WITHDRAWN: Technological Profile of Small-diameter Forest Species in a Managed Area in the Amazon

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Abstract

The use of wood from small-diameter species is still restricted, and knowledge of its characteristics is limited. In this context, the objective of this study was to characterize the technological properties of eight species of small diameters of greater occurrence in the Central Amazon to indicate sustainable use. Samples were obtained from a managed area of secondary forest (Amazonas/Brazil). 24 trees (diameter ≤ 50 cm) were selected for the determination of chemical and physicomechanical properties. The highest concentrations of extractives and total polyphenols were detected for *Eschweilera odora* (7.08 and 2.63%), and lignin and cellulose were detected for *Micrandropsis scleroxylon* (34.80%) and *Byrsonima crispa* (55.62%). For the physical-mechanical properties, the average moisture content was 12.84%. For density, the species were classified in the medium to high range (0.56-0.93 g/cm^3). In general, the studied species presented a high calorific value (~4,907 cal/g), and *Eschweilera truncata* presented higher mechanical strength (modulus of elasticity 17,350 MPa; modulus of rupture 173.93 MPa). The multivariate analysis using the K-means algorithm, based on the centroid of the data, indicated the formation of five groups, where the group of *Eschweilera truncata* was represented by higher values of MOE, MOR, and ash, while the group of Inga alba had characteristics of low-strength wood. The quality of the small-diameter wood studied here has the potential to be indicated for management since the technological characterization is a fundamental tool to assist decision-making in management plans that may indicate the use of new species in the forestry sector.

Introduction

The Brazilian territory is covered by native forests, where 2/3 of this area is formed by the Amazon forest, and coverage encompasses 1/3 of the world's tropical forests, resulting in great interest in the global trade of tropical timber. The preference for the use of wood in recent years is related to the properties of this raw material, such as its high mechanical resistance, low energy input for its production, renewable source, pleasant aesthetics, variable colors and textures, reasons of interest and intense development of research in wood technology (Varejão et al. 2009; IMAZON 2015; Nascimento et al. 2021).

The search for native wood essences of consolidated use, which have high use, can lead to overexploitation of species and a decrease in their stock in the forest. An alternative to this situation is the replacement of these species with others with similar wood properties and with sufficient growth stock in the forest. In this sense, interest and the search for studies on the technological characterization of new species have intensified (Souza et al. 2016; Araújo et al. 2019; Reis et al. 2019).

The reduced technological knowledge about Amazonian woods, together with the difficulty of exploitation, motivated research in the area of wood technology since they are intrinsically related to the ecology, economy, and social aspects of the people of the forest. Small-diameter species from tropical forests are not commonly studied, a fact that prevents their sustainable exploitation due to the lack of technical-scientific knowledge about wood quality (Christoforo et al. 2017; Coldebella et al. 2018). Hampton et al. (2008) defined small-diameter trees as individuals with DBH (diameter at breast height) in the range of 15 < DBH < 50 cm, while Siviero et al. (2020) indicated DBH from 25 to 55 cm. Oliveira and Amaral (2004) and Oliveira et al. (2008), in a floristic survey in a terra firme forest northwest of the city of Manaus (Amazonas/Brazil), recorded 771 individuals belonging to 50 families, 120 genera, and 239 species, and 70% of the arboreal individuals were of the small diameter type (> 22.1 cm), which indicated the species for logging, medicinal and ecological purposes.

In the sustainable forest management plan (PMFS) of the company Precious Woods Amazon (Amazonas/Brazil), individuals with DBH > 15 cm that were not on the list of commercial species but would have a potential indication of use in the form of poles were included, namely, *Chrysophyllum prieurii*, *Eschweilera coriacea*, and *Minquartia guianensis*. It should be noted that technical criteria were reinforced and approved by the Technical Forestry Chamber of the Executive Management of IBAMA/AM (Instituto Brasileiro do Meio Ambiente) on July 2, 2002, which approved the exploitation of species with diameters < 50 cm (PWA 2013).

The main challenge of this raw material is the lack of technological knowledge, as the barrier to use is not selective regarding the quality of the wood and is underutilized for generating heat (Wolfslehner et al. 2013). LeVan-Green and Livingston (2001) consider small-diameter trees to be a forest residue that potentiates fires in planted forests in the USA and indicates the use of these trees for various purposes, such as the use of solid wood in unconventional dimensions, engineered products (particle board), wood fiber/plastic composites, energy and other applications.

In this sense, there is a growing concern in forest management, especially due to the current paradigm shift in the forestry industry toward the production of high-value-added wood products to optimize the value chain and, ultimately, increase the sector's competitiveness in a bioeconomy context (Mascarenhas et al. 2021; Nascimento et al. 2021).

Final products require raw materials that have specific properties, a combination of characteristics for a quality product, which in this case encompasses the anatomical, physical, mechanical, and chemical properties of wood. Regarding chemical properties, components such as cellulose are related to the volumetric contraction and moisture of the species, and lignin, responsible for cementing the cells, is directly related to impact and compression resistance, acting as a protector against xylophagous microorganisms and preventing penetration. of destructive enzymes in the cell wall (Fengel and Wegener 2003). In the physical property, the basic density, a predictor of other properties, is directly related to extractives, lignin, and the mechanical properties of wood; therefore, knowledge of the technological properties of new species is essential for the correct use of this sustainable raw material (Senalik and Farber 2021).

In this context, the objective of this study was to characterize the technological properties of small-diameter species such as breu-red (*Protium tenuifolium*), ingá (*Inga alba* and *I. paraensis*), matá-matá (*Eschweilera odora* and *E. truncata*), muirajibóia (*Swartzia recurva*), murici (*Byrsonima crispa*) and piãozinho (*Micrandropsis scleroxylon*) to allow the indication of use for specific purposes, thus encouraging management studies and engineered products for small-diameter species.

