauba* (Meisn.) Taub. ex Mez. and *Manilkara bidentata* (A. DC.) Chev.

For compression strength, *R. mangle* presented values close to *Goupia glabra* Aubl. and *M. itauba*, while *A. germinans* and *L. racemosa* did not present values similar to commercial tree species from the Amazon. For bending stiffness, *R. mangle* presented values close to those of *D. excelsa*, while *A. germinans* presented values close to those of *L. pisonis*. However, *L. racemosa* did not show values like any other species. For bending strength, *R. mangle* presented values close to those of *D. excelsa*, while *A. germinans* and *L. racemosa* did not present values similar to commercial tree species from the Amazon (Table 5).

5 Conclusion

Our study provides valuable insights into the chemical, physical, and mechanical properties of typical mangrove wood species from the Amazon coast, focusing on *R. mangle*, *A. germinans*, and *L. racemosa*. This is the first scientific work to adopt this type of physical approach—showing linear contraction—for mangrove wood. Chemical analysis revealed that ash and total extractive contents were higher in *A. germinans* and *L. racemosa*, respectively, suggesting potential advantages in natural durability and resistance to xylophagous agents. In contrast, the physical–mechanical analysis indicated that *R. mangle* wood exhibited higher metrics of basic and apparent density, linear contraction, anisotropy, and mechanical strength, while *A. germinans* presented the highest values for radial contraction. Based on its higher density and mechanical strength, *R. mangle* wood is more suitable for civil construction despite its poor dimensional behavior. *Rhizophora mangle* presented high levels of lignin, which increases its mechanical strength, while the higher levels of holocellulose in *L. racemosa* make this wood more suitable for charcoal production, mainly due to its favorable gravimetric yield. To broaden our understanding of the typical woods of Amazonian mangroves and all ecoregions of the Americas, it is necessary to expand studies on their technological properties, such as assessing their natural durability and directing these studies to all mangrove tree species. These results will contribute to better-developing management strategies that ensure the maintenance of ecological functions and the conservation of existing resources in mangroves as a source of subsistence for user communities.

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Data availability
The datasets generated during and/or analyzed during the current study are available in the figshare repository [https://doi.org/10.6084/m9.figshare.28038326].

Declarations

Consent for publication
Not applicable.

Competing interests
The authors declare that they have no competing interests.

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References

Abreu MMO, Veiga N, Costa-Neto SV, Fernandes MEB (2016) Vegetação Arbórea: Distribuição Espacial. In: Fernandes MEB (ed) Os Manguezais da Costa Norte Brasileira. Bragança, Pará, pp 35–78

Adebayo GO, Hassan A, Yahya R et al (2019) Influence of wood surface chemistry on the tensile and flexural properties of heat-treated mangrove/high-density polyethylene composites. Polym Bull 76:6467–6486. https://doi.org/10.1007/s00289-019-02731-0

Alongi DM (2002) Present state and future of the world's mangrove forests. Environ Conserv 29:331–349. https://doi.org/10.1017/S0376892902000231

Alves RC, Oliveira ALC, Carrasco EVM (2017) Propriedades físicas da madeira de *Eucalyptus cloeziana* F. Muell Floresta e Ambiente 24:e00015312. https://doi.org/10.1590/2179-8087.015312

American Society for Testing and Materials (2014) ASTM D143–14: Standard test methods for small clear specimens of timber. ASTM International, West Conshohocken, PA. https://doi.org/10.1520/D0143-14

American Society for Testing and Materials (2021a) ASTM D1107–96: Standard test methods for ethanol-toluene solubility of wood. ASTM International, West Conshohocken, PA. https://doi.org/10.1520/D1107-96

American Society for Testing and Materials (2021b) ASTM D1106–21: Standard test method for acid-insoluble lignin in wood. ASTM International, West Conshohocken, PA. https://doi.org/10.1520/D1106-21

American Society for Testing and Materials (2021c) ASTM D1102–84: Standard test method for ash in wood. ASTM International, West Conshohocken, PA. https://doi.org/10.1520/D1102-84R21

American Society for Testing and Materials (2022) ASTM D2395–17: Standard test methods for density and specific gravity (relative density) of wood and wood-based materials. ASTM International, West Conshohocken, PA. https://doi.org/10.1520/D2395-17

