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Assessment of suitability of mangrove wood for different uses

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Abstract

This study analyzes the suitability of wood from tree species in Amazonian mangroves using secondary data on their chemical, physical, and mechanical properties. Mangrove species are *Rhizophora mangle* (red mangrove), *Avicennia germinans* (black mangrove), and *Laguncularia racemosa* (white mangrove). *Rhizophora mangle* stood out regarding chemical, physical, and mechanical properties, being suitable for charcoal production and civil construction due to its low ash content (0.8%) and high lignin content (24.9%). Physical and mechanical analyses confirm the high density and resistance of *R. mangle* ($\rho = 0.83 \text{ g cm}^{-3}$; $\rho_{12\%} = 1031.6 \text{ kg m}^{-3}$), while *A. germinans* and *L. racemosa*, although suitable, present some limitations. When evaluating the wood quality, the correlation matrix shows a strong correlation between the physical and mechanical properties of the mangrove tree species. More in-depth studies on the anatomy and durability of these woods are still necessary to optimize their use and conservation. The results presented here are crucial to support management and conservation policies for forest resources in mangroves on the Brazilian Amazon coast.

Keywords Charcoal, Construction, Mangrove, *Rhizophora mangle*, Wood properties, Wood quality

Introduction

Mangroves are recognized as one of the most important coastal ecosystems, providing various resources [1–3]. In many countries, coastal communities depend on exploiting mangrove forests and their resources, which represent a vital source of their daily subsistence [4]. These traditional communities that live in or around the mangrove appropriate and use its resources for various functions, such as generating income, moving local and regional commerce, and social reproduction of peoples

and cultures, in addition to carrying out productive practices from the use of environmental resources [5–7].

Brazil has one of the most extensive mangrove areas in the world, approximately 9,900 km² [8], with around 80% located on the Brazilian Amazon coast [9], where the largest continuous extension of this ecosystem throughout the planet is located [10]. Over the last 3 decades, the mangroves in this region have lost little in area to human activities [8], becoming one of the largest preserved mangrove areas worldwide. Less than 1% of its total area was affected by negative anthropogenic impacts [9], noting that these authors could not identify selective logging activities of mangrove tree species on the Amazon coast through satellite images. Most mangrove areas in this region are protected by Marine Extractive Reserves—MER, whose sustainable use aims to protect livelihoods and guarantee the use and conservation of renewable natural resources traditionally used by estuarine-coastal extractivists residing in and around the covered area [11]. This is one of the main frontiers to be explored in studies on the

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deforestation of mangrove forests using satellite images in mangrove areas.

As general characteristics, MER represents public domain areas with use granted to traditional extractive populations. They are protected areas managed by a Deliberative Council that promotes the sustainable use of natural resources and the implementation of structures aimed at improving the quality of life of communities. They also must have Management Plans that define usage standards, area zoning, and socio-economic and environmental sustainability programs, among other aspects [12].

Three species of mangrove trees dominate the mangrove landscape on the Brazilian Amazon coast: *Rhizophora mangle* L.—red mangrove (*mangueiro* in Portuguese)—is the dominant tree species [13]. This species is well adapted to brackish waters and areas with a high frequency of flooding [14]. *Avicennia germinans* (L.) L.—black mangrove (*siriúba* or *siribeira* in Portuguese)—is the second most dominant tree species [14]. They dominate hypersaline areas, forming monospecific forests with tall or dwarf trees with shrubby characteristics [15, 16]. *Laguncularia racemosa* (L.) C.F. Gaertn.—white mangrove (*tinteira* in Portuguese)—trees of this species have characteristics in common with other species. They are often found on the margins of mangrove forests and in clearings with anthropic and natural effects [14].

Timber resources are highly relevant for coastal communities in this region, with different woods used for multiple functions: civil construction, weirs, and corrals for cattle, boats, firewood, charcoal, and medicinal purposes [7]. This region's most exploited mangrove tree species are *R. mangle*, *A. germinans*, and *L. racemosa* [7]. The wood of these three mangrove species is used as firewood in potteries and bakeries, and the wood of *L. racemosa* is mainly used for making weirs [6, 7]. Weirs are fixed traps with sticks and wires strategically placed on the ground to trap schools of fish within an enclosure due to the movement of the tides. Likewise, *R. mangle* and *L. racemosa* are also used for other activities, such as producing firewood to make cassava flour and charcoal for commercialization and domestic use [6, 7]. Expanding knowledge about the wood properties of mangrove species is relevant to producing a database on their characteristics and understanding how they can direct their suitability, greater yield, and safety for use. This can also serve as a basis for management policies and developing conservation strategies for this forest resource. Few tree species form the mangroves on the Brazilian Amazon coast, and exploring their technological characteristics and quality generates significant progress toward the more appropriate use and sustainability of this resource.