Materials And Methods

Study area

The forest species were collected in the secondary forest area of non-flooded forests of the Experimental Tropical Silviculture Station of the Instituto Nacional de Pesquisas da Amazônia – EEST/INPA (02°37'55.5" S and 60°09'11” W), located at km 23 of the ZF-2 road, with access at km 934 of the BR-174 (Manaus-Boa Vista, Brazil). The station is 60 km away from the capital of Amazonas and occupies an area of 21,000 hectares (Fig. 1). The climate of the region is of the Köppen Afi type, with an average temperature of 26°C (19–39°C). The average annual rainfall is 2407.6 mm, with a rainy season between November and May, with an average monthly rainfall of 288 ± 99 mm, and the dry season between June and October, with an average monthly rainfall of 136 mm. ± 64 mm, reaching months with less than 100 mm rainfall (Tanaka et al. 2014; PELD 2015).

The study area has vegetation classified as a humid forest, with three distinct vertical strata, known as the grove, understory, and canopy, with an average canopy height of 30 m and emergent trees that can reach up to 45 m. The basal area varies from 28 to 30 m²/ha, and the soil in the area is classified as latosol with low nutrient concentration, high acidity, and high aluminum concentration (Aleixo et al. 2019).

Species studied and sampling

The samples were obtained from an inventoried plot (subplots of 100 x 4.25 m) and defined within the proposal of the INCT Madeiras da Amazônia – MCTIC/CNPq/FAPEAM. Eight species with the highest frequency in the plot with similar characteristics among individuals of the same species, such as diameter at breast height (DBH) and commercial height, were selected, totaling 24 trees. These individuals were included in the diameter class of 25 cm ≤ DBH ≤ 50 cm, and visual analyses of the health status of each tree were also performed (Table 1; supplementary information SI1 an SI2). Were obtained 50 cm-thick torete of the DBH of three individuals from each species, and the samples were sent to the wood anatomy laboratory - COTI/INPA/MCTIC/Brazil for confirmation of the identification made in the field (SI3).

For chemical studies, samples were sent to the Wood Chemistry Laboratory – COTEI/INPA, Manaus/Brazil, where they were reduced to smaller fragments using perforation and submitted to grinding in a knife mill to obtain sawdust. Subsequently, they were sieved, separated into sizes of 20, 40, 60, and 80 mesh, and stored in plastic bags. The sawdust used in the tests was material retained in 60 mesh. All determinations were performed in duplicate, following the recommendations of the American Association for Testing Materials (ASTM).

The physical-mechanical tests were carried out at the Laboratory of Engineering and Wood Artifacts - COTEI/INPA. For that, specimens were made in the dimensions 20 × 20 × 300 mm and 20 × 20 × 30 mm in the cross-section in the direction of the sapwood, according to the Brazilian Association of Technical Standards - ABNT and British Standard - BS.

In the chemical characterization analysis, fragmented samples (sawdust) of eight species were used, three individuals of each species x one log, where six determinations were carried out (total extracts, water solubility, lignin, raw cellulose, ash, and polyphenols) in duplicate. A distributed experimental design was carried out in an 8 × 3 × 1 × 6 × 2 factorial scheme, totaling n = 288.

Table 1

Small-diameter species collected from a managed area (Amazonas/Brazil)

Popular name	Collection/INPA	General characteristics of wood
Breu red *Protium tenuifolium* (Engl.) Burseraceae	258.790	High-density wood, light beige to reddish-brown, straight or irregular grain (crisscross), fine texture.
Ingá-white *Inga alba* (Sw.) Willd. Ingá-red *Inga paraensis* Ducke Fabaceae	X10.118 258.781	Medium-density wood, light brown to reddish, straight and irregular grain (crisscrossed), and generally coarse texture. Medium to high-density wood, light to dark brown in color, straight and irregular grain (crossed), and medium to coarse texture.
Matá-matá yellow *Eschweilera odora* (Poepp.) Miers. Matá-matá black *Eschweilera truncata* A.C.Sm. Lecythidaceae	218.387 224.504	High-density wood, light brown color, irregular grain (crisscross), and medium to coarse texture. High-density wood, reddish-brown color, irregular grain (crisscrossed), and fine to medium texture.
Muirajibóia *Swartzia recurva* Poepp. Fabaceae	221.367	High-density wood, light yellow to reddish-brown, straight grain, more often irregular (crossed) and fine texture.
Murici *Byrsonima crispa* A. Juss Malphigiaceae	X8.464	Medium-density wood, light brown color, straight grain, and medium texture.
Piãozinho *Micrandropsis scleroxylon* W. Rod. Euphorbiaceae	X6.145	High-density wood, light yellow to dark brown (blackened), straight grain, and coarse texture.

The physical characterization required solid and fragmented samples, and three quantifications were performed: moisture, higher calorific value (HCV), and basic density (BD). For moisture and HCV, the factorial 8 × 3 × 1 × 2 × 2 with n = 96 was used, and for

BD, the distribution was 8 × 3 × 1 × 1 × 10 n = 240. For mechanical resistance, MOE (modulus of elasticity) and MOR (modulus of rupture) had an 8 × 3 × 1 × 2 × 3 distribution, totaling n = 144.

Determination of chemical properties

Determination of the content of total extractives - ethanol/toluene (ASTM D1105, D110/2021)

In this analysis, two extractions were carried out with solvents of different polarities successively, as described below:

1st extraction: 5.00 g of sawdust was weighed and transferred to a cellulose cartridge. These are placed inside the Soxhlet extractor and adapted to the flat-bottomed flask (300 mL) containing approximately 180 mL of ethanol-toluene solution (1:2) in each flask. They were left at reflux for approximately 8 hours until complete extraction, where the solution inside the Soxhlet no longer showed any color. Cartridges with samples were dried in an oven (100°C) and subsequently stored in a desiccator. The flask with extract was concentrated and subsequently dried in an oven and weighed until constant weight. The first extraction (TE1%) was determined by the equation TE1% = (Pf – Pi)/Ps × 100, where Pi = initial dry flask weight, Pf = weight of the flask with extractives, and Ps = weight of the dry sample.

