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Wood identification and traditional boatbuilding along the Amazonian coast

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ABSTRACT

Traditional wooden boatbuilding remains essential for mobility, fishing activities, and local economies along the Brazilian Amazonian coast. In this context, wood selection often relies on empirical knowledge and vernacular nomenclature, which may obscure the taxonomic identity and technological attributes of the materials used. This study evaluated macroscopic wood anatomy as an applied tool for identifying timber employed in traditional coastal boatyards in the state of Pará, Brazil. A total of 123 wood samples were collected from active boatyards in the municipalities of Bragança (including the village of Bacuriteua), Augusto Corrêa, and Viseu. Samples were identified based on diagnostic anatomical characters observed under low magnification, supported by specialized literature, reference databases, and comparisons with wood collection specimens. Correspondence between vernacular names and botanical taxa was assessed, and technological properties relevant to boatbuilding were synthesized from the literature. Macroscopic anatomy allowed the recognition of 15 taxa and revealed non-one-to-one correspondences between vernacular nomenclature and botanical identity. Literature-reported technological data for the identified taxa and reference species showed a predominance of medium- to high-density woods, with moderate to high natural durability and substantial mechanical strength among taxa for which these properties were available. These characteristics are consistent with technological requirements previously reported for wooden boat construction. These findings show that anatomical identification can clarify the botanical identity underlying locally used timber names and provide a taxonomic basis for interpreting previously documented patterns of timber selection. Integrating anatomical identification, vernacular classification, and technological information strengthens the interface between taxonomy and traditional use and may support management, traceability, and conservation strategies for woody resources in culturally relevant production systems.

Keywords: Traditional boats; wood heritage; wood anatomy; historical anatomy; vernacular nomenclature.

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SIGNIFICANCE STATEMENT

This study contributes to ethnobiological discussions by examining how vernacular nomenclature, wood identification, and literature-reported technological characteristics relate to timber selection in traditional wooden boatbuilding along the Amazonian coast of Pará. By integrating anatomical identification, vernacular nomenclature, and technological information for the identified taxa and reference species, the research reveals both the functional logic underlying material selection documented in previous boatbuilding studies and the implications of non-one-to-one correspondence in vernacular nomenclature and genus-level identification, including the possibility that genus-level records may encompass threatened species. The findings support the interpretation of traditional boatbuilding as a structured technical-cognitive system and provide a practical framework for linking cultural heritage, sustainable resource use, and conservation-oriented monitoring of forest resources in high-diversity tropical regions.

INTRODUCTION

Throughout history, watercraft have played a central role in the technological, cultural, and economic development of many societies, establishing a close relationship between boatbuilding, empirical knowledge, and the use of forest resources (Melo Júnior 2023). Wood established itself as a strategic material in naval construction due to its technological properties, such as mechanical strength, durability, low weight, and ease of processing, which enable its adaptation to different aquatic environments and navigation regimes (Prabawa 2018; Dewi et al. 2020; Abdrabou et al. 2022). Historical, archaeological, and technological studies demonstrate that the selection of wood species for boatbuilding has rarely been random, but has been closely linked to regional availability, the functional performance required for specific structural components, and accumulated empirical knowledge of wood anatomy and behavior in aquatic environments. In this context, accurate taxonomic identification has proven essential for assessing technological performance, durability, and degradation processes of wood in both historical and contemporary naval settings (Giachi et al. 2003; Bardet et al. 2004; Capretti et al. 2008; Tripati et al. 2016; Nascimento et al. 2017).

Furthermore, the impacts resulting from uncertainty regarding the botanical identity of woods identified through vernacular names in traditional boatbuilding extend beyond technological performance. Such uncertainty may compromise user safety, the credibility of master boatbuilders, the sustainability of biodiversity, and the legal compliance of the activity with environmental regulatory agencies. From this perspective, there is an interdependent relationship between ecosystem protection and cultural preservation; evidence suggests that the erosion of community knowledge is reflected in biological degradation (Brosi et al. 2007). In this context, taxonomic identification emerges as an essential tool enabling these traditional practitioners to play an active role in environmental governance and the conservation of biodiversity. In addition, the recognition of species of cultural interest can support biodiversity conservation actions in cultural landscapes (Copete et al. 2023), in addition to generating management practices, participation, and combating climate change (Bhati and Epstein 2023).

Watercraft have historically played a central role in the processes of occupation and circulation across Brazilian territory. Even prior to European colonization, Indigenous peoples relied on ethnobotanical knowledge and technical expertise to construct watercraft capable of navigating a wide range of aquatic environments, including rivers, estuaries, and coastal marine areas, which thereby enabled mobility across extensive regions of the country (Gualberto 2012; Ferreira 2016). According to the Boats from Brazil Collection of the National Institute of Historic and Artistic Heritage, more than 150 types of watercraft have been documented, encompassing both extinct and still-active forms, with boats traditionally built from wood being clearly predominant (Cruz et al. 2019). In traditional fishing communities along the Brazilian coast, wood is the primary material resource for naval carpentry and it is sourced from forest formations located in the immediate surroundings of boatyards, with a marked preference for tree species with large trunk dimensions; as a result, each coastal region develops a distinct set of timber species employed in boat construction (Melo Júnior et al. 2025). This scenario highlights the remarkable diversity of empirical knowledge systems, construction techniques, and cultural practices that have been transmitted intergenerationally by master boatbuilders, through which wood selection, recognition, and use are guided by accumulated experience and continuous interaction with local forest resources.

In Brazil, traditional boatbuilding is an important technical and cultural heritage, particularly in regions where fluvial and coastal navigation are fundamental to mobility, trade, and local livelihoods (Melo Júnior et al. 2019). In the Amazon region, river navigation plays a strategic role, transporting millions of tons of

cargo and passengers annually (Delson 1995). In the state of Pará, traditional naval carpentry remains a socially relevant activity, supporting local economies and ensuring connectivity among riverside communities. According to the Pará State Ports and Waterways Company (CPH 2022), approximately five million passengers use fluvial transportation each year, and more than half of the state's municipalities depend exclusively on this mode of transport.

Within this context, the municipality of Bragança, located in northeastern Pará, stands out as one of the main regional centers of traditional boatbuilding, concentrating active boatyards for the construction and maintenance of boats used in coastal and estuarine fisheries. Bragança's naval carpentry is characterized by the intergenerational transmission of technical knowledge, the predominance of empirically based construction processes, and the functional adaptation of boats to local environmental conditions and productive demands, forming a consolidated and socially relevant technical system in which the recognition, selection, and use of timber are continuously shaped by accumulated practical knowledge and local experience (Costa et al. 2017; Andrade and Santos 2017; Ferreira 2024).

Despite its socioeconomic and cultural importance, traditional boatbuilding faces challenges related to taxonomic uncertainty concerning the woods used and the lack of systematic technological information on the species employed. The use of vernacular names that do not necessarily maintain a one-to-one correspondence with botanical taxa is common in traditional production chains, often leading to the association of different species or genera under the same commercial designation. This disconnection may reflect the greater importance of wood attributes in naval applications than faithful scientific identification. This practice may lead to inappropriate substitutions, compromised structural performance, and the inadvertent use of species protected by environmental legislation (Cysneiros et al. 2018; Braga Júnior et al. 2020; Brandes et al. 2020). At the same time, vernacular nomenclature constitutes a locally constructed system through which timber resources are recognized, communicated, and selected according to accumulated practical experience rather than formal botanical classification. Thus, traditional boatbuilding is not only a technical activity, but also an applied ethnobiological system, in which empirical knowledge of forest resources directly informs material selection, technological performance, and tradition of use.

Although wood is often considered a more environmentally sustainable material compared to modern alternatives due to its lower energy production costs and renewable potential (Bose and Vijith 2012), this depends directly on correct species identification and appropriate technological use. Empirical identification based solely on organoleptic characteristics, such as color, odor, and apparent density, is limited and prone to error, as these attributes may vary considerably within a single genus or be similar among distinct species (Gasson 2011; Bernal et al. 2011; Soares et al. 2014; Nobre et al. 2019). In this context, macroscopic wood anatomical identification is an effective, low-cost, applied scientific tool suitable for field use, enabling the association of diagnostic secondary xylem characters with botanical taxa and supporting monitoring, productive use, and forest conservation efforts; within a broader interdisciplinary framework, historical wood anatomy further allows these anatomical identifications to be interpreted as expressions of knowledge systems and tree use in historical and cultural contexts (Ferreira et al. 2023; Melo Júnior 2024), thereby providing an objective basis for interpreting vernacular classifications, reducing taxonomic ambiguity, and strengthening the links between traditional knowledge and scientific approaches to forest resource management and biodiversity conservation.

The objective of this study was to investigate, through macroscopic wood anatomy, the taxonomic repertoire employed in traditional boatbuilding along the Amazonian coast of Pará and to evaluate the correspondence between vernacular nomenclature and botanical identification, while examining technological properties reported in the literature for the identified taxa in relation to their traditional use in boatbuilding.

MATERIAL AND METHODS

The wood samples analyzed in this study were collected from eight artisanal boatyards for the construction and maintenance of wooden boats, located along the Amazonian coastal zone of the state of Pará, Brazil, in the municipalities of Bragança (including the village of Bacuriteua), Augusto Corrêa, and Viseu (Figure 1). The sampling included one boatyard in Augusto Corrêa, five in Bragança (including Bacuriteua), and two in Viseu. These boatyards are traditional production units responsible for a significant portion of the artisanal fishing fleet and regional waterborne transport. They are characterized by the predominant use of solid wood and by the direct involvement of local master boatbuilders, whose technical knowledge is transmitted across generations (Ferreira 2024).

