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Anatomical and Physical Variability of *Cedrela* sp. Wood in Northeastern Peru

Frank Lincoln Huamalca-Calampa [1], Katherine Julissa Oyarce-Tafur [1], Ingrid Aracelli Cassana-Huamán [1], Roger Chambi-Legoas [2], Fidel A. Roig [3,4] and Leif Armando Portal-Cahuana [1,5,*]

1 Instituto de Investigación, Innovación y Desarrollo para el Sector Agrario y Agroindustrial, Xiloteca Gocta, Facultad de Ingeniería y Ciencias Agrarias, Universidad Nacional Toribio Rodríguez de Mendoza de Amazonas, Chachapoyas 01000, Peru; 7365857382@untrm.edu.pe (F.L.H.-C.); 7248796591@untrm.edu.pe (K.J.O.-T.); ingrid.cassana@untrm.edu.pe (I.A.C.-H.)
2 Departamento Académico de Ingeniería Forestal y Medio Ambiente, Universidad Nacional Amazónica de Madre de Dios, Puerto Maldonado 17001, Peru; rchambi@unamad.edu.pe
3 Argentine Institute of Nivology, Glaciology and Environmental Sciences (IANIGLA), CONICET-Universidad Nacional de Cuyo, Mendoza 5500, Argentina; froig@mendoza-conicet.gob.ar
4 Hémera Centro de Observación de la Tierra, Escuela de Ingeniería Forestal, Facultad de Ciencias, Universidad Mayor, Santiago 8580745, Chile
5 Instituto de Investigación en Forestería y Ecosistemas Tropicales, Escuela Profesional de Ingeniería Forestal, Facultad de Ingeniería y Ciencias Agrarias, Universidad Nacional Toribio Rodríguez de Mendoza de Amazonas, Chachapoyas 01000, Peru
* Correspondence: leif.portal@untrm.edu.pe; Tel.: +51-958188738

Abstract

Tropical forests in the Amazon are vital for climate mitigation, yet detailed data on high-value timber genera such as Cedrela remain scarce, hindering sustainable management. To address this gap, this study evaluated the anatomical structure and key physical properties of *Cedrela* sp. wood from the Omia and San Carlos districts in Amazonas, northeastern Peru. Macroscopic and microscopic features, basic density, moisture content, and volumetric shrinkage were assessed using non-destructive sampling. The results indicated that *Cedrela* sp. wood exhibits medium basic density (averaging 0.50–0.52 g/cm^3) and relatively high volumetric shrinkage (averaging 21.46%), suggesting limitations for applications requiring high dimensional stability. However, its favorable properties make it suitable for furniture manufacturing in stable humidity environments. Comparative analysis revealed that the wood properties differed between locations, with Omia showing lower density (0.50 g/cm^3) compared to San Carlos, likely reflecting phenotypic plasticity in response to contrasting local environmental conditions. These baseline structural tendencies underscore the value of regional assessments to inform sustainable forest management and optimize the industrial utilization of tropical timber resources. The findings suggest that site-specific environmental conditions significantly influence wood property variations and must be factored into local forestry planning.

Keywords: dimensional stability; fiber biometry; Meliaceae; montane forests; structure–property relationships; sustainable forest management; technological properties; wood anatomy

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1. Introduction

Forests are fundamental components of the Earth system, contributing to atmospheric regulation, hydrological cycling, biodiversity conservation, and the provision of ecosystem services and forest-based resources. Their role as carbon sinks is particularly critical

in the context of global climate change, as they sequester atmospheric carbon dioxide and mitigate greenhouse gas accumulation. The effectiveness of this function is strongly dependent on forest management practices, which determine both carbon storage capacity and long-term ecosystem resilience. Consequently, optimizing management strategies is essential to maximize climate mitigation potential while ensuring sustainability [1]. Global assessments of carbon fluxes reveal persistent imbalances in carbon exchange among the atmosphere, oceans, and terrestrial biosphere, underscoring the urgency of improving the management of forest carbon sinks. In this regard, tropical forests -and especially those in the Amazon basin- are of strategic importance due to their high productivity and carbon storage capacity [2].

In Peru, approximately 57% of the national territory is covered by forests, with the Amazon region hosting a significant proportion of both biodiversity and human populations [3]. Within this region, the genus *Cedrela* (family Meliaceae) is of particular economic and ecological relevance due to the high quality of its timber. Species such as *Cedrela odorata* are widely valued for their workability, durability, and esthetic properties, making them preferred materials in fine woodworking industries [4,5]. However, due to historical overexploitation, the entire genus Cedrela is currently protected under Appendix II of the Convention on International Trade in Endangered Species (CITES) and classified as Threatened/Vulnerable under Peruvian forestry legislation [6]. Consequently, harvesting is strictly regulated through state-approved sustainable management plans, with the legally sourced timber being heavily directed toward specialized domestic and international export markets.