Using secondary data [17], this study aims to assess the suitability of wood from Amazonian mangrove tree species based on its chemical, physical, and mechanical properties.

Materials and methods

Site description

The study area is located within the Caeté-Taperaçu Extractive Reserve—MER in the northeast region of the State of Pará (0°56′03.76″S–46°36′19.48″W). The protected area is under the management of the Chico Mendes Institute for Biodiversity Conservation—ICM-Bio. 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% [18]. The dry period is from July to November, while the rainy period occurs from December to June [19]. The Caeté-Taperaçu MER was created on May 20, 2005, covering an area of around 42,068 ha, with approximately 55 extractive communities that live off subsistence fishing and family farming [11].

Data collection

The stem diameter of the trees sampled in the present study was defined based on botanical inventories previously carried out in the mangrove forest areas at the Caeté-Taperaçu MER region. The median values of Diameter at Breast Height—DBH and Height—*h* of these previously inventoried trees served as a basis for choosing the trees of each species used in the present study. A total of 15 trees (5 per species) were collected to evaluate the chemical, physical, and mechanical properties, with DBH and *H* between 20.00 and 20.24 cm, and 15 m for *R. mangle*, 23.10–23.89 cm, and 16 m for *A. germinans*, and 19.00–19.21 cm, and 7 m for *L. racemosa*. Disc and logs were selected in the commercial area, covering the stretch from the base to the first branch (Fig. 1A). The specimens were collected following License MMA/ICM-BIO/SISBIO No 77770-1. Discs were collected from 0%, 25%, 50%, 75%, and 100% positions along the stem of each mangrove tree for chemical and physical analyses, while log samples were collected between 0 and 25% positions for mechanical analyses (Fig. 1A).

For the physical characterization, radial positions were taken from the discs, from bark to bark, totaling an average of five samples per disc for *R. mangle*, seven samples for *A. germinans*, four samples for *L. racemosa* (Fig. 1B). Wedges from the collected discs were used for the chemical characterization of the mangrove species' wood, always using two opposite wedges (Fig. 1C). For the mechanical characterization, radial positions were taken from the logs, from bark to bark, free of defects, totaling