During visits to the boatyards, wood sampling followed an availability-based approach focused on documenting the timber types present in boat construction and maintenance activities at the time of the sur-

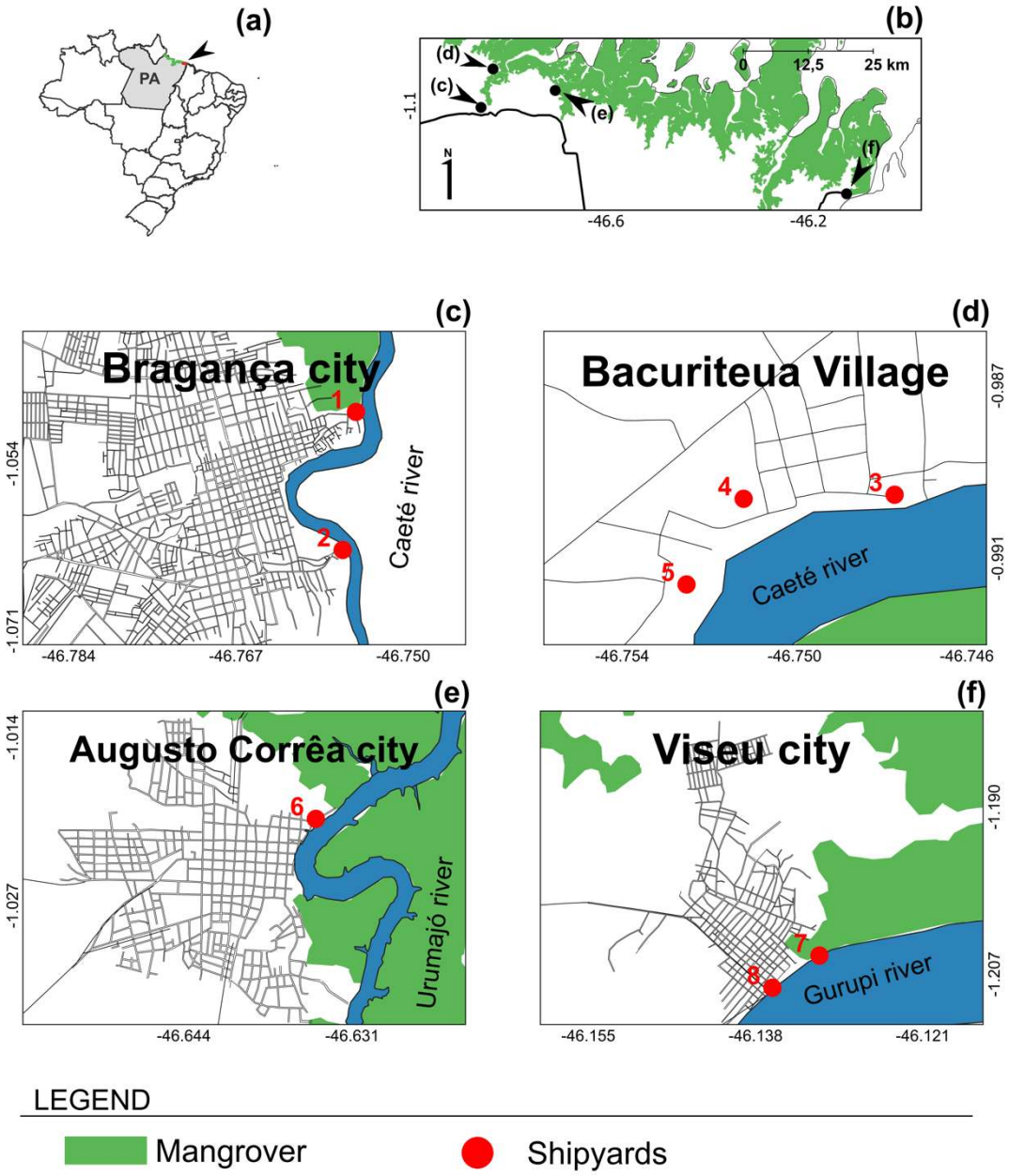

Figure 1. (a) Map of Brazil highlighting the state of Pará (in gray); (b) eastern sector of the Amazonian coast showing the location of the boatyards; (c) municipality of Bragança (boatyards 1 and 2); (d) village of Bacuriteua (boatyards 3, 4, and 5); (e) municipality of Augusto Corrêa (boatyard 6); and (f) municipality of Viseu (boatyards 7 and 8).

vey. At each boatyard, the master boatbuilder, who was also the boatyard owner, indicated the wood types using their vernacular names, and one representative sample was collected from each indicated wood type that was physically available. Each sample was registered together with the vernacular name reported at the site and its boatyard of origin, resulting in a total of 123 wood samples subsequently submitted to anatomical identification. No formal interviews were conducted for recording these names.

This sampling strategy was designed to characterize the taxonomic identity of wood materials encoun-

tered across the surveyed boatyards and to assess their correspondence with the vernacular names used locally, rather than to quantify the frequency of timber use within individual boats or structural components. Because individual boats, timber batches, and structural components were not systematically tracked during collection, the 123 samples were treated as records of sampled wood materials and not as statistically independent replicates of timber use. Accordingly, subsequent analyses were based primarily on the occurrence and taxonomic identification of the sampled wood types across the surveyed boatyards.

Test specimens measuring approximately 2.5 × 2.5 × 3.5 cm were removed from the collected samples for macroscopic anatomical analysis, exposing transverse, radial, and tangential surfaces. The transverse surfaces were trimmed and manually polished under water using waterproof sandpapers with progressively finer grits (P600, P1200, and P2000) to allow adequate macroscopic visualization of anatomical structures (Barbosa et al. 2021). Observation of macroscopic anatomical characters was performed using a 10× hand lens, simulating operational conditions of field identification and forest inspection contexts (Coradin and Muniz 1992).

Photographic documentation was obtained using a reflected-light Kern GZ 800 APO stereomicroscope (Kern, Leipzig, Germany) coupled with a Kern digital camera at 10× magnification, reproducing the magnification used during field-oriented examination with a hand lens. Quantitative anatomical features were determined at the same 10× magnification. Vessel frequency was determined as the number of vessels per square millimeter using a reference grid, while dimensional measurements were performed from calibrated digital images using ImageView software (version x64 3.7.10121.20171030, ToupTek Photonics Co., Ltd., China). Anatomical characters and the qualitative and quantitative classes adopted for their description followed the criteria of Ruffinatto et al. (2015) and Wheeler et al. (1989).

Wood was identified based on interactive and dichotomous identification keys (Mainieri 1983; Coradin et al. 2010), specialized literature on Brazilian commercial timbers (Loureiro and Silva 1968; Detienne and Jacquet 1983; Mainieri and Chimelo 1989; Brandes et al. 2020; Florsheim et al. 2020; Santini et al. 2021), and complemented by consultation of the InsideWood database (2004 onwards). Taxonomic determinations were additionally evaluated through comparison with reference specimens deposited in the Joaquim Ivanir Gomes Wood Collection (JIGw, Universidade do Estado do Pará) and the IANw Wood Collection (Embrapa Amazônia Oriental), and the identifications were discussed by at least two experienced wood anatomists among the authors. Species-level determinations were adopted only when the combination of diagnostic anatomical characters, geographic distribution, specialized literature, database information, and comparison with reference material supported this taxonomic resolution; otherwise, identification was conservatively retained at the genus level. Scientific nomenclature followed Flora do Brasil 2020. Exotic species had their names confirmed in the Royal Botanic Garden database (POWO 2026).

The vernacular names reported in the boatyards were treated as local designations associated with the collected samples rather than as taxonomic categories. The correspondence between vernacular names and anatomically identified taxa was evaluated descriptively. Cases in which the same vernacular name was associated with more than one botanical taxon were treated as name sharing, whereas cases in which the same taxon was associated with different vernacular names were treated as vernacular synonymy. These patterns were collectively described as non-one-to-one correspondences between vernacular names and botanical taxa and were not interpreted as misidentifications.

Based on the identified taxa, a bibliographic survey of the main technological properties relevant to boatbuilding, such as wood density, mechanical strength, and natural durability, was conducted using technical literature and institutional databases maintained by the Institute for Technological Research (IPT) and the Forest Products Laboratory (LPF) of the Brazilian Forest Service (IPT 2026; LPF 2026). These properties were obtained from the literature and were not measured directly in the 123 collected samples. For species-level identifications, technological information corresponding to the identified species was compiled whenever available. For genus-level identifications, available technological information from species belonging to the respective genus was used, with the source species explicitly identified. These literature-derived values were treated as indicative technological information associated with the identified taxa and not as direct measurements of the sampled woods. The conservation status of species-level identifications was assessed using the Brazilian National Official List of Threatened Flora Species, updated by MMA Ordinance No. 148/2022, complemented by assessments available through the National Centre for Flora Conservation (CNCFlora 2022), and the IUCN Red List of Threatened Species, all accessed on 25 August 2026. For samples identified only at the genus level, no conservation category was assigned to the sampled material; the occurrence of threatened species within the respective genus was considered only as contextual information, since species-level identification is required

for conservation or regulatory conclusions.

Sampling was carried out under a federal research permit issued by ICMBio/SISBIO (License No. 77453-3), and genetic access was registered in the national SISGEN database (Record AE1AF17), as required by Brazilian legislation. Representative samples of each identified taxon were deposited in the Joaquim Ivanir Gomes Wood Collection (JIGw) of the Universidade do Estado do Pará (UEPA), ensuring traceability and reproducibility of the identifications.

RESULTS

Although some taxa shared similar anatomical patterns, taxonomic identification of the analyzed woods was achieved. It allowed the recognition of 15 taxa, including nine identified at the genus level and six at the species level (Table 1, Figures 2–16). Specific axial parenchyma patterns were the main diagnostic descriptors, notably reticulate parenchyma in *Lecythis* sp. (Figure 12 a–c), diffuse parenchyma in *Goupia glabra* (Figure 9 a–c) and *Caryocar* sp. (Figure 5 a–c), and lozenge-shaped to confluent aliform parenchyma in several genera of Fabaceae. The combination of aliform parenchyma, storied rays, and large, sparsely distributed vessels enabled discrimination among closely related genera, such as *Dipteryx* sp. (Figure 8 a–c), *Bowdichia nitida* (Figure 4 a–c), *Diplotropis* sp. (Figure 7 a–c), *Dinizia excelsa* (Figure 6 a–c), and *Handroanthus* sp. (Figure 10 a–c). Complementary characters, including heartwood color and odor, further supported the identification of specific woods, such as *Peltogyne* sp., *Goupia glabra*, and *D. excelsa*. The presence of an exotic species, *Artocarpus heterophyllus* (Figure 2 a–c), among the identified woods was also recorded in the visited boatyards (Table 1).

Within the analyzed sample set of 123 samples, Fabaceae was the predominant family, comprising six genera and 29 samples, followed by Moraceae, with 18 samples distributed across two genera, and Lauraceae, with 12 samples in two genera (Table 2). The most frequent taxa within the sampled dataset were *Caryocar* sp., *Bagassa guianensis*, *Lecythis* sp., *Diplotropis* sp., *Handroanthus* sp., and *Dipteryx* sp., representing the taxa most frequently recorded among the sampled wood materials.

Analysis of the relationship between vernacular names reported in the boatyards and the anatomically identified taxa revealed non-one-to-one correspondences within the sampled dataset (Table 2). Name sharing was observed for four vernacular names: pau d'arco, angelim vermelho, cumaru, and sucupira, each of which was associated with two or three distinct taxa, including genera from different families. Vernacular synonymy was also observed, with *Bagassa guianensis* associated with amarelão, tatajuba, and pau d'arco, *Caryocar* sp. with piquiá and piquiarana, and *Lecythis* sp. with sapucaia and sucupira. These results indicate the absence of a one-to-one correspondence between vernacular names and botanical taxa within the analyzed sample set.