Despite its commercial and conservation significance, the anatomical characterization and physical properties of Cedrela species in the transitional ecosystems of northeastern Peru remain insufficiently documented. This lack of data limits the technological valorization of legally harvested wood, as processing industries lack precise guidelines for drying schedules and mechanical optimization. Wood anatomical characterization provides essential information for species identification, taxonomic classification and understanding ecological adaptations, as cellular traits are directly linked to technological performance [4]. In Meliaceae, quantitative studies show that structural tissues, such as fiber proportion and cell wall thickness, together with hydraulic tissues, such as vessel diameter and frequency, influence both mechanical resistance and water conduction [7,8]. For instance, *Trichilia dazae*, a related genus from Peruvian montane forests, shows diffuse porosity and heterocellular rays associated with high basic density, illustrating how cellular organization contributes to structural integrity under local climatic conditions [7]. Within Cedrela, wood properties also show marked plasticity along environmental gradients, affecting density, shrinkage, hygroscopicity, dimensional stability, and potential industrial performance [5,8,9].

Macroscopic traits, such as color, grain, luster, and growth ring patterns, offer preliminary diagnostic features, while microscopic characteristics, including vessel arrangement, fiber morphology, parenchyma distribution, and ray structure, provide deeper insights into functional and evolutionary relationships [10]. These features are also closely linked to wood performance in industrial applications. In parallel, physical properties such as basic density, shrinkage behavior, hygroscopicity, and dimensional stability are critical determinants of wood quality and end-use suitability. These attributes influence mechanical performance, durability, and processing behavior, thereby guiding the selection of timber for specific applications [11].

To achieve a comprehensive evaluation of wood properties without compromising forest conservation, non-destructive and semi-destructive sampling methods have gained significant prominence in tropical wood science [12,13]. Contemporary approaches for assessing biomass and wood quality in standing trees rely heavily on extracting core or

chip samples using specialized devices like handheld increment borers or augers [14,15]. This methodology has proven highly effective and reliable for quantifying both physical properties, such as basic density and moisture content, and macroscopic or microscopic anatomical structures across diverse forest species [16]. By utilizing these standardized non-destructive frameworks, researchers can successfully capture intra-specific variations and structural baseline tendencies while minimizing physiological damage to living trees, effectively bridging the gap between high-precision material characterization and sustainable forest monitoring.

The present study aims to characterize the anatomical and physical properties of *Cedrela* sp. wood in two districts of the Amazonas department, Omia and San Carlos, in northeastern Peru. Specifically, it seeks to (i) describe macroscopic and microscopic anatomical features and (ii) quantify key physical properties relevant to industrial use. We hypothesize that quantitative wood traits differ between sites, potentially reflecting localized phenotypic plasticity associated with contrasting environmental conditions. By accounting for the natural variability inherent to the genus, this study seeks to identify baseline structural tendencies in unmanaged populations, thereby providing an initial framework for site-specific timber assessment when detailed silvicultural histories are unavailable.

2. Materials and Methods

2.1. Study Area

The study was conducted in northeastern Peru, within two districts in the Amazonas Department (Figure 1): San Carlos and Omia. Both sites are located in the Andean-Amazonian transition zone and are characterized by montane forest ecosystems with distinct yet comparable environmental conditions. The first site, San Carlos district (Bongará province), is situated at 2158 m a.s.l. (−5.968115 latitude, −77.931701 longitude, WGS84 geodetic system). According to the Ecological Map of Peru and the Holdridge life zone classification, this area corresponds to a Tropical Lower Montane Moist Forest [17]. It exhibits the climatic and physiographic attributes typical of Andean cloud forests (Ceja de Selva), including persistent orographic humidity and complex topography [18]. Mean annual temperature is 18.9 °C, and average monthly precipitation reaches 103.9 mm. Precipitation is strongly seasonal, with a well-defined period from October to May and a relatively drier season from June to September [19].

The second site, Omia district (Rodríguez de Mendoza province), lies at 2213 m a.s.l. (−6.416951 latitude, −77.316945 longitude, WGS84 geodetic system). This locality is positioned within a transitional ecotone between the upper Amazonian rainforest (Selva Alta) and the Andean cloud forest (ceja de selva), reflecting a gradient of environmental conditions and vegetation types [20]. The climate is broadly comparable to that of San Carlos, with a mean annual temperature of 19.6 °C and an average monthly precipitation of 99.9 mm. Seasonal precipitation patterns are similar, with a rainy season extending from October to May and a drier interval between June and September [19].

2.2. Study Species

The focal taxon of this study is *Cedrela* sp. (Meliaceae), evaluated as a representative high-value timber resource within the transitional montane ecosystems of northeastern Peru. To analyze baseline wood properties while ensuring consistency with the known durability, dimensional stability, and workability standards established for this genus [21]. Sampling was restricted to naturally occurring mature individuals exhibiting healthy crowns, straight boles, and no visible signs of phytosanitary damage. In both the Omia and San Carlos districts, target trees were taxonomically identified at the genus level based on vegetative and reproductive morphology. This targeted selection of representative mature

specimens established the baseline material required to systematically evaluate the natural intra-specific variability of anatomical structures and physical quantitative traits across the studied environmental sites.