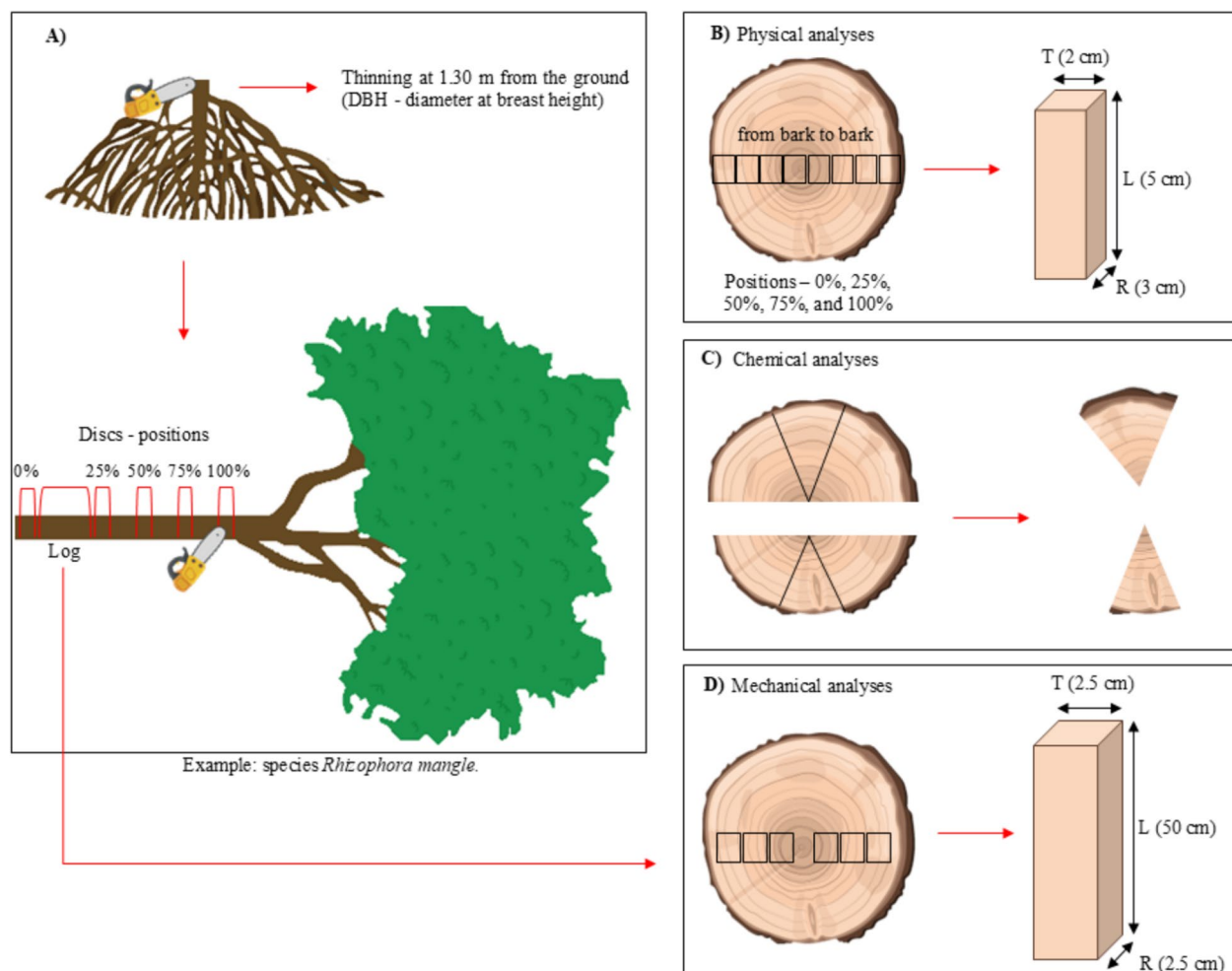


Fig. 1 Schematic of wood collection and preparation of specimens for analysis. **A** Wood cutting and selection of discs and logs; **B** Test specimens for physical analysis; **C** Wedges selected for chemical analysis; **D** Test specimens for mechanical analysis. *R* radial, *T* tangential, *L* longitudinal

an average of five samples per disc for *R. mangle*; five samples for *A. germinans*, three samples for *L. racemosa* (Fig. 1D). However, due to the difficulty in obtaining samples without defects, the dimensions of the samples were adjusted, preserving, however, their proportions—dimensions for shear (25×25 mm—height and width); compression and density (20×20×80 mm—height, width, and length); static bending (20×20×320 mm—height, width, and length).

The ash content (%) was determined following Standard NBR 13999 [20], the total extractive content (%) was determined by using Standard NBR 14853 [21], and lignin (%) was determined according to the procedures of Standard NBR 7989 [22] and Goldschmid [23]. Holocellulose (%) was determined by the difference 100—(total extractives + lignin + ash). The basic density (ρ ; g cm⁻³) was determined following Standard NBR 11941 [24], and

Mechanical properties following Standard ASTM D143 [25]. The moisture content used for all mechanical tests was 12%.

Analysis of the correlation structure of wood characteristics

We used Pearson's correlation analysis to evaluate the interaction between the chemical, physical, and mechanical characteristics presented by the wood of the mangrove species studied, using the correlation matrix of the raw values of these characteristics. Pearson linear correlation coefficient (*r*) ranges from -1 to 1, where the sign indicates the positive or negative relationship direction, and the value reflects the strength of the relationship between the variables. All statistical analyses and graphing were done using the free software RStudio and Jamovi [26, 27].

Results and discussion

Chemical properties of wood

Considering all the chemical properties analyzed here, the three mangrove tree species studied, with emphasis on *R. mangle* (Table 1), can be recommended for charcoal production.

The first characteristic of the wood analyzed was the ash content, which presented values between 0.8 and 2.3% (Fig. 2A), highlighting the wood of *R. mangle* (Table 1), and the wood should present ash contents of less than 1% [28]. Values between 20 and 24% (Fig. 2B) were recorded for the lignin content, emphasizing *R. mangle* wood (Table 1). The percentage of lignin found in the wood of this species provides an advantage in its use in the carbonization process, with the possibility of obtaining charcoal with higher levels of fixed carbon, as lignin has considerable percentages of elemental carbon in its composition [29]. The values found in this study are within the ranges considered normal for tropical woods—native species [30]. Although they are low when compared to the values found in woods from commercial *Eucalyptus* species and clones—planted species, with values around 28 to 32%—used to produce bioenergy in Brazil, a world leader in charcoal production [31].

For the holocellulose content, values between 60 and 70% were found (Fig. 2C). In addition, the behavior of holocellulose, in the face of thermal degradation processes, presents a very unstable and not very resistant profile, contributing to more significant wood degradation [29]. Therefore, high percentages of these compounds are not desirable when using wood for charcoal production, as they have low resistance to thermal degradation, resulting in higher percentages of non-condensable gases and condensable gases [32]. Based on this characteristic alone, none of the three species can be recommended for charcoal production, and it is necessary to analyze all of the wood's energetic characteristics.

Considering the total extractives, values between 4 and 14% were recorded (Fig. 2D), with emphasis on wood from *A. germinans* and *L. racemosa*, which can, therefore, be recommended for use in the production of charcoal. Wood extractives comprise a group of cell wall chemicals, including lipids, phenolic compounds, terpenoids, fatty acids, resin acids, sterols, waxes, and other minor organic compounds [33]. These compounds can promote better stability in the thermal degradation of wood [34, 35], which, depending on the percentage, can increase or decrease the gravimetric yield of charcoal [36].