Some samples identified only at the genus level belonged to groups that include species classified as threatened, particularly *Hymenaea* sp., *Mezilaurus* sp., and *Peltogyne* sp. No conservation category was assigned to these samples because species-level identification was not achieved. However, these genera include threatened species occurring in Pará, such as *Hymenaea parvifolia*, *Mezilaurus itauba*, and *Peltogyne maranhensis*, which are classified as Vulnerable (VU) in Brazilian conservation assessments (MMA 2022; CNCFlora 2022). Among the six taxa identified at the species level, *Bagassa guianensis*, *Bowdichia nitida*, *Dinizia excelsa*, *Goupia glabra*, and *Sextonia rubra* are classified as Least Concern (LC) by the IUCN Red List (IUCN 2026), whereas *Artocarpus heterophyllus* is recorded as Not Evaluated (NE) by CNCFlora (CNCFlora 2022).

The technological data compiled from the literature for the identified taxa and reference species indicated a predominance of medium- to high-density woods, with moderate to high natural durability among taxa for which durability information was available. Of the 15 identified taxa, one (6.7%) fell within the low-density class, four (26.7%) within the medium-density class, and ten (66.7%) within the high-density class (Table 3).

Compressive strength parallel to the grain (fc,0,m) ranged from 48.0 to 94.2 MPa among the analyzed species. Bending strength (fM) ranged from 77.8 to 187.1 MPa among taxa for which these properties were available (Table 3). These values correspond to literature-reported properties of the identified species or, for genus-level identifications, of the reference species indicated in Table 3.

Table 1. Diagnostic macroscopic anatomical features used for taxonomic identification in traditional boatyards. Vessel groupings (VG): a. solitary and in radial multiples of 2–3 vessels, b. exclusively solitary (90% or more); Vessel frequency (VF): a. 5 vessels per square millimeter, b. 6–20 vessels per square millimeter, c. > 20 vessels per square millimeter; Pore visibility/Vessel diameter (PV): a. Medium (just visible to the naked eye, 80–130 μm), b. Large (commonly visible to the naked eye, larger than 130 μm); Tyloses abundant (TY): present. +, absent. -; Vessel deposits (VD): a. deposits white, b. deposits yellow, c. deposits dark, absent. -; Axial parenchyma distribution (AP); Ray visibility to the naked eye on the transverse surface (RTR): a. rays not visible, b. all rays visible, c. only larger rays visible; Ray visibility to the naked eye on the tangential surface (RTG): a. rays not visible, b. rays visible; Ray storying (RS): present. +, absent. -; Rays per mm (RF): a. 5–12/mm, b. >12/mm; Traumatic canals (CAN): present. +, absent. -; Heartwood color (HC): a. heartwood basically brown or shades of brown, b. heartwood purple, c. heartwood basically yellow or shades of yellow, d. heartwood basically white to gray ; Heartwood odor (HO): distinctly present and unpleasant (foetid). +, absent.

Taxa identified	VG	VF	PV	TY	VD	AP (predominant pattern)	RTR	RTG	RS	RF	CAN	HC	HO	Figure
Artocarpus heterophyllus Lam.	a	a	b	-	b	axial parenchyma lozenge-aliform and confluent	c	a	-	a	-	c	-	2 a–c
Bagassa guianensis Aubl.	a	b	b	+	b	axial parenchyma vasicentric, scanty	b	a	-	a	-	a	-	3 a–c
Bowdichia nitida Spruce ex Benth.	a	b	b	-	a	axial parenchyma lozenge-aliform and confluent	a	a	+	a	-	a	-	4 a–c
Caryocar sp.	a	a	b	+	-	axial parenchyma diffuse and diffuse-in-aggregates	a	a	-	a	-	c	-	5 a–c
Dinizia excelsa Ducke	a	b	b	-	a	axial parenchyma lozenge-aliform and confluent	c	a	-	a	-	a	+	6 a–c
Diplotropis sp.	a	a	b	-	a, c	axial parenchyma lozenge-aliform and confluent	c	a	-	a	-	a	-	7 a–c
Dipteryx sp.	a	b	b	-	a	axial parenchyma lozenge-aliform and confluent	c	a	+	a	-	c	-	8 a–c
Goupia glabra Aubl.	b	b	b	-	a, c	axial parenchyma diffuse	a	a	-	b	-	a	+	9 a–c
Handroanthus sp.	a	b	a	-	b	axial parenchyma winged-aliform and confluent	a	a	+	a	-	a	-	10 a–c

Continued...

Table 1. Diagnostic macroscopic anatomical features used for taxonomic identification in traditional boatyards. Vessel groupings (VG): a. solitary and in radial multiples of 2–3 vessels, b. exclusively solitary (90% or more); Vessel frequency (VF): a. 5 vessels per square millimeter, b. 6–20 vessels per square millimeter, c. > 20 vessels per square millimeter; Pore visibility/Vessel diameter (PV): a. Medium (just visible to the naked eye, 80–130 μm), b. Large (commonly visible to the naked eye, larger than 130 μm); Tyloses abundant (TY): present. +, absent. -; Vessel deposits (VD): a. deposits white, b. deposits yellow, c. deposits dark, absent. -; Axial parenchyma distribution (AP); Ray visibility to the naked eye on the transverse surface (RTR): a. rays not visible, b. all rays visible, c. only larger rays visible; Ray visibility to the naked eye on the tangential surface (RTG): a. rays not visible, b. rays visible; Ray storying (RS): present. +, absent. -; Rays per mm (RF): a. 5–12/mm, b. >12/mm; Traumatic canals (CAN): present. +, absent. -; Heartwood color (HC): a. heartwood basically brown or shades of brown, b. heartwood purple, c. heartwood basically yellow or shades of yellow, d. heartwood basically white to gray ; Heartwood odor (HO): distinctly present and unpleasant (foetid). +, absent.

Taxa identified	**VG**	**VF**	**PV**	**TY**	**VD**	**AP (predominant pattern)**	**RTR**	**RTG**	**RS**	**RF**	**CAN**	**HC**	**HO**	**Figure**
Hymenaea sp.	a	a	b	-	-	axial parenchyma lozenge-aliform and in marginal or in seemingly marginal bands	b	b	-	a	-	a	-	11 a–c
Lecythis sp.	a	b	b	+	-	axial parenchyma reticulate	a	a	-	a	+	a	-	12 a–c
Mezilaurus sp.	a	c	a	+	-	axial parenchyma winged-aliform, scanty	c	a	-	a	-	a	-	13 a–c
Peltogyne sp.	a	b	b	-	a	axial parenchyma lozenge-aliform and confluent	b	b	-	a	-	b	-	14 a–c
Qualea sp.	a	a	b	-	a	axial parenchyma winged-aliform and confluent	a	b	-	a	-	a	-	15 a–c
Sextonia rubra (Mez) van der Werff	a	a	b	+	-	axial parenchyma lozenge-aliform	a	a	-	a	-	a	-	16 a–c

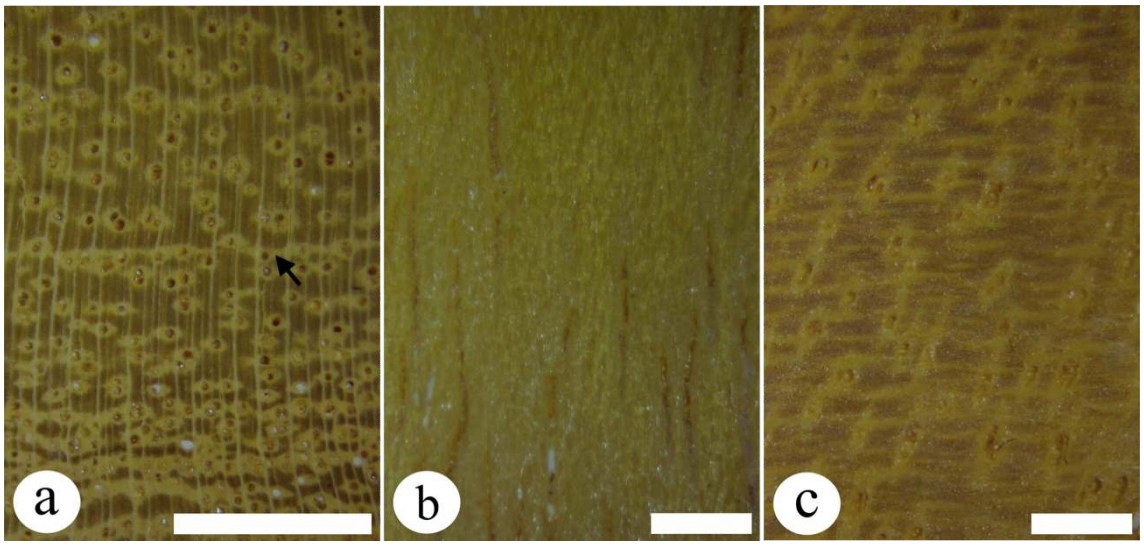

Figure 2. Wood anatomy of *Artocarpus heterophyllus*. Macroscopic surfaces. a. Transverse surface, scale = 2 mm. b. Radial surface, scale = 1 mm. c. Tangential surface, scale = 1 mm. Diagnostic anatomical feature is indicated by an arrow (axial parenchyma).

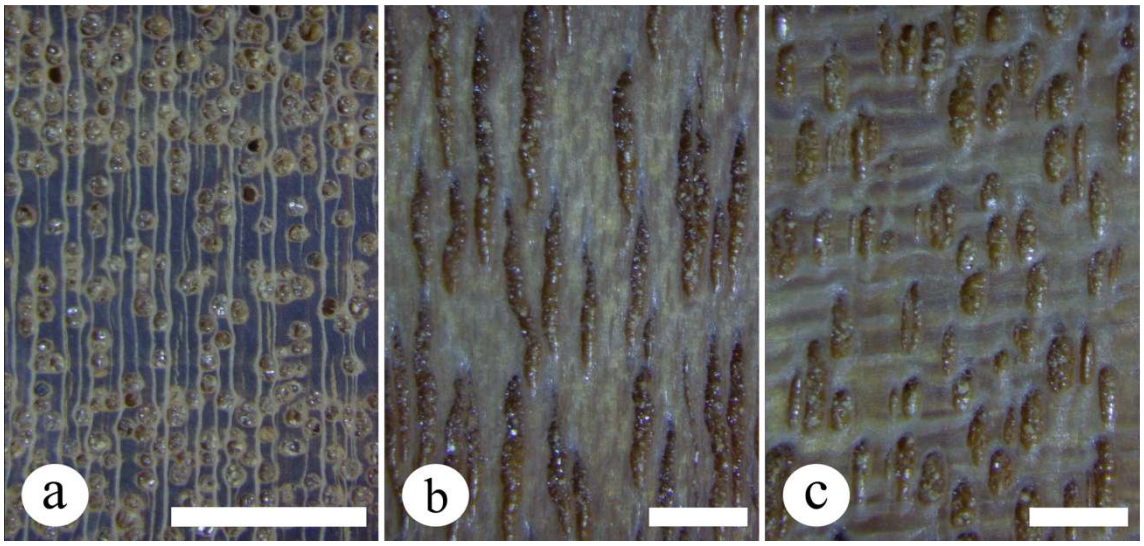

Figure 3. Wood anatomy of *Bagassa guianensis*. Macroscopic surfaces. a. Transverse surface, scale = 2 mm. b. Radial surface, scale = 1 mm. c. Tangential surface, scale = 1 mm.