2nd extraction: The previous procedure was repeated, and the extraction solvent in this step was ethanol. Finally, the TE2% is determined, and the indices of the two extractions (TE1 + TE2) are added. This result is referred to as the total extractive content.

Determination of solubility in hot water (ASTM D1110/2021)

The sawdust extracted with ethanol-toluene was dried and weighed for extraction in water. In an Erlenmeyer flask, 1 L was transferred to the extracted sample, and ~ 1 L of boiling distilled water was added and placed in a water bath for 4 hours, changing the water every hour. The material was filtered at the end of this period in Gooch crucibles (M), dried in an oven (100°C) for 24 hours, and then weighed until constant weight. The content of soluble material in hot water was calculated as follows: solubility in hot water % = (P1 – P2)/P1 × 100, P1 = Weight of the initial sample; P2 = Sample weight after extraction.

Determination of lignin content (ASTM D1106/2021)

A total of 1.00 g of the extractive-free wood sample was weighed in a beaker and treated with 72% H_2SO_4. The medium was left to rest for 2 hours (cold bath), after which 560 mL of water was added. The vial was placed in a water bath (100°C) for 4 hours. After the reaction time, the samples were filtered in a Gooch crucible (M). The material was washed with 500 mL of heated distilled water and dried in an oven (100°C) for 12 hours. The samples were weighed to constant weight, and the lignin content was determined using the formula: lignin % = P2/P1 × 100, where P1 = initial dry weight of the sample. P2 = Dry weight of lignin obtained.

Determination of raw cellulose content (Ramadan and Nasser 2008)

Cellulose determination was performed with extractive-free sawdust (1.00 g). A underwent the first treatment with 20 mL of nitric acid (3%). The material was refluxed in a water bath (80°C) for 30 minutes After this period, the solution was filtered, and the retained material was subjected to a second treatment with 25 mL of sodium hydroxide (3%) and heated for further digestion. Finally, the residue (cellulose) was washed with 50 mL of ethanol, 100 mL of ethanol-water solution (1:1), and finally with water until a neutral medium was reached. The crude pulp obtained was dried in an oven (100°C) and then weighed until constant weight. The cellulose content was calculated by the following formula: crude cellulose % = P2/P1 × 100, where P1 = initial dry weight of the sample. P2 = Dry weight of the cellulose obtained.

Determination of ash content (ASTM D1102/2021)

In a porcelain crucible, 1.00 g of sawdust was added and placed in an oven (100 ± 3°C) for 1 hour to remove moisture. Then, the container is taken to the muffle for incineration, starting with gradual heating up to 580–600°C. After incineration, the crucible is weighed to constant weight. The ash content was determined by the formula Ash% = (Pash/Ps) × 100, Pash = Ash weight, and Ps = Dry sawdust weight.

Determination of tannins and other polyphenols (Vetter and Barbosa 1995)

A portion of 2.00 g (sawdust 40 mesh) of each species (mixture of three individuals) was placed under reflux with water (100 ml) in a water bath (90°C, 60 minutes). Then, the extract was filtered and reserved, and the wood residues were taken again for extraction for another 60 minutes. Then, the material was filtered again, added to the first extractive fraction, and diluted to a final extractive solution of 500 mL (standard solution). Then, a volume of 100 mL of the stock solution was placed in a flask, where 10 mL of 40% formaldehyde (volume/volume) and 5 mL of concentrated HCl were added. The system was refluxed in a water bath for 30 minutes, according to the Stiasny method for tannin determination. The precipitate was filtered, washed with water, oven dried, and weighed. The aliquot obtained was extrapolated to the total volume of extract, and the tannin content was calculated using the equation Tan% = MTT/PMS × 100, where MTT = total mass of tannins (g) and PMS = dry weight of wood.

Determination of physical-mechanical properties

Determination of moisture content (ASTM D2016/2021)

A total of 1.00 g of sawdust (60 mesh) was weighed in a filter weighing machine and dried in an oven at 100 ± 2°C for 4 hours, at the end of which time the material was weighed to a constant weight. The moisture content was calculated using the formula TU% = (Pu – Ps)/Ps × 100, Pu = wet mass. Ps = dry mass.

Determination of higher calorific value (ASTM D2015/2021)

The higher calorific value (HCV) tests were performed on a dry basis with the aid of a calorimetric bomb. Approximately 0.80 g of sawdust (60 mesh) was placed in the metallic capsule and introduced inside the pump, a wool wire was placed next to the metallic ignition wire, the pump was closed, and oxygen gas was injected. The bomb is placed in a metal bucket with water, and the ignition system of the calorimeter is coupled to the pump, where quantification begins. After approximately 15 minutes, the PARR calorimeter operating system prints the reading result in cal/g.

Determination of basic density (NBR 7190/2022)

The method of determining the basic density (BD) consists of monitoring the displacement of water in the wood. The specimens (20 × 20 × 30 mm) were saturated to obtain the green volume, weighed (model Marte AS2000 scale, with a precision of 0.001 g), and then dried in an oven (100 ± 3°C) until they reached a constant weight. Subsequently, the basic density was calculated according to the formula: Db = Ps/Vv, where Ps = dry weight in g, and Vv = sample volume in a saturated state in cm^3.