Table 1 Classification of uses based on secondary data on average values for wood from mangrove species [17] for the ash content (%), lignin (%), holocellulose (%), total extractives (%), basic density (ρ ; g cm⁻³), contractions for radial and tangential (%), anisotropy (%), 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) of wood from the three dominant tree species in Amazonian mangroves

	Rm (n)	Ag (n)	Lr (n)
Chemical			
Ash	Charcoal* (15)	No indication (15)	No indication (15)
Lignin	Charcoal* (15)	Charcoal (15)	Charcoal (15)
Holocellulose	No indication (15)	No indication (15)	No indication (15)
Total Extractives	No indication (15)	Charcoal* (15)	Charcoal* (15)
Physical			
ρ	Charcoal and construction* (63)	Small constructions (71)	Small constructions (39)
Radial	Construction (63)	Construction (71)	Construction (39)
Tangential	Construction (63)	Construction (71)	Construction (39)
Volumetric variation	No indication (63)	Construction (71)	Construction (39)
Anisotropy	No indication (63)	Construction (71)	Construction (39)
Mechanical			
$\rho_{12\%}$	Charcoal and construction* (29)	Charcoal and construction (25)	Small constructions (13)
f_{v0}	Construction* (29)	Small constructions (25)	Small constructions (12)
f_{c0}	Construction* (27)	Small constructions (24)	Small constructions (13)
E_{M0}	Construction* (28)	Small constructions (25)	Small constructions (13)
f_M	Construction* (28)	Small constructions (25)	Small constructions (13)

Rm *Rhizophora mangle*, Ag *Avicennia germinans*, Lr *Laguncularia racemosa*

* featured species

* The numbers in parentheses indicate the number of samples per variable analyzed