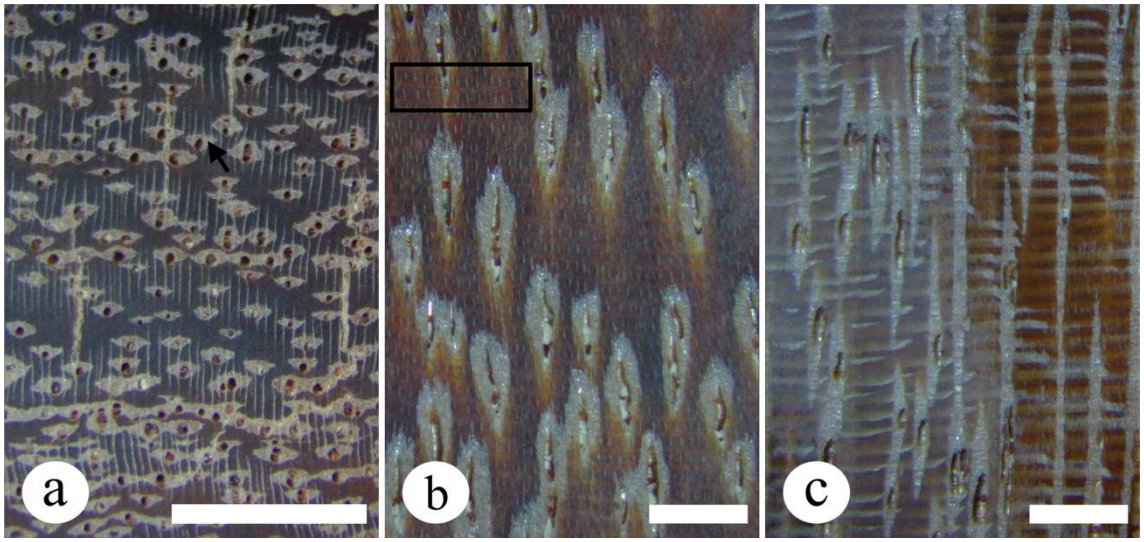

Figure 4. Wood anatomy of *Bowdichia nitida*. Macroscopic surfaces. a. Transverse surface, scale = 2 mm. b. Radial surface, scale = 1 mm. c. Tangential surface, scale = 1 mm. Diagnostic anatomical features are indicated by an arrow (axial parenchyma) and a rectangle (storied rays).

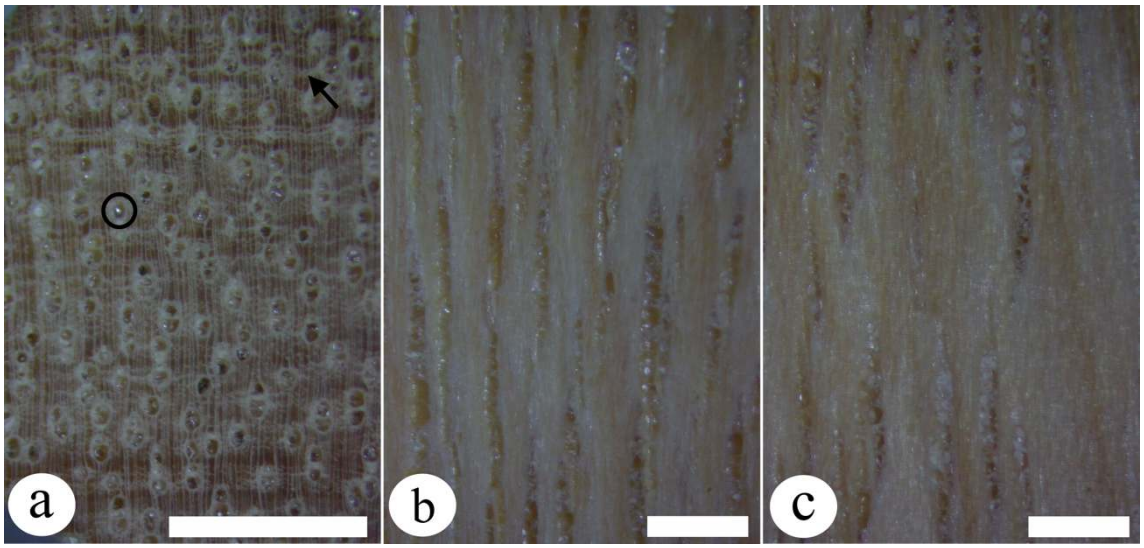

Figure 5. Wood anatomy of *Caryocar* sp. Macroscopic surfaces. a. Transverse surface, scale = 2 mm. b. Radial surface, scale = 1 mm. c. Tangential surface, scale = 1 mm. Diagnostic anatomical features are indicated by an arrow (axial parenchyma) and a circle (vessel with tyloses).

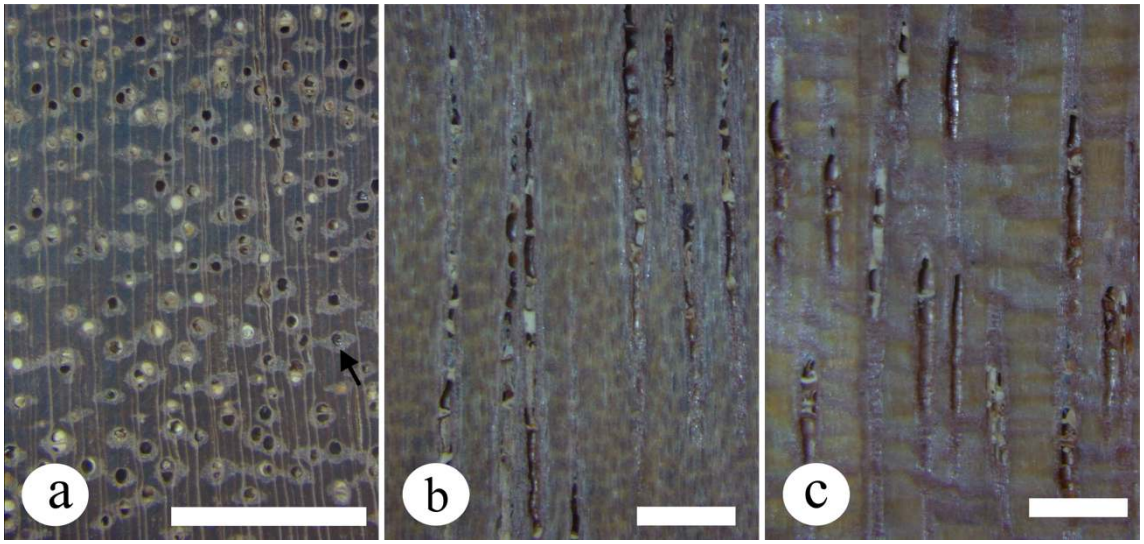

Figure 6. Wood anatomy of *Dinizia excelsa*. Macroscopic surfaces. a. Transverse surface, scale = 2 mm. b. Radial surface, scale = 1 mm. c. Tangential surface, scale = 1 mm. Diagnostic anatomical feature is indicated by an arrow (axial parenchyma).

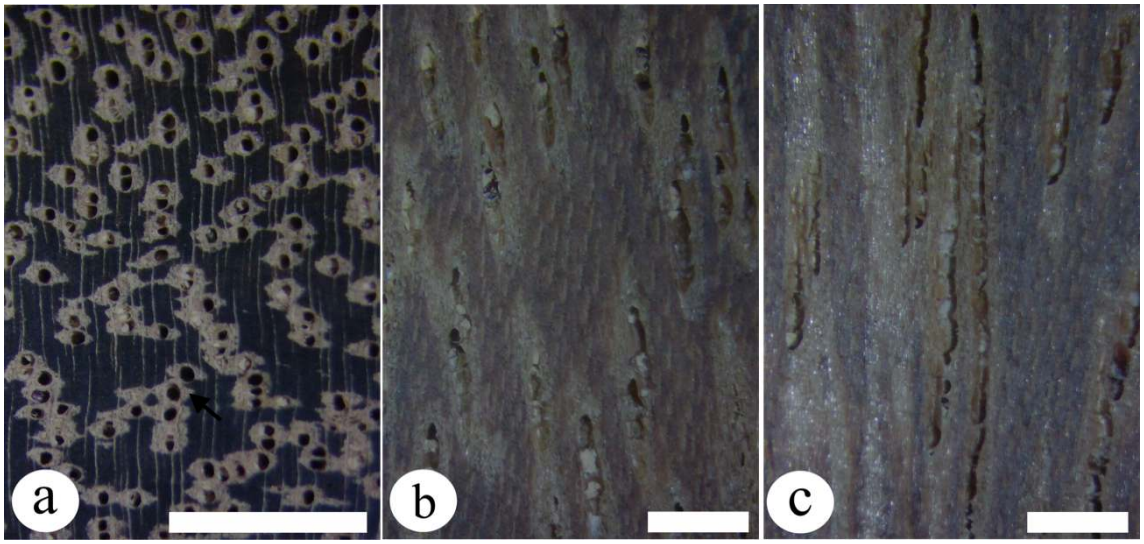

Figure 7. Wood anatomy of *Diplotropis* sp. Macroscopic surfaces. a. Transverse surface, scale = 2 mm. b. Radial surface, scale = 1 mm. c. Tangential surface, scale = 1 mm. Diagnostic anatomical feature is indicated by an arrow (axial parenchyma).