Determination of static bending of wood (MOR and MOE) (BS 373/1999)

Specimens (20 × 20 × 300 mm) were stored in an air conditioning chamber (for seven days, 20 ± 2°C and relative humidity of 65 ± 5%) to stabilize the moisture (~ 12%). Static flexion tests were performed with three repetitions for each individual. The samples are coupled horizontally (parallel to the fibers) in the universal machine (20 tons. and speed of 1.0 mm/minutes) and subject to centralized loading, where the support distance is set at 280 mm. MOR (modulus of rupture) was calculated from the maximum load at which each wood sample failed, $MOR = 3.P.L/2.b.h^2$, where P = applied load/force (N), L = distance between supports (280 mm), b = width of test sample (mm), and h = thickness of test sample (mm). The MOE (modulus of elasticity) was calculated using the load for the deflection curve. $MOE = \Delta P.L^3/4.\ \Delta y.b.h^3$, where ΔP = change in required load occurs below the proportional limit and Δy = change in deflection due to load - strain (mm). Chemometric models were built using a traditional methodology (MOE and MOR) and NIR spectra, and the results were estimated in MPa.

Amazon wood grouping

Multivariate statistics were used to analyze groups of wood from small-diameter trees in the Amazon, considering the results of technological characterization (physical-mechanical and chemical properties) as the sample universe. In this type of analysis, it is possible to determine a rational structure (groups) to a set of information (properties), classifying them and allowing the analysis of similarities between each grouping (Nascimento et al. 1997; Araújo 2007; Melo et al. 2013; Silveira et al. 2013).

The PAST statistical program (version 4.06b – Hammer et al. 2001) was used in this stage of the study, analyzing the set of physical, mechanical, and chemical properties. Data analysis was performed by comparing the averages obtained for the properties of each species. Subsequently, the correlation analysis between the properties and similarity analysis was performed through the grouping of species (cluster analysis). The groups formed to make it possible to understand the interrelation of the different technological characteristics finally correlated with the standard species (medium and high density) and an indication of end uses.

Statistical analysis

Statistical tests were performed on the raw data of the physical, mechanical and chemical properties to satisfy the assumptions of normality, homogeneity, and independence of the residues (SI4). ANOVA was applied, and when $p \leq 0.05$ indicated the occurrence of a statistically significant difference in the evaluated property, the Tukey test (Minitab® 21.1) was applied. Finally, a correlation matrix was created between the predicted properties. For this, the data that did not meet the normality assumption underwent the following data transformations, Log 10 and Box–Cox, to meet the assumption of Pearson's correlation analysis. Correlations were classified as strong ($r^2 > 0.70$), moderate ($0.40 < r^2 < 0.69$), and weak ($r^2 < 0.39$) according to Baba et al. (2014).

Results And Discussions

The characterization of the wood consists of determining the anatomical, chemical, and physical-mechanical traits, which define the quality and its sustainable use. Table 2 and Figs. 3 and 4 show the results of the chemical and physicomechanical characterization of the small-diameter species *Byrsonima crispa* (Malphigiaceae), *Eschweilera odora*, and *E. truncata* (Lecythidaceae); *Inga alba, I. paraensis* and *Swartzia recurva* (Fabaceae); *Micrandropsis scleroxylon* (Euphorbiaceae); and *Protium tenuifolium* (Burseraceae).

Chemical properties of wood from small-diameter trees

The extractives, polyphenol, and water solubility results provide quantitative information on the composition of secondary metabolites in wood (Table 2). The content of soluble extractives in toluene-ethanol ranged from 2.37 (*M. scleroxylon*) to 7.08% (*E. odora*), and total polyphenols ranged from 0.19 (*B. crispa*) to 2.63% (*E. odora*), while for hot water solubility, the variation was from 6.54 (*S. recurva*) to 14.69% (*M. scleroxylon*). The macrometabolites lignin and cellulose varied from 26.65 (*I. alba*) to 34.80% (*M. scleroxylon*) and 43.33 (*E. truncata*) to 55.62% (*B. crispa*), respectively. For the ash content, the values were below 0.90%.

Table 2
Chemical properties of small-diameter woods

Species	Total Extractives	Total Polyphenols	Hot water	Lignin	Cellulose raw	Ash
Byrsonima crispa	3.48 c ± 0.30	0.19 d ± 0.02	12.04 b ± 1.15	32.51 ab ± 0.02	55.62 a ± 1.34	0.63 ab ± 0.19
Eschweilera odora	7.08 a ± 0.57	2.63 a ± 0.03	7.23 d ± 0.68	29.47 cd ± 0.17	44.19 cde ± 1.33	0.62 ab ± 0.10
Eschweilera truncata	6.08 ab ± 0.85	0.84 b ± 0.06	7.50 cd ± 0.52	30.33 bc ± 1.24	43.33 de ± 0.29	0.83 a ± 0.10
Inga alba	4.68 c ± 0.06	0.64 c ± 0.02	7.16 d ± 0.14	26.65 cd ± 0.27	53.98 ab ± 0.64	0.33 cd ± 0.02
Inga paraensis	4.77 c ± 0.14	0.86 b ± 0.07	8.15 cd ± 0.48	34.04 a ± 0.46	47.92 bcd ± 3.78	0.53 bc ± 0.05
Micrandropsis scleroxylon	2.37 d ± 0.70	0.21 d ± 0.07	14.69 a ± 1.53	34.30 a ± 0.50	48.18 bcd ± 2.38	0.29 cd ± 0.04
Protium tenuifolium	5.92 abc ± 1.46	1.05 b ± 0.22	9.52 c ± 0.92	30.67 bc ± 1.34	48.65 bcd ± 3.21	0.82 a ± 0.19
Swartzia recurva	5.50 bc ± 0.86	2.42 a ± 0.21	6.54 d ± 0.14	30.16 bcd ± 0,32	49.86 abc ± 0.96	0.39 bcd ± 0.06

Means followed by the same letter in the column do not differ statistically by Tukey's test at the 5% probability level.