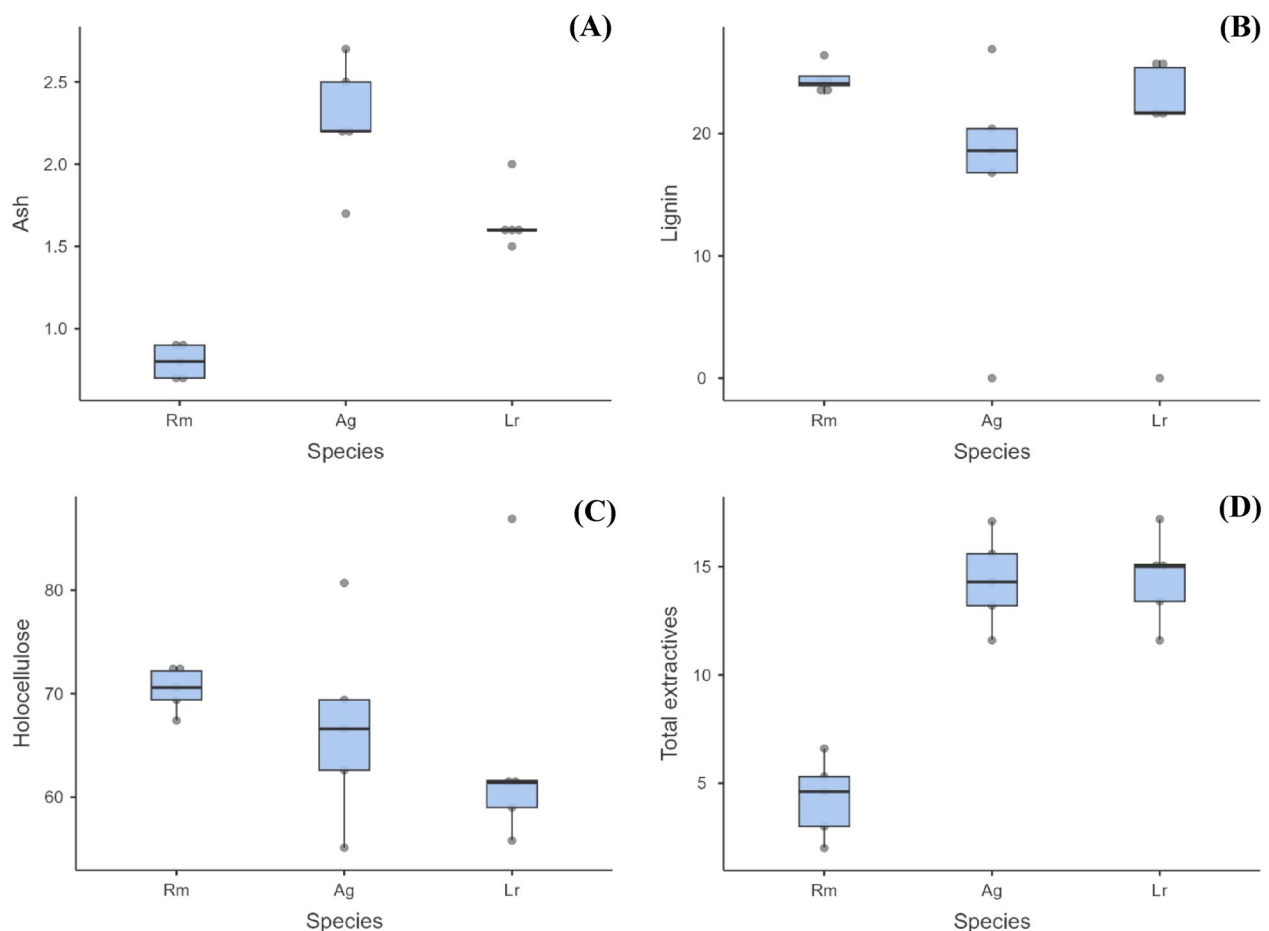


Fig. 2 Evaluation of the chemical properties of wood from mangrove tree species. **A** Ash content (%). **B** Lignin (%). **C** Holocellulose (%), and **D** Total extractives (%). *Rm* *Rhizophora mangle*, *Ag* *Avicennia germinans*, and *Lr* *Laguncularia racemosa*

Physical and mechanical properties of wood

Based on the analyzed physical and mechanical properties, the three mangrove tree species, emphasizing *R. mangle*, can be recommended for charcoal production, civil construction, and/or small buildings (Table 1).

The basic density of wood of mangrove tree species varied from 0.61 to 0.83 g cm⁻³ (Fig. 3A), with *R. mangle* being the species with the highest values. This property of wood is an important criterion for selecting trees for charcoal production, as this physical characteristic is directly linked to energy density and gravimetric yield [37], even considering that the gravimetric yield also depends on other factors, mainly the final temperature of the carbonization process [32].

Other physical characteristics, such as linear contractions in radial positions, varied from 4.0 to 5.1% (Fig. 3B), tangential from 5.1 to 11.5% (Fig. 3C), volumetric variation from 9.0 to 19.5% (Fig. 3D), and

anisotropy coefficient from 1.6 to 2.8% (Fig. 3E). These characteristics have little influence on charcoal properties [38]. This occurs because the carbonization process is independent of the organization of microfibrils in the wood tissue, most of which are degraded by high temperatures [38]. On the other hand, these characteristics are important during the wood drying process and can affect the mechanical resistance of charcoal.

The mechanical feature apparent density varied from 726.8 to 1031.6 kg m⁻³ (Fig. 4A), shear strength from 12.1 to 21.8 MPa (Fig. 4B), compression strength from 39.1 to 79.6 MPa (Fig. 4C), bending stiffness from 5.8 to 18.8 Gpa (Fig. 4D), and bending strength from 86.4 to 190.0 MPa (Fig. 4E). *Rhizophora mangle* wood stood out in all mechanical analyses, such as described from secondary data in Table 1. Our findings indicate this species has the most suitable wood for charcoal production and civil construction. One of the most critical properties to