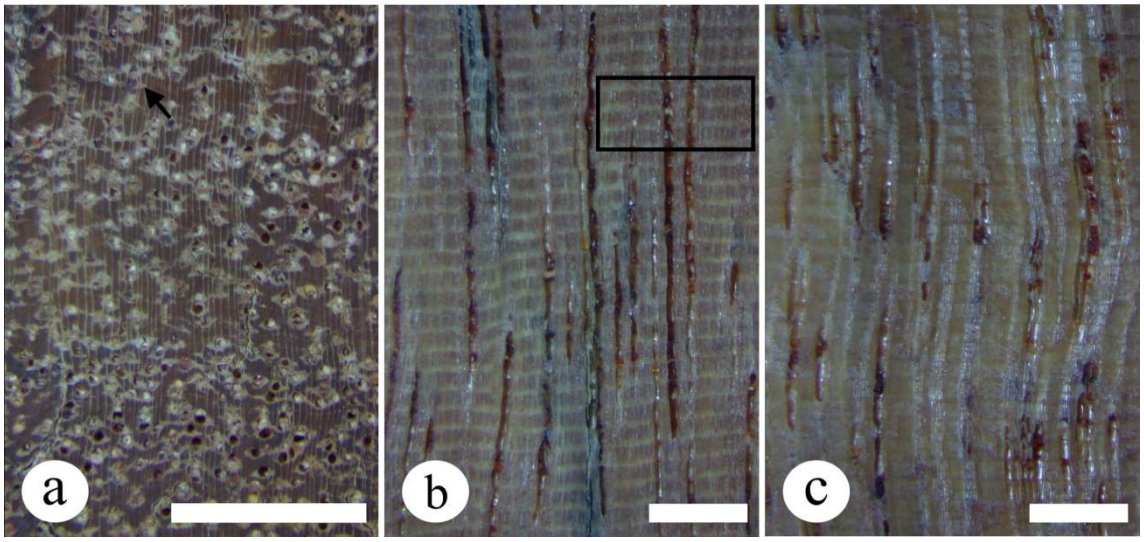

Figure 8. Wood anatomy of *Dipteryx* sp. Macroscopic surfaces. a. Transverse surface, scale = 2 mm. b. Radial surface, scale = 1 mm. c. Tangential surface, scale = 1 mm. Diagnostic anatomical features are indicated by an arrow (axial parenchyma) and a rectangle (storied rays).

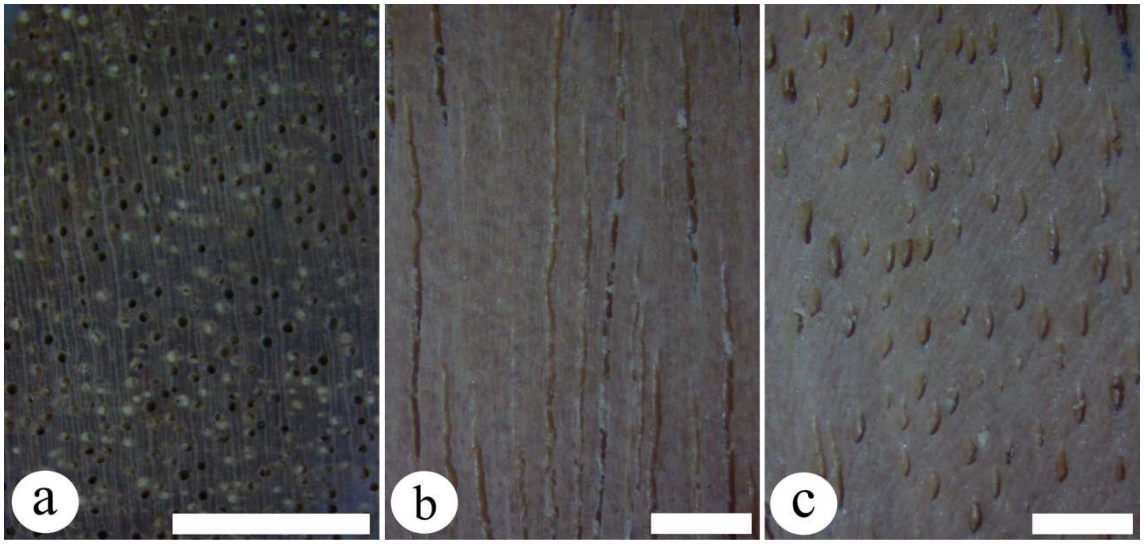

Figure 9. Wood anatomy of *Goupia glabra.* Macroscopic surfaces. a. Transverse surface, scale = 2 mm. b. Radial surface, scale = 1 mm. c. Tangential surface, scale = 1 mm.

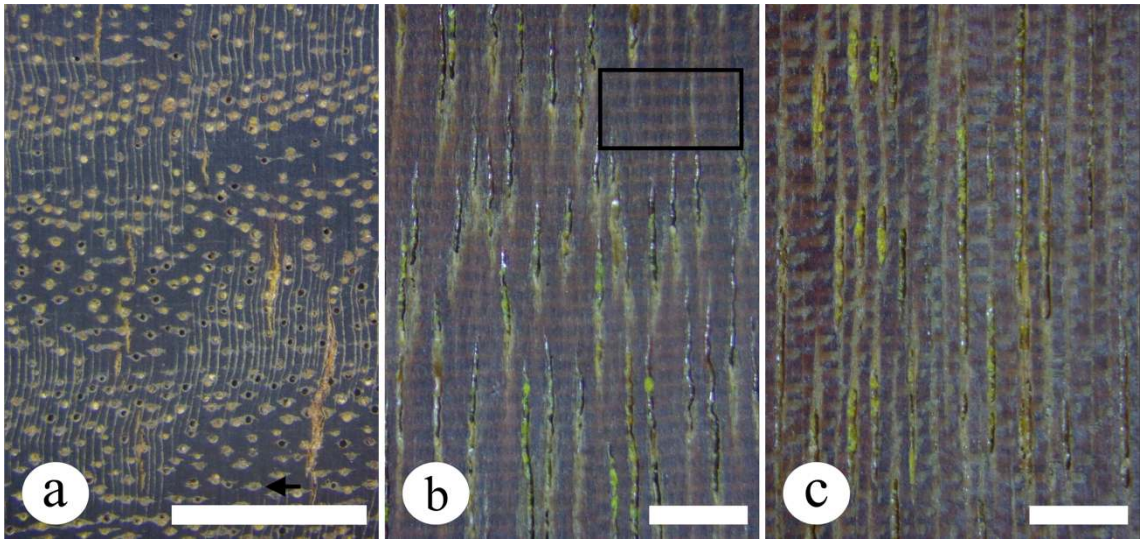

Figure 10. Wood anatomy of *Handroanthus* sp. Macroscopic surfaces. a. Transverse surface, scale = 2 mm. b. Radial surface, scale = 1 mm. c. Tangential surface, scale = 1 mm. Diagnostic anatomical features are indicated by an arrow (axial parenchyma) and a rectangle (storied rays).

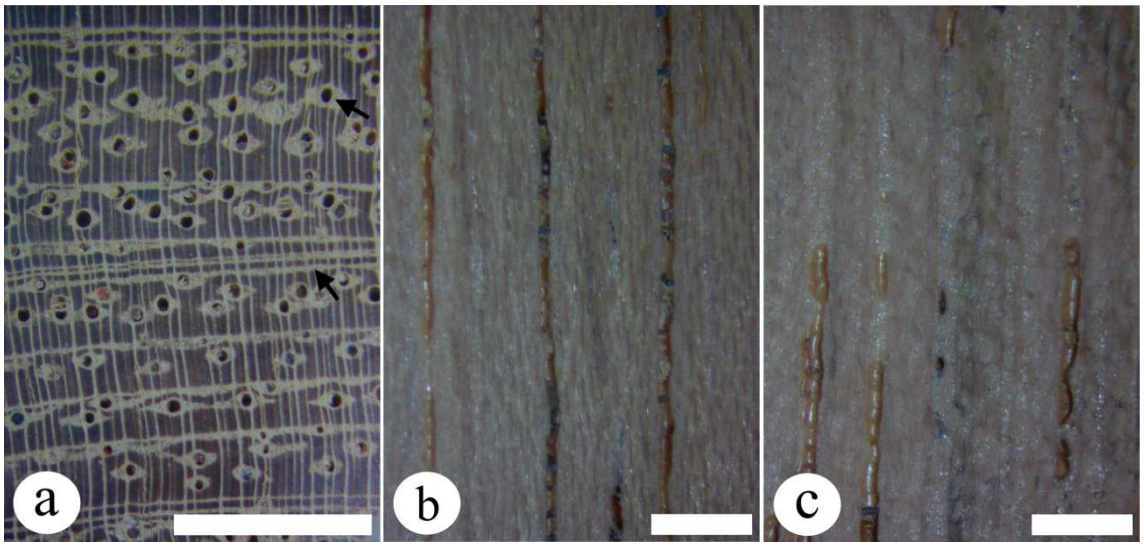

Figure 11. Wood anatomy of *Hymenaea* sp. Macroscopic surfaces. a. Transverse surface, scale = 2 mm. b. Radial surface, scale = 1 mm. c. Tangential surface, scale = 1 mm. Diagnostic anatomical feature is indicated by an arrow (axial parenchyma).

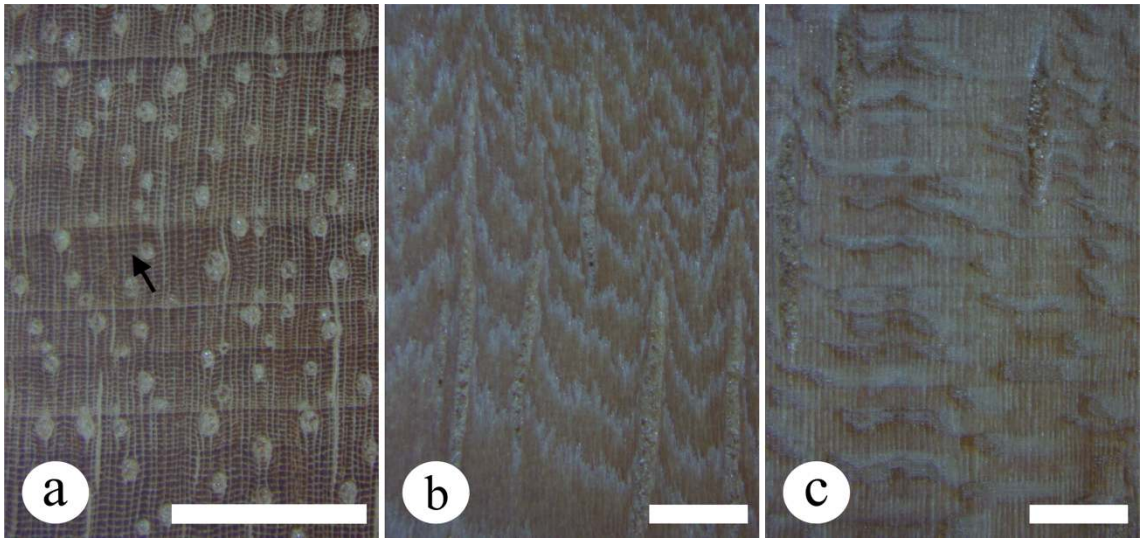

Figure 12. Wood anatomy of *Lecythis* sp. Macroscopic surfaces. a. Transverse surface, scale = 2 mm. b. Radial surface, scale = 1 mm. c. Tangential surface, scale = 1 mm. Diagnostic anatomical feature is indicated by an arrow (axial parenchyma).