Amusant N, Beauchene J, Fournier M et al (2004) Decay resistance in *Dicorynia guianensis* Amsh.: analysis of inter-tree and intra-tree variability and relations with wood colour. Ann for Sci 61:373–380. https://doi.org/10.1051/forest:2004030

Andrade A (2015) Pisos de madeira: características de espécies brasileiras. Associação Nacional dos Produtores de Pisos de Madeira (ANPM). Piracicaba, São Paulo, pp 3–184

Associação Brasileira de Normas Técnicas (2003) ABNT NBR–11941: Madeira — Determinação da densidade básica em madeira. Rio de Janeiro, pp 1–6

Ayres M, Ayres MJr, Ayres DL, Santos AS (2007) BiosEstat 5.0: Aplicações estatísticas nas áreas das ciências biológicas e médicas. Belém, Pará, Brasil

Balboni BM, Batista AS, Rodrigues RA, Garcia JN (2020) Relationship between strength and density in juvenile and mature *Eucalyptus* sp. wood / Relação entre resistência e densidade em madeira juvenil e adulta de *Eucalyptus* sp. Brazilian Journal of Animal and Environmental Research 3:983–991. https://doi.org/10.34188/bjaerv3n3-019

Batista L, Stangerlin DM, Melo RRD, Souza APD, Silva EDS et al (2021) Resistência mecânica e composição química de madeiras amazônicas deterioradas em ensaios de campo. Madera y bosques, 27:e2712079. https://doi.org/10.21829/myb.2021.2712079

Chambi-Legoas R, Chaix G, Castro VR et al (2021) Inter-annual effects of potassium/sodium fertilization and water deficit on wood quality of *Eucalyptus grandis* trees over a full rotation. For Ecol Manage 496:119415. https://doi.org/10.1016/j.foreco.2021.119415

Dewi LF, Pringgenies D, Ridlo A (2018) Pemanfaatan Mangrove *Rhizophora mucronata* Sebagai Pewarna Alami Kain Katun. J Mar Res 7:79–88. https://doi.org/10.14710/jmr.v7i2.25896

Diniz C, Cortinhas L, Nerino G et al (2019) Brazilian mangrove status: three decades of satellite data analysis. Remote Sens (Basel) 11:808. https://doi.org/10.3390/rs11070808

Domingos I, Ayata U, Ferreira J et al (2020) Calorific power improvement of wood by heat treatment and its relation to chemical composition. Energies (Basel) 13:5322. https://doi.org/10.3390/en13205322

Fernandes MEB, Oliveira FP, Eyzaguirre IAL (2018) Mangroves on the Brazilian Amazon coast: uses and rehabilitation. In: Makowski C, Finkl CW (eds) In: Makowski, C., Finkl, C. (eds) Threats to Mangrove Forests. Coastal Research Library, Springer, Cham. Springer International Publishing, Cham, pp 621–635. https://doi.org/10.1007/978-3-319-73016-5_29

Fiorelli J, Dias AA, Coiado B (2009) Propriedades mecânicas de peças com dimensões estruturais de *Pinus* spp: correlação entre resistência à tração e classificação visual. Revista Árvore 33:741–750. https://doi.org/10.1590/S0100-67622009000400017

Food and Agriculture Organization of the United Nations, International Fund for Agricultural Development, United Nations Children's Fund, World Food Programme and World Health Organization. The state of food security and nutrition in the world 2023. FAO, Rome. https://doi.org/10.4060/cc3017en

Galvão ML, Rodrigues TNM, Santos IS, Fernandes MEB (2024) Traditional ecological knowledge of mangrove wood use on the Brazilian Amazon coast. Ethnobiology and Conservation 13:1–19. https://doi.org/10.15451/ec2024-01-13.03-1-19

Goldschmid O (1971) Ultravioleta Spectra. In: Sarkanem K, Ludwing C (eds) Lignins: ocurrence, formation, structure and reactions. John Wiley & Sons, New York, pp 241–298

Gouvêa AFG, Trugilho PF, Assis CO et al (2015) Evaluation of syringyl/guaiacyl ratio of eucalypt lignin in the charcoal production. Ciência da Madeira 6:71–78. https://doi.org/10.12953/2177-6830/rcm.v6n2p71-78