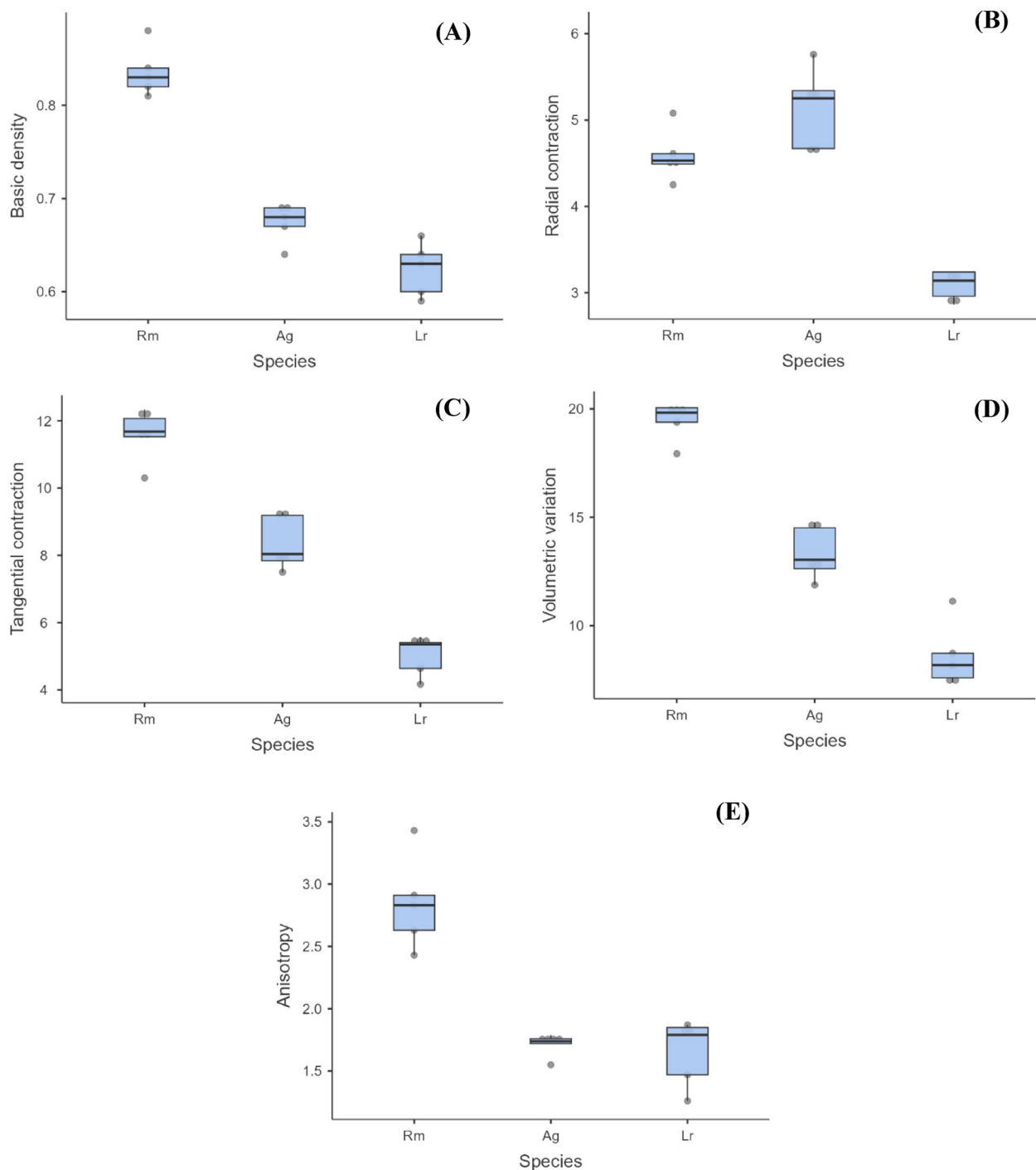


Fig. 3 Evaluation of the physical properties of wood from mangrove tree species. **A** Basic density (g cm^{-3}). **B** Radial shrinkage (%). **C** Tangential shrinkage (%). **D** Volumetric variation (%), and **E** Anisotropy (%). Rm *Rhizophora mangle*, Ag *Avicennia germinans*, and Lr *Laguncularia racemosa*

define these uses is wood density, as high-density wood results in products with better mechanical properties

[38–40]. Consequently, higher density wood has a great energy content per volume and more mechanical resistance [41, 42].