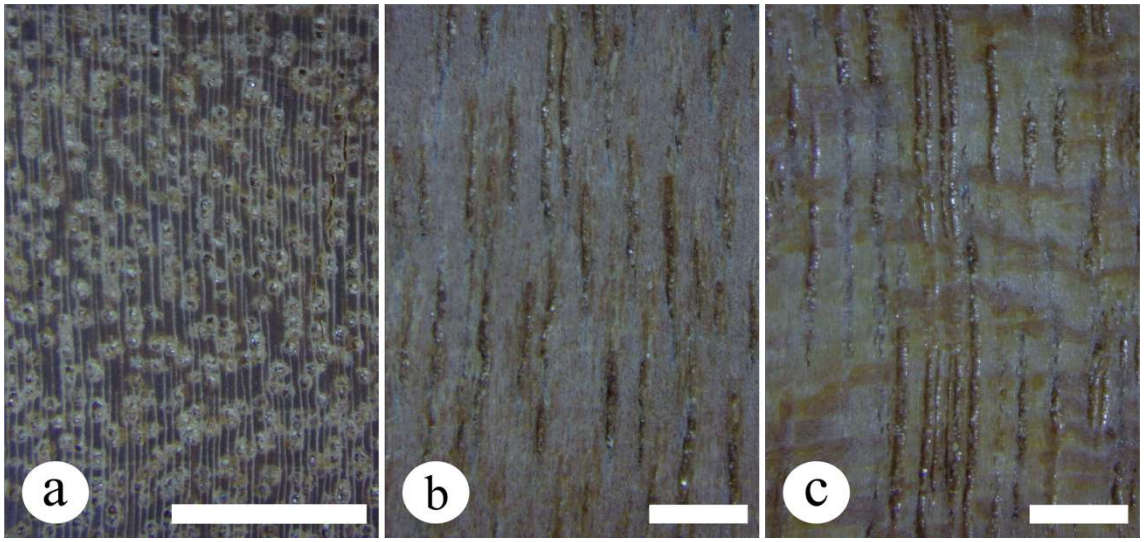

Figure 13. Wood anatomy of *Mezilaurus* sp. Macroscopic surfaces. a. Transverse surface, scale = 2 mm. b. Radial surface, scale = 1 mm. c. Tangential surface, scale = 1 mm.

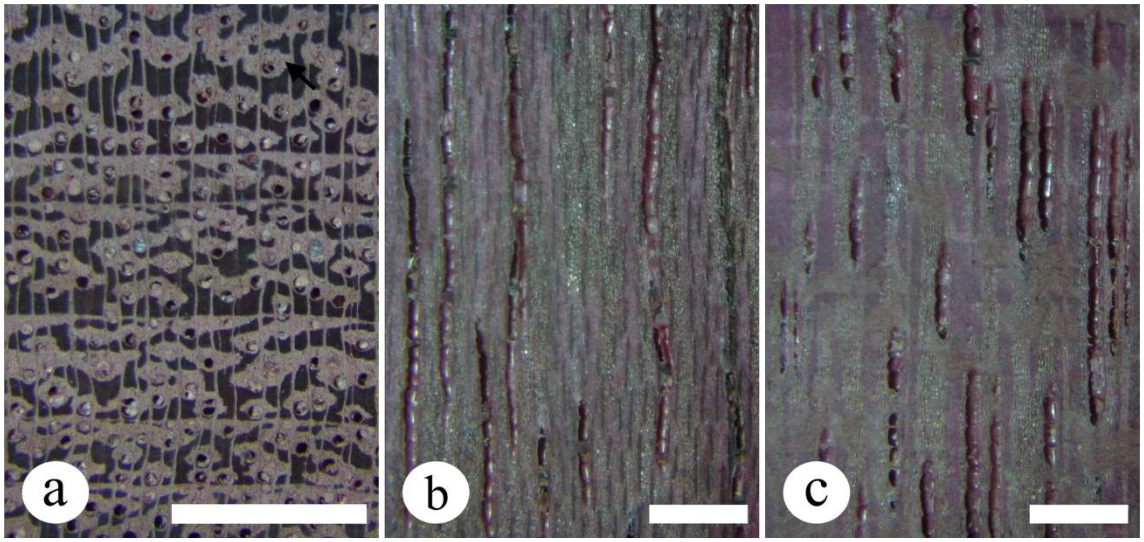

Figure 14. Wood anatomy of *Peltogyne* sp. Macroscopic surfaces. a. Transverse surface, scale = 2 mm. b. Radial surface, scale = 1 mm. c. Tangential surface, scale = 1 mm. Diagnostic anatomical feature is indicated by an arrow (axial parenchyma).

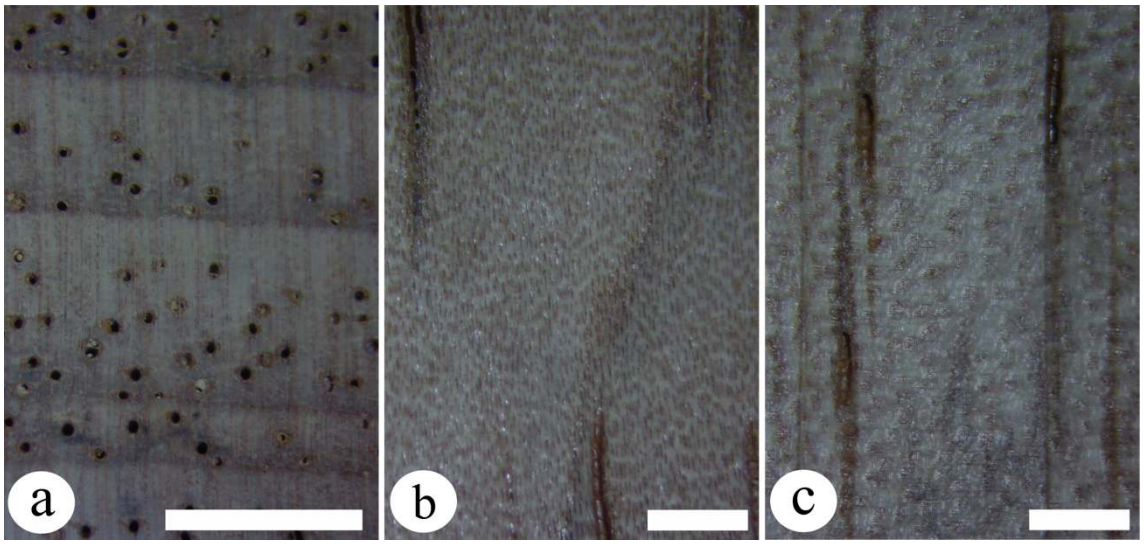

Figure 15. Wood anatomy of *Qualea* sp. Macroscopic surfaces. a. Transverse surface, scale = 2 mm. b. Radial surface, scale = 1 mm. c. Tangential surface, scale = 1 mm.

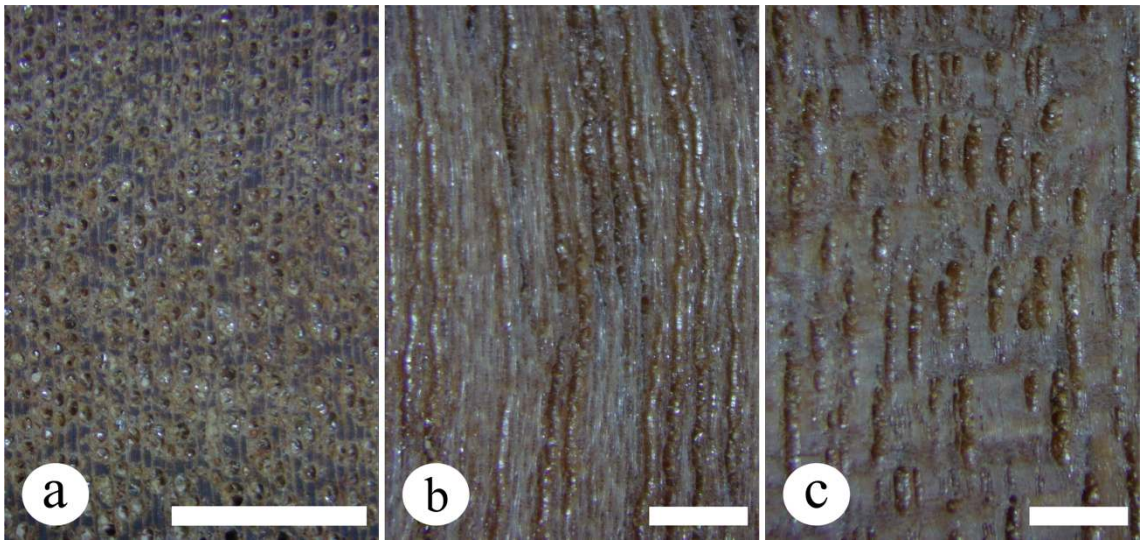

Figure 16. Wood anatomy of *Sextonia rubra*. Macroscopic surfaces. a. Transverse surface, scale = 2 mm. b. Radial surface, scale = 1 mm. c. Tangential surface, scale = 1 mm.

Table 2. Relationship between vernacular names reported at the boatyards and anatomically identified taxa, with accession numbers in the Joaquim Ivanir Gomes Wood Collection (JIGw).

Vernacular name (number of samples)	JIGw accession no.	Anatomically identified taxon	Family	Correspondence pattern
amarelão (5)	311	*Bagassa guianensis* Aubl.	Moraceae	—
anani (6)	478	*Qualea* sp.	Vochysiaceae	—
angelim vermelho (5)	312	*Dinizia excelsa* Ducke	Fabaceae	Name sharing
	316	*Dipteryx* sp.	Fabaceae	
cumaru (8)	310	*Handroanthus* sp.	Bignoniaceae	Name sharing
	367	*Dipteryx* sp.	Fabaceae	
cupiúba (6)	474	*Goupia glabra* Aubl.	Goupiaceae	—
itaúba (5)	314	*Mezilaurus* sp.	Lauraceae	—
jaca (6)	477	*Artocarpus heterophyllus* Lam.	Moraceae	—
jatobá (5)	476	*Hymenaea* sp.	Fabaceae	—
louro vermelho (7)	307	*Sextonia rubra* (Mez) van der Werff	Lauraceae	—
pau d'arco (5)	361	*Bagassa guianensis* Aubl.	Moraceae	Name sharing
	369	*Handroanthus* sp.	Bignoniaceae	
	374	*Bowdichia nitida* Spruce ex Benth.	Fabaceae	
piquiá (25)	365	*Caryocar* sp.	Caryocaraceae	—
	470			
	471			
	472			
	473			
piquiarana (11)	317	*Caryocar* sp.	Caryocaraceae	—
	364			
roxinho (5)	313	*Peltogyne* sp.	Fabaceae	—

Continued...