Understanding the variability of the chemical constituents of wood is critical for the quality, processing, and use of wood, aspects that are relevant in the indication and application of forest management techniques. Species rich in extractives and high concentrations of lignin reveal greater natural durability (toxicity of extractives), density, and resistance; on the other hand, species with a lower concentration of extractives and high cellulose content present low-density woods, with low natural biological resistance to xylophagous organisms, but have high rigidity (Almeida et al. 2015; Senalik and Farber 2021).

The chemical properties of certain species can also favor or harm the gluing process in engineered products. Araújo et al. (2019), working with EGP manufacturing using Amazonian wood, associated good performance in gluing angelim-pedra wood (*Hymenolobium pulcherrimum*) to low mineral concentrations (0.17%). In another study with wood panels, Kniess et al. (2015) associated the high performance of adhesive bonds with the chemical composition of the wood (pH, extractives, and ash).

Another obstacle for wood occurs in the log splitting stage; certain extractives and the high concentration of minerals, the main silica in tropical woods, are responsible for corrosion and loss of the edge of cutting tools (Sjöström 2013).

Knowledge of the lignin content is essential for studies on the energy potential of biomass. Lignin has a high calorific value (6,100 kcal/kg), and strong evidence indicates its significant contribution to the formation of residual carbon, where species with a higher concentration of lignin produce charcoal with a greater glow (Moutinho et al. 2011; Silva et al. 2014).

An analysis of the results of the chemical characterization of the species allows us to affirm that the *Eschweilera* species are rich in extractives, which can confer high biological resistance to their woods. The species *M. scleroxylon* has indications of its use for structural purposes and energy potential given its high concentration of lignin and low ash content. For other species, a common feature was the low concentration of ash that can be related to minerals based on salts and phosphates of Ca, K and P, and Mg (Fengel and Weneger 2003).

Physical-mechanical properties of wood from small-diameter trees

In particular, wood quality is defined as the specific combination of its properties that are most suitable for a specific final product, where density is the most responsive physical characteristic, accompanied by other traits such as moisture, modulus of elasticity, and chemical aspects. and anatomically (Zieminska et al. 2013; Nascimento et al. 2017).

The moisture and basic density (BD) results are shown in Fig. 2. The average value of the moisture content was 12.84%. *M. scleroxylon* (14.04%), *I. alba* (13.17%), *I. paraensis* (13.09%), and *P. tenuifolium* (13.02%) showed the highest value for this physical variable, while *E. odora* (11.58%) showed the lowest rate. For density, the species studied presented a profile of medium to high density (0.56–0.93 g/cm^3), with emphasis on the denser woods (0.86 g/cm^3), *M. scleroxylon*, and *E. odora*. The wood of the species *I. alba* and *B. crispa* was classified as having medium density ($\leq$ 0.63 g/cm^3).

The higher calorific value (HCV) of wood is the amount of energy per unit mass released in the combustion of wood. This physical variable is commonly related to the physical-chemical processes of wood, especially when one wants to apply the wood for energy purposes. In general, the species studied showed high values of HCV (Fig. 3), which ranged from 4,253 (*E. odora*) to 4,907 cal/g (*S. recurva*).

In engineering, mechanical properties such as strength, compression (fc0), shear (fs), modulus of elasticity (MOE), and rupture (MOR) are the variables that dictate the use of wood for structural purposes, while in ecology studies, the traits Mechanical (MOE and MOR) explain standing tree strength and plant hydraulic processes (Fan et al. 2017; Senalik and Farber 2021). The species *E. truncata* showed the highest mechanical strength (MOE = 17,350.00 MPa; MOR = 173.93 MPa), and the lowest value in the study was verified for *I. alba* (MOE = 9,219.00 MPa; MOR = 94.43 MPa) (Fig. 4). It is worth mentioning that the values for the physical-mechanical properties are in the range for medium- to high-density tropical woods (INPA/CPPF 1991; Balboni et al. 2018).

Wood is a complex tissue composed of three main types of cells, vessels, fibers, and parenchyma. In this fabric, the different structural characteristics and proportions in the wood directly reflect the physical and mechanical properties. Vessels transport water, and species with large vessel diameters and high frequencies, in general, have low DB and high humidity and dimensional instability. Species with a high concentration of cellulose (fibers) tend to give wood greater elasticity (MOE), while in the parenchyma that stores and transports nutrients, this cell directly influences the extractives content and consequently the DB of the wood (Jacobsen et al. 2007; Zieminska et al. 2013).

Knowing the physical and mechanical properties allows a more rational use of wood. In wood quality studies, BD is directly related to mechanical strength, which makes it a good predictor of wood strength and stiffness. Another factor that implies quality is biological resistance, where denser species are more resistant to attacks by xylophagous organisms (INPA/CPPF 1991; Chave et al. 2009; Almeida et al. 2017).

The physical and mechanical properties vary according to the moisture content of the wood; this variable is inversely proportional to BD, HCV, MOE, and MOR (Kollmann and Cotê Junior 1968; Silveira et al. 2013). This behavior was verified by the species *I. alba*, which presented one of the highest moisture contents (13.17%) with a basic density of 0.55 g/cm^3, the lowest in the study, and consequently the lowest mechanical strengths (MOE and MOR). On the other hand, *E. odora* had the highest basic density (0.86 g/cm^3) and MOE (14,495.00 MPa), and MOR (147.50 MPa), and its moisture content was the lowest in the study (11.58%). The values for HCV found in the present study are in the range of Amazonian woods. Moutinho et al. (2011) found values of 4,438-4,758 cal/g for wood from matá-matá (*Eschweilera* sp.), and Silva et al. (2014) detected values ranging from 4,608 (cedrinho, *Scleronema* sp.) to 4,928 cal/g (louro, *Ocotea* sp.).