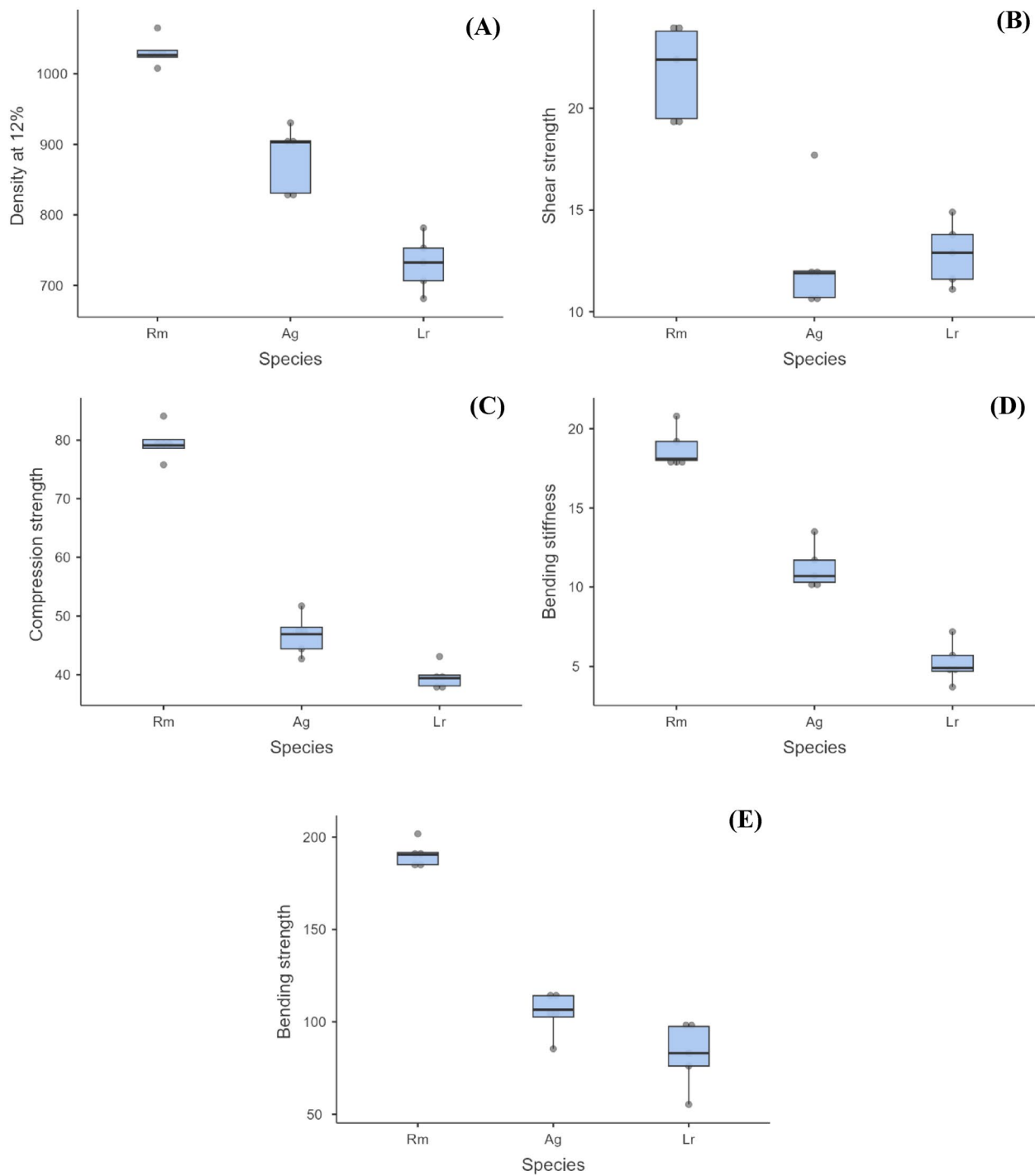


Fig. 4 Evaluation of the mechanical properties of wood from mangrove tree species. **A** Apparent density at 12% (kg m⁻³). **B** Shear strength (MPa). **C** Compression strength (MPa). **D** Bending stiffness (GPa), and **E** Bending strength (MPa). *Rm* *Rhizophora mangle*, *Ag* *Avicennia germinans*, and *Lr* *Laguncularia racemosa*

Correlation structure of wood characteristics

Based on Pearson's correlation matrix, it is possible to see, from the values, that there were correlations between the same wood properties and between

different properties (Table 2). A strong positive linear correlation exists between the chemical properties of A vs. TE (0.828) and negative in L vs. H (-0.775). Among the physical properties, there was a strong positive

Table 2 Pearson's correlation matrix for the values of uses based on secondary data on average values for wood from mangrove species [17] of A=ash content (%), L=lignin (%), H=hemicellulose (%), TE=total extractives (%), ρ =basic density (g cm^{-3}), contractions for R=radial, T=tangential (%), VV=volumetric variation (%), and AN=anisotropy (%), $\rho_{12\%}$ =apparent density at 12% (kg m^{-3}), f_{v0} =shear strength (MPa), f_{c0} =compression strength (MPa), E_{M0} =bending stiffness (GPa), and f_M =bending strength (MPa) of wood from the three dominant tree species in Amazonian mangroves

	A	L	H	TE	ρ	R	T	VV	AN	$\rho_{12\%}$	f_{v0}	f_{c0}	E_{M0}	f_M
A	—													
L	-0.282	—												
H	-0.297	-0.775 ***	—											
TE	0.828 ***	-0.307	-0.362	—										
ρ	-0.663 **	0.423	0.162	-0.877 ***	—									
R	0.133	0.056	-0.086	0.037	0.280	—								
T	-0.501	0.276	0.204	-0.725 **	0.908 ***	0.445	—							
VV	-0.556 *	0.313	0.186	-0.749 **	0.936 ***	0.502	0.984 ***	—						
AN	-0.804 ***	0.347	0.204	-0.805 ***	0.834 ***	0.161	0.788 ***	0.818 ***	—					
$\rho_{12\%}$	-0.536 *	0.248	0.253	-0.756 **	0.895 ***	0.345	0.968 ***	0.943 ***	0.742 **	—				
f_{v0}	-0.733 **	0.473	0.056	-0.772 ***	0.874 ***	0.075	0.797 ***	0.813 ***	0.825 ***	0.781 ***	—			
f_{c0}	-0.787 ***	0.346	0.266	-0.907 ***	0.946 ***	0.201	0.902 ***	0.920 ***	0.869 ***	0.925 ***	0.864 ***	—		
E_{M0}	-0.619 *	0.311	0.252	-0.847 ***	0.903 ***	0.320	0.931 ***	0.924 ***	0.793 ***	0.963 ***	0.735 ***	0.946 ***	—	
f_M	-0.760 ***	0.376	0.235	-0.907 ***	0.924 ***	0.131	0.886 ***	0.887 ***	0.851 ***	0.929 ***	0.861 ***	0.976 ***	0.955 ***	—