Table 2. Relationship between vernacular names reported at the boatyards and anatomically identified taxa, with accession numbers in the Joaquim Ivanir Gomes Wood Collection (JIGw).

Vernacular name (number of samples)	JIGw accession no.	Anatomically identified taxon	Family	Correspondence pattern
sapucaia (9)	309	*Lecythis* sp.	Lecythidaceae	—
	371			
sucupira (10)	362	*Lecythis* sp.	Lecythidaceae	Name sharing
	315	*Diplotropis* sp.	Fabaceae	
	475			
tatajuba (5)	363	*Bagassa guianensis* Aubl.	Moraceae	—

Note: Name sharing indicates one vernacular name associated with multiple taxa; vernacular synonymy indicates one taxon associated with multiple vernacular names. A dash (—) indicates a one-to-one correspondence within the sampled dataset.

Table 3. Physical, mechanical, and natural durability properties reported in the literature for the anatomically identified taxa or reference species used for genus-level identifications.

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Taxa identified	Species used for technological data	ρbas ($g \cdot cm^{-3}$)	fc,0,m (MPa)	fM (MPa)	Natural durability	Density range[a]	Source
Artocarpus heterophyllus	—	0.46	48.0	111.1	–	Low	Xavier et al. (2023)
Bagassa guianensis	—	0.68	79.7	138.2	Moderate	Medium	IPT (2026)
Bowdichia nitida	—	0.78	–	–	Moderate	High	IPT (2026)
Caryocar sp.	*Caryocar villosum* (Aubl.) Pers.	0.93	86.5	145.7	High	High	IPT (2026)
Dinizia excelsa	—	0.83	80.9	138.1	High	High	IPT (2026)
Diplotropis sp.	*Diplotropis purpurea* (Rich.) Amshoff.	0.87	94.2	143.4	High	High	LPF (2026)
Dipteryx sp.	*Dipteryx odorata* (Aubl.) Willd.	0.91	94.2	178.3	High	High	IPT (2026)
Goupia glabra	—	0.71	67.2	122.1	High	Medium	IPT (2026)
Handroanthus sp.	*Handroanthus serratifolius* (Vahl) S.Grose	0.99	85.2	169.2	–	High	LPF (2026)
Hymenaea sp.	*Hymenaea courbaril* L.	0.85	75.8	137.2	High	High	LPF (2026)
Lecythis sp.	*Lecythis pisonis* Cambess.	0.88	53.6	118.8	High	High	IPT (2026)
Mezilaurus sp.	*Mezilaurus itauba* (Meisn.) Taub. ex Mez	0.80	68.4	126.5	High	High	IPT (2026)
Peltogyne sp.	*Peltogyne paniculata* Benth.	0.93	90.5	187.1	High	High	LPF (2026)
Qualea sp.	*Qualea dinizii* Ducke	0.61	51.3	102.3	–	Medium	LPF (2026)
Sextonia rubra	—	0.55	49.9	77.8	–	Medium	LPF (2026)

ρbas: basic density; fc,0,m: mean compressive strength parallel to the grain; fM: bending strength. Natural durability and technological properties were obtained from the sources indicated in the table. [a] Density classes based on basic density: low (≤ 0.50 g cm^{-3}), medium (> 0.50 and < 0.72 g cm^{-3}), and high (≥ 0.72 g cm^{-3}), according to LPF/SFB. For genus-level identifications, values refer to the indicated reference species and were obtained from the literature, not measured directly. A dash (—) indicates that technological data refer directly to the species identified anatomically.

DISCUSSION

The macroscopic anatomical characterization of the woods collected from boatyards in coastal municipalities of the state of Pará allowed the identification of 15 taxa, corresponding to nine genera and six species. This demonstrates the operational applicability of wood anatomy as an applied tool for taxonomic identification in operational settings and for documenting the timber repertoire encountered in traditional boatbuilding practices. The combination of diagnostic characters proved particularly efficient, especially the presence or absence of storied rays associated with confluent aliform paratracheal axial parenchyma, which was useful for distinguishing genera belonging to the families Fabaceae and Bignoniaceae (InsideWood 2004 onwards; Wheeler et al. 2020). In addition, the occurrence of exclusively solitary vessels (at least 90%) was observed only in *Goupia glabra*, providing an additional diagnostic feature for field identification. Although not always formalized as a macroscopic descriptor, the presence of scalariform perforation plates could be readily recognized under 10× magnification and contributed to the taxonomic screening of *G. glabra*. Reticulate parenchyma, associated with the presence of traumatic intercellular canals, proved useful for distinguishing genera within Lecythidaceae (Bernal et al. 2011; Moutinho et al. 2012) and enabled the macroscopic segregation of *Lecythis* sp. from the remaining taxa. The identification of *Artocarpus heterophyllus*, an exotic species naturalized in the Amazon region, further highlights the occasional incorporation of non-native taxa into the wood repertoire recorded in the surveyed boatyards, as also reported in other tropical contexts (Nishida et al. 2008; Magalhães et al. 2022).

Based on the obtained identifications, a comparison with surveys conducted in other regions of Pará, including municipalities in northeastern and southeastern Pará (Lopes et al. 2019; Braga Júnior et al. 2020), revealed the recurrence of specific taxonomic groups in traditional boatbuilding. The family Fabaceae stood out as the most representative in all studies considered, indicating the recurrent presence of this family among timbers documented in regional boatbuilding surveys. In addition, the surveys by Lopes et al. (2019) and Braga Júnior et al. (2020) also recorded 33.3% of the genera identified in this study, namely *Bagassa*, *Caryocar*, *Dinizia*, *Goupia*, and *Qualea*, indicating the existence of a shared taxonomic core across different geographic contexts within the state, consistent with the persistence of a recurrent repertoire of timber resources documented in traditional boatbuilding.

This shared taxonomic core is also expressed at the vernacular level. At the boatyards in Bragança, Andrade and Santos (2017) recorded the recurrent use of timbers locally known as cumaru, piquiá, sapucaia, ipê (pau d'arco), tatajuba, and louro vermelho. The correspondence between the popular names ipê and pau d'arco is particularly notable, which illustrates the coexistence of multiple vernacular designations within local timber nomenclature. Rather than representing inconsistencies with botanical taxonomy, these vernacular designations reflect locally shared systems of communication and timber recognition that facilitate the transmission of practical knowledge among master boatbuilders, even when they do not correspond directly to botanical taxonomy.

Comparisons with previous boatbuilding surveys also indicate the recurrent occurrence of *Caryocar* among the timber groups documented in Pará. In the present study, *Caryocar* sp. was likewise among the most frequently recorded taxa within the sampled dataset. Given the availability-based sampling design used here, this pattern should not be interpreted as a quantitative measure of regional preference. Nevertheless, its recurrence across independent surveys is consistent with the established use of this group in wooden boat construction and with previous reports relating timber selection to technological performance and traditional knowledge. Together, these patterns reinforce the applicability of macroscopic wood anatomy for taxonomic identification in technological and cultural use contexts by providing an objective framework for interpreting traditional timber selection practices (Melo Júnior et al. 2025).

It should also be considered that changes have occurred in the process of acquiring the timbers used in traditional boatbuilding. Raw materials that were previously extracted directly from native forests by master boatbuilders are now obtained through a supply chain of commercial vendors (Ferreira et al. 2025; Lins 2019). This shift has directly influenced how contemporary master boatbuilders identify the wood species employed in boat construction, altering the way traditional knowledge is applied during timber selection. This phenomenon is observed in other regions of the Brazilian coast and signals the gradual loss of traditional knowledge in naval carpentry (Conceição and Melo Júnior 2027).

When timber was directly extracted from forest environments, master boatbuilders relied on ethnobotanical knowledge associated with the morphological recognition of forest species, combined with the assessment of wood anatomical characteristics, to identify the materials used. Now, with the transformation of acquisition practices, identification depends predominantly on the evaluation of organoleptic and anatomical features of processed wood. This context reinforces

the need to develop and apply methods that facilitate in situ anatomical wood identification, thereby reducing the likelihood of taxonomic uncertainty in timber identification and supporting the continuity of traditional timber selection practices under changing supply conditions.

The non-one-to-one correspondences between vernacular names and anatomically identified taxa observed in this study demonstrate that popular names do not maintain a one-to-one correspondence with botanical taxa within the sampled boatyards. Cases such as pau d'arco, associated with *Bagassa guianensis*, *Handroanthus* sp., and *Bowdichia nitida*, as well as cumaru and sucupira, which were assigned to different genera and families, reflect patterns of name sharing previously documented for boatbuilding in the state (Braga Júnior et al. 2020). These results show that vernacular nomenclature and botanical taxonomy operate at different levels of classification and should not be treated as directly interchangeable systems. Local timber names may incorporate empirical criteria, such as color, apparent density, odor, texture, and wood behavior in use. Consequently, vernacular names can function as practical categories for communication and timber selection within traditional boatbuilding, rather than as direct equivalents of botanical taxa. In addition, the occurrence of vernacular synonymy reinforces this distinction, as observed for *Bagassa guianensis* (amarelão, tatajuba, and pau d'arco), for *Caryocar* sp. (piquiá and piquiarana), and for *Lecythis* sp. (sapucaia and sucupira) (Nascimento et al. 2017; Cysneiros et al. 2018). Although such vernacular classifications are highly effective for maintaining traditional construction practices, non-one-to-one correspondence with botanical taxonomy can complicate timber traceability and the recognition of conservation-sensitive taxa when vernacular names are used as the sole basis for taxonomic identification.