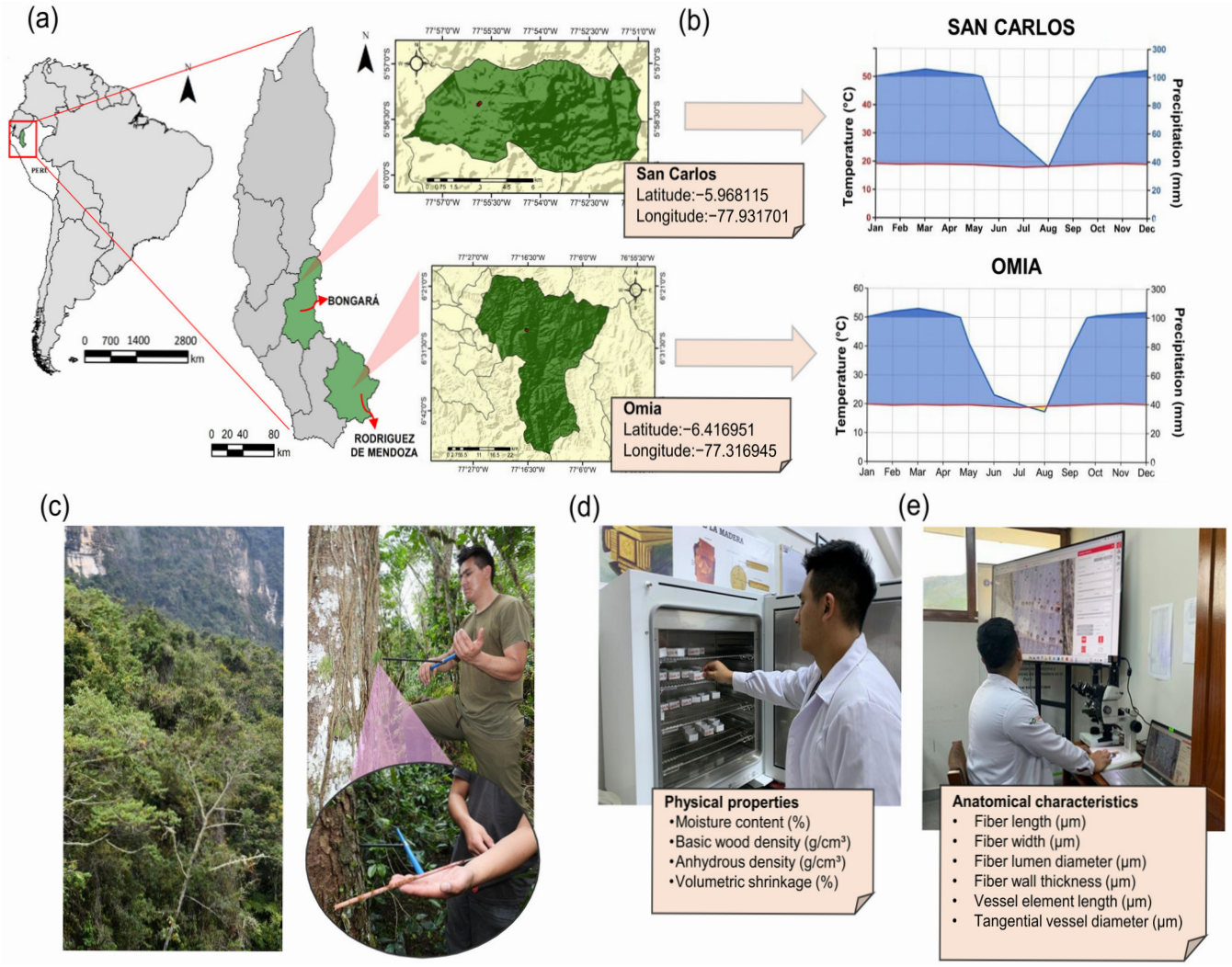

Figure 1. Geographic location and experimental workflow of the study: (**a**) Geographic localization of San Carlos and Omia districts within the Amazonas Department, northeastern Peru; (**b**) Climographs for both study sites spanning the 1993–2022 period [19], where the red line represents mean monthly temperature and the blue shaded area denotes the monthly precipitation distribution; (**c**) Representation of the montane moist forest ecosystem and the non-destructive sampling process using an increment borer to extract wood cores from standing *Cedrela* sp. trees; (**d**) Laboratory processing for physical properties characterization; and (**e**) Microscopic and digital image analysis setup for determining cellular and anatomical wood characteristics.