The physical variable basic density is directly related to chemical constituents, and Nuopponen et al. (2006), working with tropical species, confirmed this relationship, where higher densities were associated with higher lignin concentrations. Araújo et al. (2019), studying wood from species managed in the Amazon, identified a predominance of wood with high density (0.71 to 1.18 g/cm^3), and within this range, Fróes et al. (2019) found mean values of 0.77 g/cm^3 for *E. truncata* wood (matá-matá black).

Knowledge of the mechanical properties of wood is essential when it is intended to indicate them for structural purposes. Jesus et al. (2015), evaluating the resistance class of commercial woods from Mato Grosso/Brazil, obtained average values of 16,000 MPa for the MOE of some woods, *Bagassa guianensis* (tatajuba), *Courotari stellata* (tauari-red), *Mezilaurus itauba* (itaúba), *Manilkara huberi* (maçaranduba), *Nectandra* sp. (canelão), *Qualea trichilioides* (cedro-marinho) and *Tabebuia serratifolia* (ipê yellow), where they are classified as D60 (hardwood resistance), a high-resistance wood level according to NBR 7190-1 (2022). Balboni et al. (2018) characterized the physical and mechanical properties of the Amazonian woods *Pseudopiptadenia psilostachya* (timborana) and *Eschweilera ovata* (biriba-white) and obtained MOR values of 103.90 and 127.10 MPa, respectively.

In the present study, the species *Eschweilera odora* (matá-matá yellow), *E. truncata* (matá-matá black), *Micrandropsis scleroxylon* (piãozinho), and *Swartzia recurva* (muirajibóia) showed the highest values in the properties, thus indicating a high-quality profile. That is, they can be used for both structural and nonstructural purposes, which indicates their first use in internal and external environments, while the other species studied must be evaluated individually regarding their characteristics to verify their best use.

Clustering of technological characteristics of managed forest species

Cluster analysis is a research technique that identifies the main groups within a sample universe (similarity). Therefore, the data of an entire population are reduced to a certain number of profiles. This provides an understandable and concise description of the observations, with limited loss of information (Phohlman 2007). In this study, cluster analysis was used to understand the similarities and differences between wood species using the spectrum of technological properties (chemical and physicomechanical).

The first stage of the grouping consists of verifying the correlations (Pearson correlation) presented in Table 3. The correlation coefficient between the variables that make up the evaluated properties was highly significant ($p < 0.001$), and from a total of 78 correlations performed, 29.49% were classified as weak, while the others were moderate to strong (70.51%), with the majority being positive correlations, and an inverse (negative) relationship was observed for HCV (extracts, polyphenols, solubility in water, moisture and ash), moisture (HCV, BD, and MOR) and BD (cellulose). The most correlated properties were BD and MOR (12), followed by DAP and MOE (11), HCV and lignin (9), extractives and polyphenols (8), H and cellulose (7), and moisture and water solubility (6), and the ash content was the variable with the least correlation (4).

Table 3
Pearson's correlation coefficients obtained from the correlations between the physical-mechanical and chemical variables

	DAP	**H**	**MOI**	**HCV**	**BD**	**MOE**	**MOR**	**TOE**	**TOP**	**HOW**	**LIG**	**CEL**	**Ash**
DAP		0,94	0,90	0,70	0,48	0,48	0,50	0,69	0,89	0,61	0,92	0,94	0,23
H			0,07	0,10	0,61	0,80	0,68	0,06	0,30	0,19	0,68	0,64	0,05
MOI				-0,76	-0,68	0,42	-0,94	0,03	0,01	0,52	0,28	0,21	0,29
HCV					0,39	0,10	0,47	-0,47	-0,44	-0,62	0,53	0,13	-0,72
BD						0,84	0,88	0,47	0,75	-0,31	0,47	-0,34	0,30
MOE							0,90	0,47	0,49	0,91	0,89	0,45	0,47
MOR								0,53	0,94	0,46	0,70	0,54	0,70
TOE									0,75	-0,10	0,50	0,32	0,18
TOP										0,25	0,30	-0,09	0,23
HOW											0,07	0,28	0,13
LIG												0,41	0,15
CEL													0,07
Ash													

DBH: diameter at breast height; H: height; MOI: moisture; HCV: higher calorific value; BD: basic density; MOE: modulus of elasticity; MOR: modulus of rupture; TOE: total extracts; TOP: total polyphenols; HOW: hot water; L1: lignin; CEL: crude cellulose. All results show significance; the test is done with 95% confidence

Wood characterization studies developed by Fernandes et al. (2017), Araújo et al. (2019) and Xiao et al. (2021) found high correlations between BD and the mechanical properties of MOE and MOR, which ranged from 0.64 to 0.97. Lobão et al. (2011), Moutinho et al. (2011), and Silva et al. (2014) found correlations above 0.70 between BD and the chemical components of wood. The correlations found in the present study for HCV (BD, lignin, moisture, extractives, and ash), BD (HCV, extractives, MOE, MOR, lignin, moisture, and cellulose), and moisture (BD, MOR, HCV, and water solubility) were close to those found in the literature (Nascimento et al. 1997; Lobão et al. 2011; Silveira et al. 2013; FPL 2021; Nascimento et al. 2021).

The averages of chemical and physicomechanical properties (Table 4) were used to form groups (Fig. 5). The analysis of these data can explain the possible groupings of the species. G3 had the highest average characteristics for MOE, MOR, and ash, and G4 had the highest average for BD, extractives, and polyphenols and even lower values for moisture and HCV. G5 showed a high concentration of cellulose but low density, MOE, and MOR. In general, the results of the cluster analysis possibly indicate that the quality of the studied species is related to the highest general average of the variables; that is, the robustness of the species indicates this relationship, so the species *Eschweilera truncata* (G3) gathers the highest value characterization, and *Inga alba* (G5) was the smallest in this study.