Hilmi E (2018) Mangrove landscaping using the modulus of elasticity and rupture properties to reduce coastal disaster risk. Ocean Coast Manag 165:71–79. https://doi.org/10.1016/j.ocecoaman.2018.08.002

Hilmi E, Sari LK, Siregar AS et al (2021) Tannins in mangrove plants in segara anakan lagoon, central java, indonesia. Biodiversitas 22. https://doi.org/10.13057/biodiv/d220850

Instituto Brasileiro do Meio Ambiente e dos Recursos Naturais Renováveis – IBAMA (2023) Banco de dados de madeiras brasileiras. https://lpf.florestal.gov.br/pt-br/madeiras-brasileirashttps://lpf.florestal.gov.br/pt-br/madeiras-brasileiras. Accessed 24 Aug 2023

Instituto Nacional de Meteorologia – INMET (2022) Banco de dados meteorológicos para ensino- pesquisa. http://www.inmet.gov.br. Accessed 9 Mar 2023

Irman N, Abd Latif NH, Brosse N et al (2022) Preparation and characterization of formaldehyde-free wood adhesive from mangrove bark tannin. Int J Adhes Adhes 114:103094. https://doi.org/10.1016/j.ijadhadh.2022.103094

Islam MN, Ratul SB, Sharmin A et al (2019) Comparison of calorific values and ash content for different woody biomass components of six mangrove species of Bangladesh Sundarbans. J Indian Acad Wood Sci 16:110–117. https://doi.org/10.1007/s13196-019-00246-9

Jacobsen AL, Ewers FW, Pratt RB et al (2005) Do xylem fibers affect vessel cavitation resistance? Plant Physiol 139:546–556. https://doi.org/10.1104/pp.104.058404

Jahan MS, Nasima A (2009) Pulping of Keora (*Sonneratia apetala*) a major mangrove species of Bangladesh. IPPTA J 21:51–54. https://ippta.co/wp-content/uploads/2021/01/2009_Issue_2_IPPTA_Articel_02.pdf

Jakob M, Mahendran AR, Gindl-Altmutter W et al (2022) The strength and stiffness of oriented wood and cellulose-fibre materials: a review. Prog Mater Sci 125:100916. https://doi.org/10.1016/j.pmatsci.2021.100916

Kačík F, Šmíra P, Kačíková D et al (2015) Chemical alterations of pine wood saccharides during heat sterilisation. Carbohydr Polym 117:681–686. https://doi.org/10.1016/j.carbpol.2014.10.065

Khalid I, Wahab R, Sudin M et al (2010) Chemical changes in 15 year-old cultivated acacia hybrid oil-heat treated "at 180, 220 and 220°C." Int J Chem 2. https://doi.org/10.5539/ijc.v2n1p97

Lorenzo JÁP, Muñoz GR (2018) Inter-tree and intra-tree variation in the physical properties of wood of laurel (*Laurus nobilis*). Eur J for Res 137:507–515. https://doi.org/10.1007/s10342-018-1119-y

Mainieri C, Chimelo JP (1989) Fichas de características das madeiras brasileiras. Instituto de Pesquisas Tecnológicas – IPT, Divisão de Madeiras. São Paulo

Manguriu G, Oyawa W, Abudha S (2013) Physical and mechanical properties of mangrove from Kilifi in Kenya. Global Eng Technol Rev 3:1–5

Mascarenhas ARP, Sccoti MSV, Melo RR et al (2021) Characterization of wood from *Schizolobium parahyba* var. *amazonicum* Huber × Ducke trees from a multi-stratified agroforestry system established in the Amazon rainforest. Agrofor Syst 95:475–486. https://doi.org/10.1007/s10457-020-00576-5v

Medeiros DT, Melo RR, Cademartori PHG et al (2021) Caracterização da madeira de espécies da Amazônia. Madera y bosques 27:e2722209. https://doi.org/10.21829/myb.2021.2722209

Medina E, Giarrizzo T, Menezes M et al (2001) Mangal communities of the "Salgado Paraense": ecological heterogeneity along the Bragança peninsula assessed through soil and leaf analyses. Amazoniana: Limnologia et Oecologia Regionalis Systematis Fluminis Amazonas 16:397–416