The genus-level identification of *Hymenaea* sp., *Mezilaurus* sp., and *Peltogyne* sp. deserves particular attention from a conservation perspective because these genera include species occurring in Pará that are classified as threatened, such as *Hymenaea parvifolia*, *Mezilaurus itauba*, and *Peltogyne maranhensis*, currently classified as Vulnerable (VU) in Brazilian conservation assessments (MMA 2022; CNCFlora 2022). However, because the samples were not identified to species level, no threatened status can be attributed to the sampled materials themselves. Rather than demonstrating the use of threatened species, these records highlight a limitation of genus-level identification for conservation screening when a genus contains both threatened and non-threatened species. Given the high extinction risk associated with Amazonian tree species, particularly those with restricted distributions and histories of selective exploitation (Guevara-Andino et al. 2025), greater taxonomic resolution may therefore be necessary when wood identification is intended to support regulatory or conservation assessments. The observed non-one-to-one correspondence between vernacular names and botanical taxa further reinforces the value of combining local nomenclature with anatomical identification rather than relying exclusively on vernacular designation. Regarding the origin of the wood used in boatbuilding in Bragança, Ferreira et al. (2025) observed that it was purchased in the city or ordered from different municipalities (Cachoeira do Piriá, Nova Esperança do Piriá, São Miguel do Guamá, Paragominas, and Piriá). Many of the carpenters interviewed in the study reported concerns about the increasing scarcity of raw materials, highlighting the growing importance of accurate timber identification for both biodiversity conservation and the long-term maintenance of traditional boatbuilding practices.

The technological properties compiled from the literature for the identified taxa and reference species indicate a predominance of medium- to high-density woods among the timber types recorded in the surveyed boatyards. Ten of the 15 identified taxa (66.7%) were represented by literature values within the high-density class, four (26.7%) within the medium-density class, and one (6.7%) within the low-density class. The available literature data also indicate substantial mechanical strength and moderate to high natural durability for several of these woods (Table 3). Because these properties were obtained from published sources rather than measured directly in the sampled material, they should be interpreted as indicative technological characteristics of the identified taxa or their designated reference species. Nevertheless, this technological profile is consistent with the mechanical and environmental demands reported for wooden boat construction in previous studies. Higher-density woods with superior mechanical performance are preferentially assigned to structural components subjected to greater stresses, such as hulls and decks, while intermediate-density species tend to be used in secondary or sealing elements, particularly in parts not permanently submerged (Andrade and Santos 2017; Braga Júnior et al. 2020; Faller et al. 2023; Ferreira et al. 2025). In this context, literature data for taxa such as *Mezilaurus* and *Dipteryx* indicate combinations of high density and natural durability that are compatible with demanding uses in wooden boat construction, attributes directly related to service life and resistance to xylophagous organisms and decay fungi (Faller et al. 2023).

The recurrence of genera such as *Caryocar*, *Mezilaurus*, *Dipteryx*, *Lecythis*, and *Handroanthus* in the

present dataset and previous boatbuilding studies is consistent with the technological characteristics reported in the literature for these groups, including mechanical strength, natural durability, and dimensional stability, characteristics widely recognized for woods used in environments with high biological aggressiveness (Mainieri and Chimelo 1989). The technological properties compiled for the identified taxa and reference species therefore provide a basis for comparing the botanical identifications obtained here with the empirical criteria traditionally reported for timber selection by master boatbuilders.

An investigation conducted by Ferreira (2024) with master boatbuilders working in boatyards in Bragança, based exclusively on the use of vernacular species names, demonstrates that timber selection is directly associated with the application of technological properties, as informed by the empirical knowledge of these professionals and the functional requirements of wooden boats. Structural components such as the keel, stempost, deck, and *patilhão* require timbers with high mechanical strength and elevated natural durability, as they are responsible for supporting the boat's weight, withstanding drag forces, resisting impacts with obstacles, and enduring attacks by marine xylophagous organisms, such as shipworms, in addition to being components that are difficult to replace. These observations from previous ethnographic and technological studies indicate that vernacular timber selection is not arbitrary, but reflects accumulated technical knowledge associating wood performance with specific construction functions.

In response to these demands, master boatbuilders preferentially select timbers such as cumaru, sapucaia, pau d'arco, and angelim vermelho for the aforementioned structural components, while piquiá is more commonly used in the construction of the *patilhão* (Ferreira 2024; Ferreira et al. 2025). Cumaru, sapucaia, and pau d'arco may also be employed in hull planking, particularly in boats intended for navigation in more distant environments and under harsher operational conditions. In contrast, louro vermelho and itaúba are more frequently used in the planking of boats for fishing activities in areas closer to their region of origin. Piquiá, in turn, is most commonly employed in the frames and superstructure (Ferreira 2024). Although structural components were not systematically recorded for the individual samples analyzed in the present study, the anatomical identifications obtained here and the literature-reported technological properties of the corresponding taxa are compatible with these previously documented patterns of timber use. Thus, the present results provide taxonomic and technological context for, rather than independent verification of, the functional associations reported by Ferreira (2024) and Ferreira et al. (2025).

In marine and estuarine contexts, the historical selection of tropical timbers is closely linked to resistance to marine borers and the ability to maintain structural performance under partial or permanent immersion, with frequent references to species traditionally known as angelim vermelho and itaúba (Gérard et al. 2024). Wood resistance to biodeterioration in these environments does not depend solely on density, but rather results from the interactions among hardness, cellular microstructure, and, especially, the content and nature of heartwood extractives. In some tropical hardwoods, extractive content may play a more decisive role than hardness itself (Palanti et al. 2015). In addition, variability in susceptibility to borer organisms as a function of environmental conditions, such as temperature and salinity, contributes to empirical selection favoring species with proven performance in service. These observations support the interpretation proposed in previous studies that timber selection in traditional boatyards reflects accumulated empirical knowledge of wood performance (Andrade and Santos 2017; Braga Júnior et al. 2020), in which repeated observations of wood performance have shaped and maintained a stable body of technical knowledge transmitted across generations.

The anatomical, technological, and nomenclatural patterns documented and discussed in this study are consistent with traditional boatbuilding along the Amazonian coastal zone of Pará as a structured technical and cognitive system, in which specialized material decisions are guided by accumulated empirical knowledge transmitted across generations. The recurrence of specific taxa across this and previous surveys, together with the correspondence between literature-reported technological properties and functional uses documented in previous studies, is consistent with timber selection being influenced by historical experimentation and practical validation in service. Ethnographic evidence shows that master boatbuilders systematically recognize and apply physical and mechanical wood attributes, such as weight, strength, durability, and load-bearing behavior, which, even without formal scientific conceptualization, constitute a functional body of technical knowledge adapted to local environmental conditions and productive demands (Costa et al. 2017; Ferreira 2024; Ferreira et al. 2025). On this subject, Emperaire (2002: 389) points out that the perception of the plant world differs between groups of people based on their different ways of thinking and knowledge, using different criteria of morphology, ecology, utility, and cultivated or wild status, among others. The present study demonstrates that macroscopic wood anatomy provides an objective means of documenting the botanical identity underly-

ing these locally constructed systems of timber recognition, revealing points of correspondence and divergence between vernacular classifications and botanical taxonomy in the context of traditional boatbuilding. The same was observed in a recent study in estuarine environments in southern Brazil, where naval carpentry has adopted Amazonian species with similar technological characteristics found in Atlantic Forest species due to the depletion of forest resources or legal impediments (Conceição and Melo Júnior, 2027).

For wooden vessels to attain the efficiency and level of sophistication achieved by traditional boatbuilders, an in-depth understanding of the morphoanatomical characteristics of the wood species employed is essential (Andrade et al. 2018). In this regard, the development and adaptation of taxonomic identification methods to the needs and working conditions of traditional wooden boatbuilders represent useful strategies for improving the taxonomic precision of timber identification, while also supporting informed timber selection in the performance of their activities.

Despite the challenges faced by the traditional boatbuilding sector, arising from both the decline in demand associated with depleted fish stocks and the risk of generational discontinuity (Adomilli et al. 2019; Brosi et al. 2007, fishing-boatbuilding communities and traditional shipwrights continue to sustain and transmit their practices and knowledge. Against this backdrop, it is imperative to recognize these communities and traditional boatbuilders, as members of a human–plant–sea socioecological system, as active agents in strategies aimed at safeguarding the natural and cultural heritage associated with the craft of traditional wooden boatbuilding (Andrade et al. 2018).

Thus, integrating anatomical identification, literature-based technological information, and analysis of vernacular nomenclature allows these practices to be recognized as technical and cultural heritage associated with the use of forest biodiversity, while also providing objective support for cultural safeguarding, forest management, and improved taxonomic screening of timber resources. Further advances in studies on the anatomical identification of wood used in traditional boatbuilding may also contribute to investigating the geographic and commercial origin of timber resources and to understanding the historical, ecological, and sociocultural aspects associated with their procurement, including harvesting practices, commercialization, and transportation prior to their incorporation into the boatbuilding process by traditional shipwrights. Furthermore, this approach contributes to elucidating the historical patterns of wood species use in traditional boatbuilding, as demonstrated by Melo Júnior and Barros (2017).

CONCLUSION

Macroscopic wood anatomy was an operationally useful tool for taxonomic identification of woods used in traditional boatbuilding along the Amazonian coast of Pará, helping to resolve taxonomic uncertainties associated with non-one-to-one correspondence in vernacular nomenclature. The consistency between the anatomical identifications, literature-reported technological properties, and functional patterns documented in previous boatbuilding studies supports the interpretation that wood selection is not random but instead results from consolidated functional criteria developed through accumulated experience in traditional use contexts.

This study contributes to the understanding of traditional uses of Amazonian forest biodiversity from an applied botanical perspective by showing correspondences among taxonomic identity, traditional timber recognition, and literature-reported technological characteristics. By integrating anatomical identification with vernacular nomenclature and technological information, the study shows that scientific wood identification can complement rather than replace traditional systems of timber recognition, while also improving the taxonomic resolution needed for timber documentation and conservation-related assessment. The integration of anatomical identification with technological information provides objective support for understanding timber use in traditional production systems and can contribute to management and monitoring strategies that reconcile cultural continuity, functional efficiency, and the conservation of forest resources.

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DATA AVAILABILITY

The data used to support the findings of this study are available from the corresponding author upon reasonable request.

CONFLICT OF INTEREST

The authors have no conflicts of interest to declare.

CONTRIBUTION STATEMENT

Conceived of the presented idea: RSLB, LELM. Carried out the experiment: DSSS, GMA, LJS, DYOB, LVS, YBS.
Carried out the data analysis: DSSS, GMA, LJS, DYOB, LVS, PSF, MCQS, MPMM, LELM.
Wrote the first draft of the manuscript: DSSS, GMA, LJS, DYOB, LVS, PSF.
Review and final write of the manuscript: JCFMJ, ISS, RSLB, MCQS, MPMM, LELM.
Supervision: RSLB, LELM.

DISCLOSURE OF AI USE

The authors used ChatGPT (OpenAI) to assist with language editing, clarity, and organization during manuscript revision. All scientific content, interpretations, and conclusions were reviewed and approved by the authors, who take full responsibility for the final content of the manuscript.

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