Table 4
Average chemical and physicomechanical properties for each group formed by multivariate analysis

Properties/Groups	G1	G2	G3	G4	G5
Moisture (%)	12,90	13.33	12.74	11.90	13.17
HCV (g/cal)	4,630	4,812	4,461	4,425	4,889
BD (g/cm^3)	0.64	0.81	0.81	0.82	0.55
MOE (MPa)	11,159	13,451	17,138	15,109	9,219
MOR (MPa)	115.39	147.62	173.93	151.23	94.43
Extractives (%)	4.13	4.60	6.08	6.49	4.68
Polyphenols (%)	0.53	1.23	0.84	1.69	0.64
Hot water (%)	10.10	10.25	7.50	7.54	7.60
Lignin (%)	33.28	31.71	30.33	30.86	29.65
Cellulose (%)	51.77	48.90	43.33	45.27	53.98
Ash (%)	0.58	0.50	0.83	0.55	0.33
Average general	1,456	1,683	1,988	1,799	1,301

The grouping of small diameter species by the similarity of technological characteristics validates other technological studies (Lobão et al. 2011; Melo et al. 2013; Reis et al. 2019) on raw material wood, which indicates that this technique is a robust tool for the indication and use of poorly studied and/or commercially known species.

The pairing of cumaru (*Dipteryx odorata*) and guariúba (*Clarisia racemosa*) wood data in the cluster analysis (Fig. 5 and SI5) allowed us to correlate the quality of these woods and associate possible uses of the species studied here. The species was then divided into three use classes based on the technological profile of the groups formed. Class 1 is formed by the species G2, G3, and G4 (*Eschweilera odora, E. truncata, M. scleroxylon, P. tenuifolium*, and *S. recurva*), Class 2 is formed by the species G1 (*B. crispa* and *I. paraensis*), and Class 3 is formed by the species *I. alba* – G3. Based on this division, Table 5 recommends the set of species used by each class group.

Table 5
Indication of the use of small-diameter Amazonian species

Class/ Group	Species	Uses and applications
1 G2, G3, and G4	*Eschweilera odora, E. truncata, Micrandropsis scleroxylon, Protium tenuifolium*, and *Swartzia recurva*	Heavy construction (beams, posts), indoor and outdoor use, floors, bridges, clubs, cross ties musical instruments, sheets and panels (EGP), furniture, sports, and energy items.
2 G1	*Byrsonima crispa* and *Inga paraensis*	Light construction, internal use (boards, frames, doors, and windows), pallet, furniture, and decorative household items, turned, and sheets
3 G5	*Inga alba*	Internal use, nonstructural parts for housing (linings, wainscoting, shutters), plywood and sheets, crafts, packaging, and energy.

Conclusion

The results of the present work allow us to conclude that (i) the chemical profile of the *Eschweilera odora* specie indicates high concentrations of extractives and total polyphenols (7.08% and 2.63%), and *Microndropsis scleroxylon* had the highest concentration of lignin (34.80%), and *Byrsonima crispa* had a higher content of crude cellulose (55.62%); (ii) the physical-mechanical profile of the species was classified as medium to high-density woods, and the species *Eschweilera truncata* and *Micrandropsis scleroxylon* presented the highest mechanical strengths (MOE and MOR); and (iii) cluster analysis was an effective tool for grouping woods considering their similarities. G3 (*Eschweilera truncata*) had the highest average characteristics for MOE, MOR, and ash, and G4 (*Eschweilera odora*) had the highest average for BD, extractives, and polyphenols and even lower values for moisture and HCV. On the other hand, G5 (*Inga alba*) showed a high concentration of cellulose, low density, and lower values of MOE and MOR; (iv) determining the quality of small-diameter wood from a managed area in the Amazon through technological characterization can help decision-making in forest management plans that may indicate the use of new species in the forestry sector.