2.3. Tree Inventory and Selection

A field inventory was conducted to quantify the local population of *Cedrela sp.*, establish a representative sampling network, and select individuals for detailed analysis. Surveys were performed in the districts of Omia and San Carlos, Amazonas department, Peru, where a total of 21 *Cedrela* sp. individuals were recorded: 11 in Omia and 10 in San Carlos. Geographic coordinates for each tree were obtained using a handheld GPS device (Garmin GPSMAP 65s, Garmin International, Inc., Olathe, KS, USA), ensuring accurate spatial referencing. In addition, standard dendrometric variables were measured, including diameter at breast height, total height (TH), and commercial height (CH). From the inventoried population, 10 individuals (DBH $\geq$ 25 cm) were selected following established

sampling criteria [22]. Prioritized selection trees exhibiting optimal phytosanitary and structural conditions, namely straight boles, absence of visible pests or disease damage, and intact bark, as well as representative dendrometric attributes (Table 1). This approach ensured that sampled individuals were both structurally sound and suitable for assessing intrinsic wood properties while minimizing confounding effects associated with external damage or physiological stress.

Table 1. Characteristics of the selected trees.

Tree	Collection Site	UTM Coordinates X	Y	Altitude (m a.s.l.)	DBH (cm)	TH (m)	CH (m)
CEDM-16	Omia	247,826	9,283,948	2008	60	30	7
CEDM-17	Omia	247,966	9,283,849	2082	30	10	5
CEDM-18	Omia	247,976	9,283,855	2083	23	10	5
CEDM-19	Omia	247,977	9,283,848	2084	43	25	10
CEDM-20	Omia	248,026	9,283,829	2101	40	25	10
CEDM-21	San Carlos	175,398	9,339,420	2114	34	15	8
CEDM-22	San Carlos	175,423	9,339,423	2179	53	20	10
CEDM-23	San Carlos	175,497	9,339,506	2185	39	18	9
CEDM-24	San Carlos	175,504	9,339,510	2185	25	18	7
CEDM-25	San Carlos	175,516	9,339,508	2184	31	18	7

DBH: Diameter at breast height; TH: Total height; CH: Commercial height.

2.4. Wood Sampling and Specimen Preparation

Wood sampling was conducted under authorization from the National Forest and Wildlife Service (SERFOR), in accordance with current Peruvian regulations governing forest resource use for scientific research. Four increment cores per tree were extracted at breast height (1.30 m) using a Pressler increment borer, a non-destructive technique widely adopted in wood science and dendrochronological studies [16,23,24]. Wood cores approximately 20 cm in length were extracted from each selected tree using an increment borer. After extraction, the cores were carefully removed with a metal extractor and mounted on labeled wooden holders measuring 1 × 1 × 20 cm, thereby helping to maintain sample integrity and traceability and to prevent deformation during drying [16]. Each sample was coded systematically (e.g., CM01R1 indicating *Cedrela* sp., tree 01, radius 1). Boreholes were subsequently sealed with liquid silicone and treated with a protective compound to minimize pathogen entry and promote wound compartmentalization.

In parallel, three botanical vouchers per individual were collected using telescopic pruning tools. Samples were pressed and preserved in newsprint for subsequent taxonomic verification and deposited at the MOL Herbarium (Universidad Nacional Agraria La Molina).

Increment cores were sectioned using a scalpel into subsamples tailored to specific analytical requirements. For anatomical characterization, segments encompassing the sapwood-heartwood transition were isolated, along with additional cylindrical specimens (5 mm diameter × 25 mm length). Maceration analysis utilized four heartwood fragments (5 mm diameter × 2 mm length), while microscopic observations employed two additional samples of similar diameter and 25 mm length. For physical property determination, 6–8 specimens per tree were prepared with standardized dimensions (Figure 2).