Chemical properties—light blonde color (80%), physical—light gold (60%), and mechanical—light gold (40%). Chemical and physical relationship—light blue color (80%), Chemical and mechanical relationship—light blue (60%), and physical and mechanical relationship—light blue (40%)

p-value: * = 0.05; ** $\leq$ 0.01; *** $\leq$ 0.001

correlation between ρ vs. VV (0.936), ρ vs. T (0.908), T vs. VV (0.984), ρ vs. AN (0.834), T vs. AN (0.788), and VV vs. AN (0.818). For the mechanical properties, there was a strong positive correlation between $\rho_{12\%}$ vs. E_{M0} (0.963), $\rho_{12\%}$ vs. f_M (0.929), $\rho_{12\%}$ vs. f_{c0} (0.925), f_{c0} vs. f_M (0.976), f_{c0} vs. E_{M0} (0.946), and E_{M0} vs. f_M (0.955).

Among the chemical and physical properties, there was a negative correlation between A vs. AN (-0.804), TE vs. ρ (-0.877), and TE vs. AN (-0.805). For the chemical and mechanical properties, there was a negative correlation between A vs. f_{c0} (-0.787), A vs. f_M (-0.760), TE vs. f_{c0} (-0.907), TE vs. f_M (-0.907), TE vs. E_{M0} (-0.847), and TE vs. f_{v0} (-0.772). Finally, there was a strong positive correlation between the physical and mechanical properties of ρ vs. f_{c0} (0.946), ρ vs. f_M (0.924), ρ vs. E_{M0} (0.903), T vs. $\rho_{12\%}$ (0.968), T vs. E_{M0} (0.931), T vs. f_{c0} (0.902), VV vs. $\rho_{12\%}$ (0.943), VV vs. E_{M0} (0.924), and VV vs. f_{c0} (0.920).

These results only highlight the strong correlation between physical and mechanical properties [38, 43, 44]. Therefore, it is essential to characterize such properties to evaluate the wood quality of mangrove tree species, especially when considering their use for civil construction. On the other hand, the chemical characteristics correlate little with the different properties for evaluating wood quality but are of great relevance for characterizing the energetic properties aimed at the production of charcoal [45, 46].

Conclusions

The study concludes that the three mangrove species analyzed, especially *R. mangle*, are suitable for charcoal production, civil construction, and small building applications due to favorable chemical, physical, and mechanical properties. *Rhizophora mangle* stands out for its high lignin content, which supports higher fixed carbon levels in charcoal, and its high wood density, enhancing energy density and mechanical resistance. Although the species show elevated hemicellulose levels, which typically decrease thermal stability, their total extractives provide some thermal resilience, particularly in *A. germinans* and *L. racemosa*. Furthermore, *R. mangle* exhibits excellent mechanical characteristics, including high density, compression, and bending strength, making it particularly suitable for durable construction materials and energy-efficient charcoal. One of these gaps is the need for studies on the energetic properties of charcoal from these species for a better understanding of the characteristics of the basic density of charcoal, carbonization yield, volatile matter content, ash content, fixed carbon content, and fixed carbon yield and calorific value, to try to relate them to the chemical, physical and mechanical properties of these woods. The macroscopic and microscopic anatomy of these woods is necessary to relate these characteristics with the physical–mechanical properties and support the traceability of these species in the region.

Another gap concerns natural durability through rotting experiments, which is relevant for understanding the behavior of *L. racemosa* wood, a species mainly used in constructing weirs in the region on the Amazon coast of Brazil.

Abbreviations

MER	Marine extractive reserve
DBH	Diameter at breast height
MMA	Ministry of the Environment, Brazil
ICMBIO	Chico Mendes Institute for Biodiversity Conservation
SISBIO	Biodiversity system
MPa	Megapascal
Gpa	Gigapascal
A	Ash content
L	Lignin
H	Holocellulose
TE	Total extractives
R	Radial
T	Tangential
VV	Volumetric variation
AN	Anisotropy
ρ	Basic density
$\rho_{12\%}$	Apparently density
f_{v0}	Shear strength
f_{c0}	Compression strength
E_{MO}	Bending stiffness
f_M	Bending strength

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Author contributions

MLG: conceptualization, investigation, methodology, data analysis, software, visualization writing—original draft, funding acquisition, project administration. JRCN and BMB: investigation, visualization, methodology. ISS and MEBF: supervision, visualization, writing—review and editing. All authors read and approved the final manuscript.

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Availability of data and materials

The data used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

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