Melo RR, Del Menezzi CHS, Souza MR, Stangerlin DM (2013) Evaluation of physical, chemical, mechanical and surface properties of the *Schizolobium amazonicum* Veneer. Floresta e Ambiente 20:238–249. https://doi.org/10.4322/floram.2013.004

Menezes MPM, Berger U, Mehlig U (2008) Mangrove vegetation in Amazonia: a review of studies from the coast of Pará and Maranhão States, North Brazil. Acta Amazon 38:403–420. https://doi.org/10.1590/S0044-59672008000300004

Menucelli JR, Amorim EP, Freitas MLM et al (2019) Potential of *Hevea brasiliensis* clones, *Eucalyptus pellita* and *Eucalyptus tereticornis* wood as raw materials for bioenergy based on higher heating value. Bioenergy Res 12:992–999. https://doi.org/10.1007/s12155-019-10041-6

Mokhtar N, Wahab R, Sulaiman MS et al (2018) *Rhizophora apiculata*: comparative properties between solid and engineered laminated boards. Borneo J Sci Technol 2:41–47. https://doi.org/10.35370/bjost.2020.2.1-08

Moraes BC, Costa JMN, Costa ACL, Costa MH (2005) Variação espacial e temporal da precipitação no estado do Pará. Acta Amazon 35:207–214. https://doi.org/10.1590/S0044-59672005000200010

Moreschi JC (2012) Propriedades da madeira. Departamento De Engenharia e Tecnologia Floresta l-UFPR Paraná 4:1–208