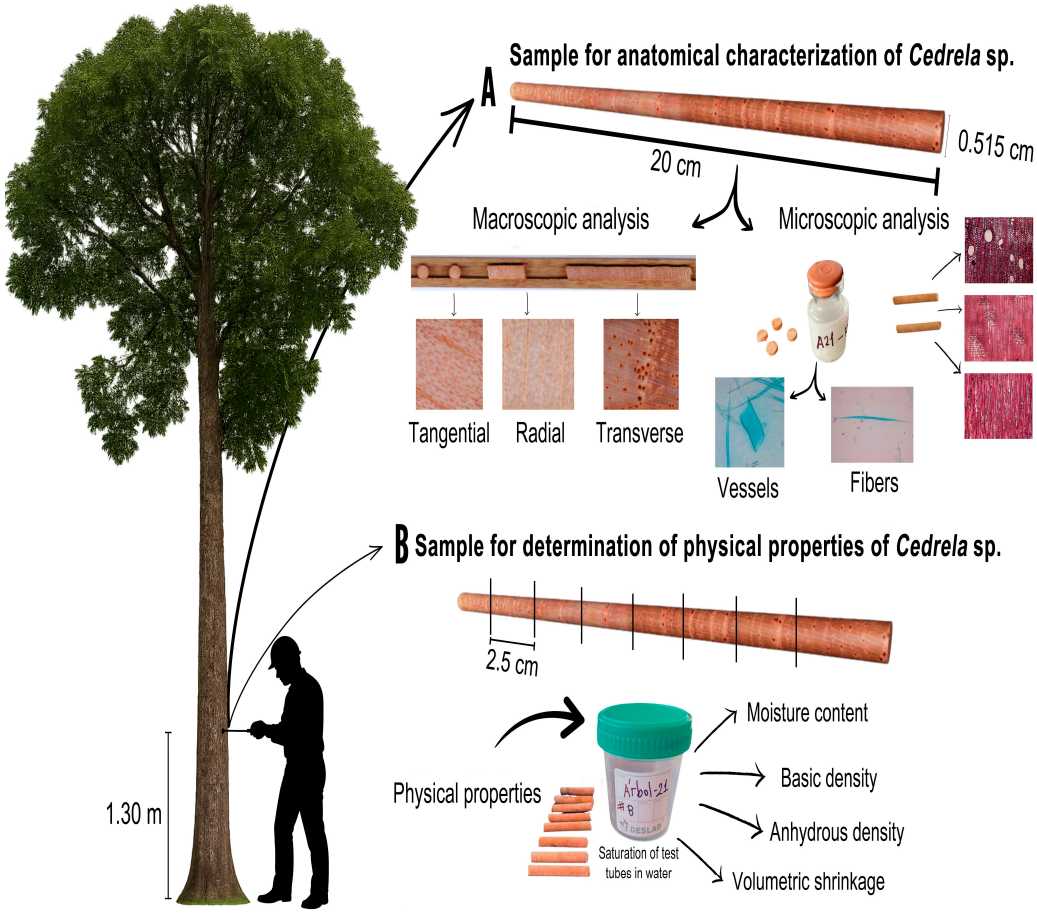

Figure 2. Developed methodology. (**A**) Sample for anatomical analysis; (**B**) sample for physical analysis.

2.5. Wood Anatomy of Cedrela sp.

Wood cores were affixed to wooden supports (1 × 1 × 20 cm) using a commercial high-strength polyvinyl acetate (PVA) wood adhesive, cotton thread, and tape to ensure stability and correct anatomical orientation (transverse, radial, and tangential planes). After 24 h of curing, samples were sanded progressively (grit 80–1200) using an electric orbital sander (Model GSS 140, Robert Bosch GmbH, Gerlingen, Germany) to obtain smooth, defect-free surfaces suitable for anatomical examination. All procedures followed standardized protocols [25,26].

2.5.1. Organoleptic and Macroscopic Features

Wood properties were assessed in accordance with Pan American Standards Commission (COPANT 30:1-019) [25]. Strictly organoleptic attributes were evaluated first, including luster (low, medium, or high), odor (distinctive aromatic, unpleasant, or imperceptible), and taste (distinctive or non-distinctive). Concurrently, general macroscopic traits were recorded, such as the sapwood-heartwood transition (gradual, abrupt, or indistinct) and wood texture (classified as fine, medium, or coarse based on pore size and distribution), which provide a preliminary indication of wood structure and potential technological performance [25,27].

Detailed structural analysis was performed on samples prepared in transverse, tangential, and radial sections (5 mm × 25 mm). Observations were conducted using a stereomicroscope (Model SM-16, Motic Instruments Inc., Xiamen, China) to characterize growth ring visibility, boundary definition (e.g., fiber wall thickening or marginal parenchyma), and regularity. Vessel features were described in terms of porosity type, spatial arrangement, grouping, size, and shape. Axial parenchyma and ray characteristics

(visibility, frequency, and distribution) were also recorded, along with the presence of mineral or organic inclusions.

2.5.2. Microscopic Characteristics

Microscopic analysis followed the International Association of Wood Anatomists (IAWA) [26] recommendations, integrating both qualitative descriptions and quantitative measurements. Two heartwood samples per tree, measuring 5 mm × 25 mm, were processed histologically: softened in water (72 h), dehydrated through a graded ethanol series (30%–90%), stained with safranin, and mounted for sectioning in transverse, radial, and tangential planes.

For fiber and vessel biometry, maceration was performed on four heartwood samples using acid-hydrogen peroxide solution (1:1) at 80 °C for 24 h [28]. The dissociated cells were rinsed, stained with methylene blue, and mounted in glycerin for microscopic observation [16].

Micrographs were captured using a 10 MP digital camera coupled to an AmScope T490B-10MT microscope (AmScope/United Scope LLC, Irvine, CA, USA). A total of 50 images (4× magnification) were used to quantify fiber and vessel length, and 25 images (10× magnification) for measurement of fiber diameter, lumen diameter, and cell wall thickness. Image analysis was conducted with Image-Pro Plus software to derive descriptive statistics (mean, range, standard deviation), enabling the construction of a representative biometric profile supported by boxplot visualization.

2.6. Physical Properties of Wood

Physical properties were determined following standardized protocols (NTP and ASTM). Evaluated parameters included moisture content [29], basic density, and oven-dry density [30], and volumetric shrinkage [31]. Experimental tests were conducted following protocols from previous studies [7,32,33], adhering to the methodology described by [16].

Before testing, specimens were fully saturated by ultrapure water for 30 days, with periodic water replacement to prevent contamination. Drying was conducted under controlled conditions, increasing temperature gradually from 25 °C to 103 °C ± 2 °C in 5 °C daily increments. Samples were weighed daily until a constant mass was achieved, corresponding to volumes at saturated and oven-dry states.