Declarations

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Figures

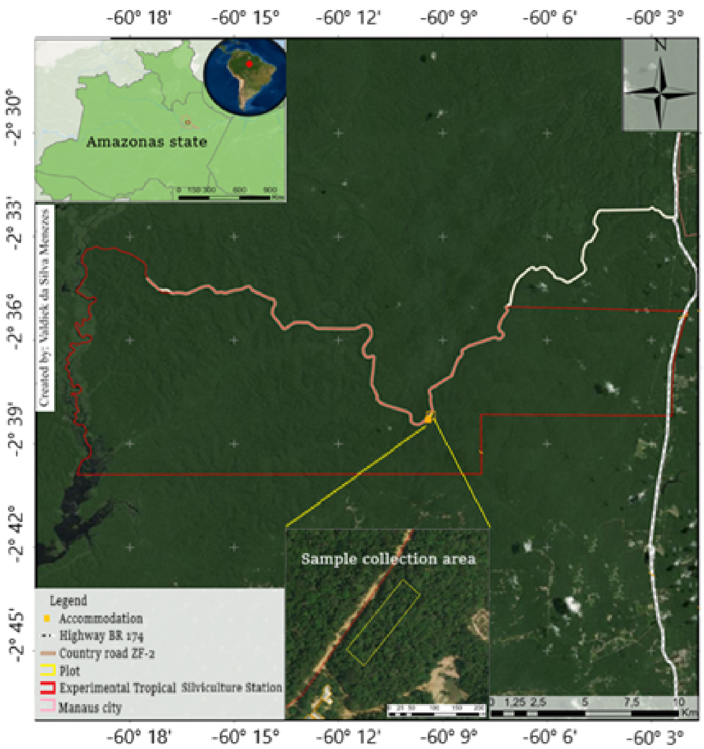

Figure 1

Geographic location of the sample collection area

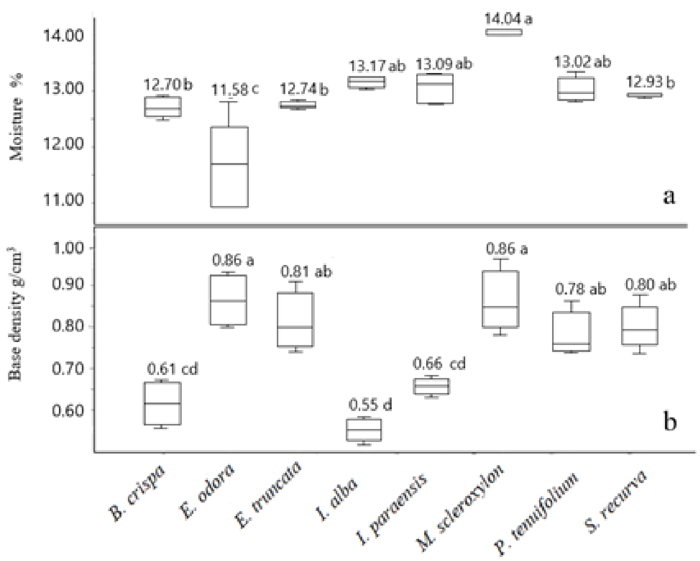

Figure 2

Results of the physical properties of wood from small-diameter trees: a – moisture; b – basic density

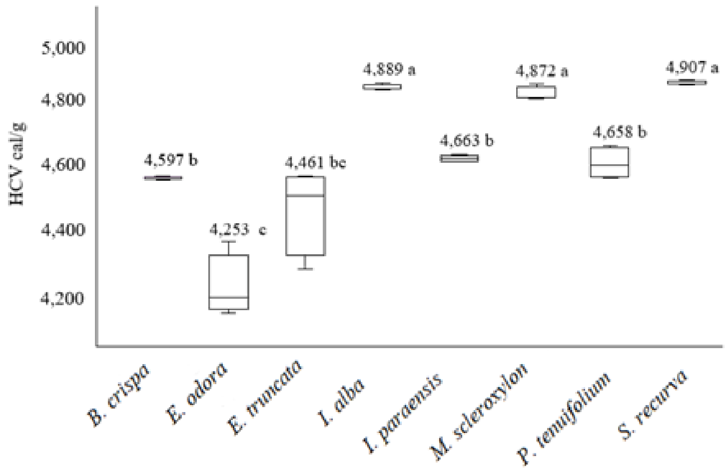

Figure 3

Results of the higher calorific value of small-diameter tree wood

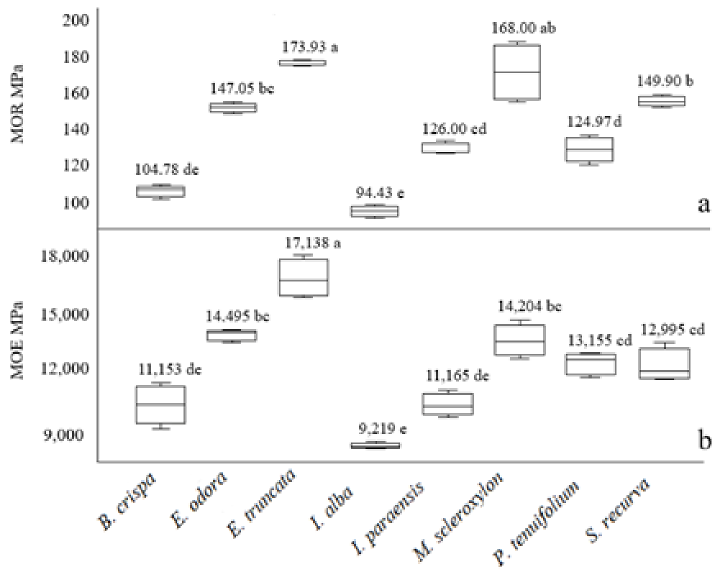

Figure 4

Results of the mechanical properties of wood from small-diameter trees: a – MOR; b - MOE

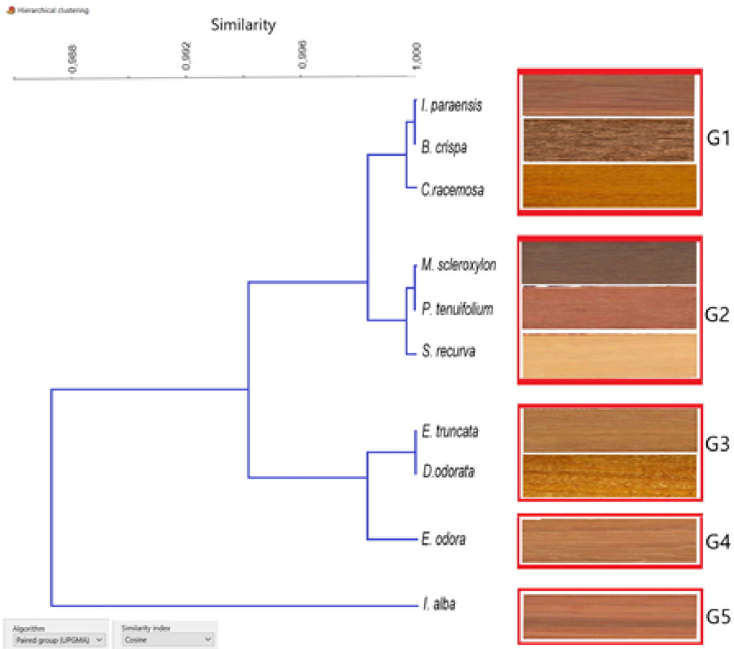

Figure 5

Dendrogram of wood from small-diameter trees obtained by cluster analysis using similarity (cosine) concerning physical, mechanical, and chemical properties

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