Motta JP, Oliveira JTS, Braz RL et al (2014) Characterization of wood of four forest species. Ciência Rural 44:2186–2192. https://doi.org/10.1590/0103-8478cr20130479
Mun SP, Jahan MS, Al-Maruf A, Chowdhury DAN (2011) Chemical characterization of six mangrove species in Bangladesh. Wood Sci Technol 45:281–288. https://doi.org/10.1007/s00226-010-0333-7
Nahuz AR, Miranda M, Ielo PKY et al (2013) Catálogo de madeiras brasileiras para a construção civil - São Paulo: IPT Instituto de Pesquisas Tecnológicas do Estado de São Paulo
Paes JB, Medeiros Neto PN, Lima CR et al (2013) Efeitos dos extrativos e cinzas na resistência natural de quatro madeiras a cupins xilófagos. Cerne 19:399–405. https://doi.org/10.1590/S0104-77602013000300006
Protásio TP, Lima MDR, Teixeira RAC et al (2021) Influence of extractives content and lignin quality of *Eucalyptus* wood in the mass balance of pyrolysis process. Bioenergy Res 14:175–189. https://doi.org/10.1007/s12155-020-10166-z
Ramos RMQ, Siacor FDC, Taboada EB (2019) Chemical properties of waste mangrove bark and its potential uses. Intern Wood Prod J 10:162–167. https://doi.org/10.1080/20426445.2019.1698810
Rodríguez-Anda R, Fuentes-Talavera FJ, Silva-Guzmán JA et al (2018) Relationship of the cellular structure of teak wood (*Tectona grandis* L. f.) with different ages and growth sites. Revista Chapingo Serie Ciencias Forestales y Del Ambiente 24:101–114. https://doi.org/10.5154/r.rchscfa.2017.07.050
Rowell RM, Pettersen R, Han JS et al (2005) Cell wall chemistry. Handbook of Wood Chemistry and Wood Composites 2:33–72
Sakurai Y, Kobayashi J, Sakai Y, Naruse I (2023) Pyrolysis and steam gasification properties of mangroves. Chemosphere 345:140388. https://doi.org/10.1016/j.chemosphere.2023.140388
Sales DF, Balboni BM, Batista AS, Moutinho VHP (2021) Amazon false cedar: a substitute for medium-density timbers from vulnerable species. Revista Ibero-Americana De Ciências Ambientais 12:29–37. https://doi.org/10.6008/CBPC2179-6858.2021.003.0003
Santini NS, Schmitz N, Lovelock CE (2012) Variation in wood density and anatomy in a widespread mangrove species. Trees 26:1555–1563. https://doi.org/10.1007/s00468-012-0729-0
Santos RC, Carneiro ACO, Vital BR et al (2016) Influência das propriedades químicas e da relação siringil/guaiacil da madeira de eucalipto na produção de carvão vegetal. Ciência Florestal 26:657–669. https://doi.org/10.5902/1980509822765
Souza Filho PWM (2005) Costa de manguezais de macromaré da Amazônia: cenários morfológicos, mapeamento e quantificação de áreas usando dados de sensores remotos. Revista Brasileira De Geofísica 23:427–435. https://doi.org/10.1590/S0102-261X2005000400006
Spalding M, Kainuma M, Collins L (2010) World atlas of mangroves. Routledge. https://doi.org/10.4324/9781849776608
Tomlinson PB (2016) The botany of mangroves. Cambridge University Press, ISBN: 978-1-107-08067-6
Topanotti LR, Vaz DR, Carvalho SPC et al (2021) Growth and wood density of *Pinus taeda* L. as affected by shelterwood harvest in a two-aged stand in Southern Brazil. Eur J for Res 140:869–881. https://doi.org/10.1007/s10342-021-01372-1
Vainio-Kaila T, Zhang X, Hänninen T et al (2017) Antibacterial effects of wood structural components and extractives from *Pinus sylvestris* and *Picea abies* on methicillin-resistant *Staphylococcus aureus* and *Escherichia coli* O157: H7. Bioresources 12:7601–7614. https://doi.org/10.15376/biores.12.4.7601-7614
Vale and do, Dias ÍS, Santana MAE (2010) Relações entre propriedades químicas, físicas e energéticas da madeira de cinco espécies de cerrado. Ciência Florestal 20:137–145. https://doi.org/10.5902/198050981767
Verheyden A, Roggeman M, Bouillon S et al (2005) Comparison between $\delta^{13}C$ of α-cellulose and bulk wood in the mangrove tree *Rhizophora mucronata*: implications for dendrochemistry. Chem Geol 219:275–282. https://doi.org/10.1016/j.chemgeo.2005.02.015
Vidaurre GB, Lombardi LR, Oliveira JT, S, Arantes MDC (2012) Lenho juvenil e adulto e as propriedades da madeira. Floresta e Ambiente 18:469–480. https://doi.org/10.4322/floram.2011.066
Vidaurre GB, Lombardi LR, Nutto L et al (2013) Propriedades da madeira de reação. Floresta e Ambiente 20:26–37. https://doi.org/10.4322/floram.2012.041
Virgulino-Júnior PCC, Carneiro DN, Nascimento WR Jr et al (2020) Biomass and carbon estimation for scrub mangrove forests and examination of their allometric associated uncertainties. PLoS ONE 15:e0230008. https://doi.org/10.1371/journal.pone.0230008
Voigt M (2011) The co-management approach of the Marine Extractive Reserve "Caeté–Taperaçu" in northern Brazil: analysis of selected biological and socio-economic aspects. Trabalho de Conclusão de Curso de Bacharelado em Biologia Faculdade de Matemática e Ciências Naturais, Technische Universität Dresden
Wahab R, Ghani RSM, Samsi HW, Rasat MSM (2017) Changes in colour, strength and chemical properties of oil heat treated 18-years old planted *Acacia mangium*. Int J Biol 9:12. https://doi.org/10.5539/ijb.v9n3p12
Wahab R, Mohd Fauzi N, Mokhtar N et al (2020) Enhancing mechanical properties of *Rhizophora apiculata* through engineered laminated boards. Agric For 66:53–64. https://doi.org/10.17707/AgricultForest.66.3.05
Walker JCF (2006) Basic wood chemistry and cell wall ultrastructure. In: Walker JCF (ed) Primary Wood Processing: Principles and Practice. Springer Netherlands, Dordrecht, pp 23–67. https://doi.org/10.1007/1-4020-4393-7_2
White RH (1987) Effect of lignin content and extractives on the higher heating value of wood. Wood Fiber Sci 19:446–452
Zeniya N, Endo-Ujiie K, Obataya E et al (2019) Effects of water-soluble extractives on the vibrational properties and color of hygrothermally treated spruce wood. Wood Sci Technol 53:151–164. https://doi.org/10.1007/s00226-018-1069-z

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