2.6.1. Moisture Content

Moisture content was determined according to ASTM D4442-2 [29]:

$$\mathrm{MC}\ (\%) = \left(\frac{W_h - W_d}{W_d}\right) * 100$$

where MC% is the moisture content percentage calculated on an oven-dry basis; W_h is the weight of the moist test sample (g); and W_d is the oven-dry weight (g).

2.6.2. Basic Density

Basic density was calculated following ASTM D143-19 guidelines [30]:

$$\rho b\ (g/cm^3) = \frac{m_d}{v_s}$$

where m_d is the oven-dry mass (g), and v_s is the saturated (green) volume (cm^3).

Wood was classified into three categories based on basic density values: low density ($\leq$0.40 g/cm^3), medium density (0.41–0.60 g/cm^3), and high density ($\geq$0.61 g/cm^3) [34].

2.6.3. Anhydrous Density

Anhydrous density was determined according to ASTM D143-19 [30]:

$$\rho d\ (g/cm^3) = \frac{m_d}{v_d}$$

where m_d is the anhydrous mass (g), and v_d is the anhydrous volume (cm^3).

According to the classification by [35], wood was categorized as: very light (<0.35 g/cm^3), light (0.36–0.55 g/cm^3), moderately heavy (0.56–0.75 g/cm^3), heavy (0.76–1.0 g/cm^3), and very heavy (>1.0 g/cm^3).

Additionally, normal density (initial wet density) was determined using the standard gravimetric relationship at the moment of extraction:

$$\rho n\ (g/cm^3) = \frac{m_w}{v_s}$$

where m_w is the initial wet (green) mass (g) and v_s is the initial saturated (green) volume (cm^3), both measured immediately after sampling before any moisture loss occurred.

2.6.4. Volumetric Shrinkage

Volumetric shrinkage was calculated according to ASTM D143-94 [31]:

$$VS\ (\%) = \frac{V_i - V_f}{V_i} * 100$$

where VS is the volumetric shrinkage; V_i is the initial (saturated) volume (cm^3); and V_f is the final (oven-dry) volume (cm^3). Based on Sibille (2006), volumetric shrinkage was classified as: very low (<7%), low (7.1%–10%), medium (10.1%–13%), high (13.1%–15%), and very high (>15%).

2.7. Potential Wood Uses

Potential end uses were inferred on the integrative framework combining organoleptic, anatomical [35], and physical properties. Wood performance categories (very low to very high) were assigned following established criteria, enabling the identification of suitable industrial applications [34].

2.8. Statistical Data Analysis

Data were curated and screened for outliers prior to analysis. Statistical procedures were conducted in R version 4.3.1 [36] within the RStudio version 2026.01.1 Build 403. Differences between sites (Omia and San Carlos) were calculated using one-way ANOVA when assumptions of normality and homoscedasticity were met. Otherwise, the Kruskal–Wallis test was applied, followed by Dunn's post hoc comparisons. Statistical significance was set at $\alpha = 0.05$. This analytical framework ensured robust inference regarding site-related variability in anatomical and physical wood traits.

3. Results

3.1. Wood Anatomy of Cedrela sp. in the Amazonas Department

The organoleptic assessment of *Cedrela* sp. wood from Omia and San Carlos revealed a gradual transition between sapwood and heartwood (Figure 3). The wood is characterized by medium luster, absence of a perceptible odor, and a non-distinctive taste. Texture is classified as medium, indicating a relatively uniform anatomical structure.

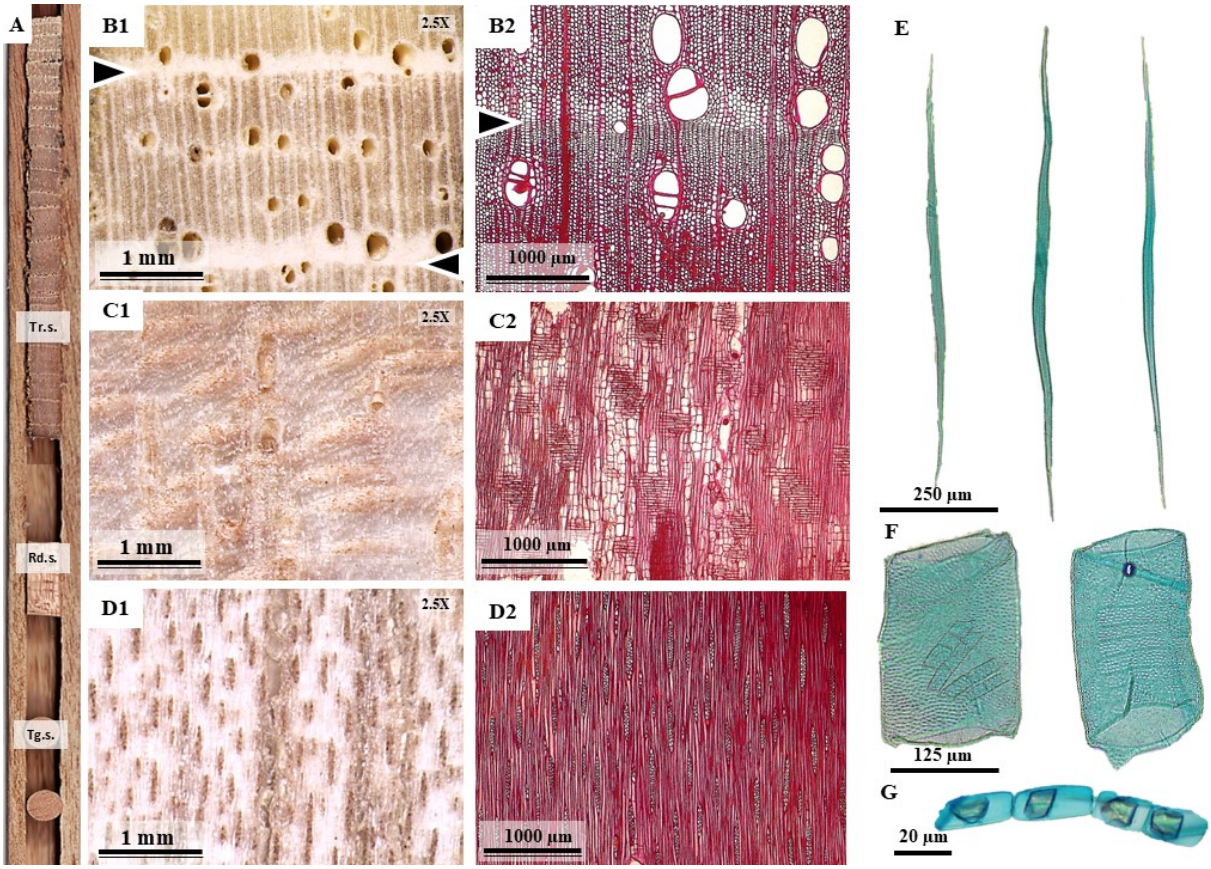

Figure 3. Anatomical features of *Cedrela* sp. wood. (**A**) Wood core mounted for sectioning, showing transverse (Tr. s.), radial (Rd. s.), and tangential (Tg. s.) orientations. (**B1**–**D1**) Macroscopic views (stereomicroscope, 2.5 ×): (**B1**) Transverse section showing semi-ring-porous wood and distinct growth ring boundaries (black arrowheads); (**C1**) Radial section; (**D1**) Tangential section. (**B2**–**D2**) Microscopic sections (light microscopy, safranin-stained): (**B2**) Transverse section displaying vessel arrangement and marginal parenchyma (arrowhead); (**C2**) Radial section showing ray structure; (**D2**) Tangential section showing non-storied multiseriate rays. (**E**–**G**) Macerated tissue (methylene blue-stained): (**E**) Libriform fibers; (**F**) Vessel elements with simple perforation plates and alternate pitting; (**G**) Prismatic crystals in a subdivided ray cell (crystal chains). Scale bars: 1 mm (**B1**–**D1**) and 1000 µm (**B2**–**D2**).

At the macroscopic level, wood from both districts exhibited clearly defined growth rings demarcated by marginal parenchyma. The wood is semi-ring-porous, with vessels slightly visible to the naked eye, predominantly arranged predominantly in radial patterns and relatively uniformly distributed (Figure 3). Vessels occur mainly as solitary elements, although radial multiples of two to four vessels are occasionally observed. They are of medium size, oval in outline, and lack visible inclusions. Axial parenchyma is conspicuous without magnification, displaying a vasicentric paratracheal pattern with marginal bands. Rays are discernible under 10× magnification, of medium size, and non-storied in the tangential plane. Vessel lines are irregular, and ray flecks on the radial surface exhibit low contrast.

3.2. Microscopic Characterization

Microscopic analysis (Figure 3) revealed consistent anatomical patterns across sites, with minor quantitative differences. In Omia, fiber length was 1097.55 µm (±127.52), with an average fiber diameter of 26.96 µm (±4.90). The lumen diameter averaged 19.96 µm (±4.29), and cell wall thickness was 3.50 µm (±0.65). Based on these biometrics, the derived wood fiber quality indices reflected a high flexibility coefficient of 74.04%, a medium-to-

high aspect ratio of 40.71, and a low-to-medium wall fraction of 25.96%. Vessel elements had a mean length of 240.34 µm (±72.84), a tangential diameter of 111.55 µm (±39.25), and a frequency of approximately 5 (±2.17) vessels/mm^2 (Figure 4). Rays averaged 246.61 µm (±70.79) in height (approximately 10 ±3.06 cells), and 42.78 ± 13.80 µm in width (approximately 3 ± 0.78 cells), with a frequency of 5 ±1.21 rays mm^{-1}. Prismatic crystals arranged in chains were observed in ray cells.

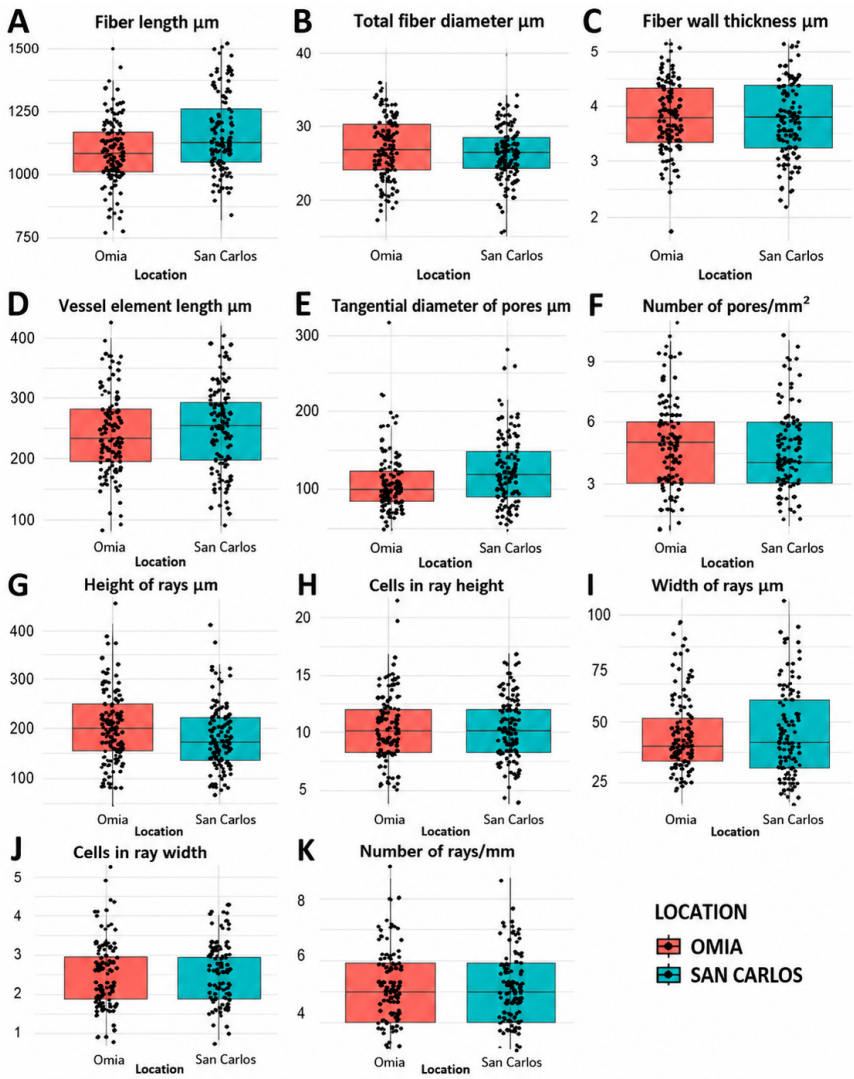

Figure 4. Box plot of mean values for the microscopic characteristics of *Cedrela* sp. wood from the Omia and San Carlos districts. (**A**) Fiber length (µm). (**B**) Total fiber diameter (µm). (**C**) Fiber wall thickness (µm). (**D**) Vessel element length (µm). (**E**) Tangential pore diameter (µm). (**F**) Number of pores per mm^2. (**G**) Ray height (µm). (**H**) Ray height in cells. (**I**) Ray width (µm). (**J**) Ray width in cells. (**K**) Number of rays per mm.

In San Carlos, fiber length was slightly greater (1173.86 µm, ±160.21), while fiber diameter (26.13 µm; ±3.69), lumen diameter (19.07 µm; ±3.45), and wall thickness (3.53 µm; ±0.73) were comparable to Omia. Correspondingly, the fiber quality indices for this population demonstrated a flexibility coefficient of 72.98%, an aspect ratio of 44.92, and a wall fraction of 27.02%. Vessel elements showed a mean length of 248.47 µm ± 73.04, a tangential diameter of 125.29 µm ± 44.38, and a frequency of 5 ± 1.95 vessels/mm^2. Rays were slightly shorter (224.75 µm ± 62.75), with similar width (43.78 µm ± 16.76); 3 cells wide (±0.74) and frequency (5 ± 1.16) (Figure 4). Crystal chains were likewise presented.

Overall, the anatomical structure of *Cedrela* sp. is highly conserved between sites, with variability primarily expressed in quantitative traits rather than qualitative features.

3.3. Physical Properties of Cedrela sp. Wood

In Omia, the mean moisture content was 108.20 ± 28.18%. Basic density averaged 0.52 g/cm^3 (Figure 5), classifying the wood as medium density (0.41–0.60 g/cm^3) according to [34]. Anhydrous density averaged 0.46 g/cm^3, corresponding to light wood based on the classification of [35] (0.36 to 0.55 g/cm^3). Volumetric shrinkage reached 21.46%, placing it in the "very high" category, as it exceeds the 15% threshold established by [35].

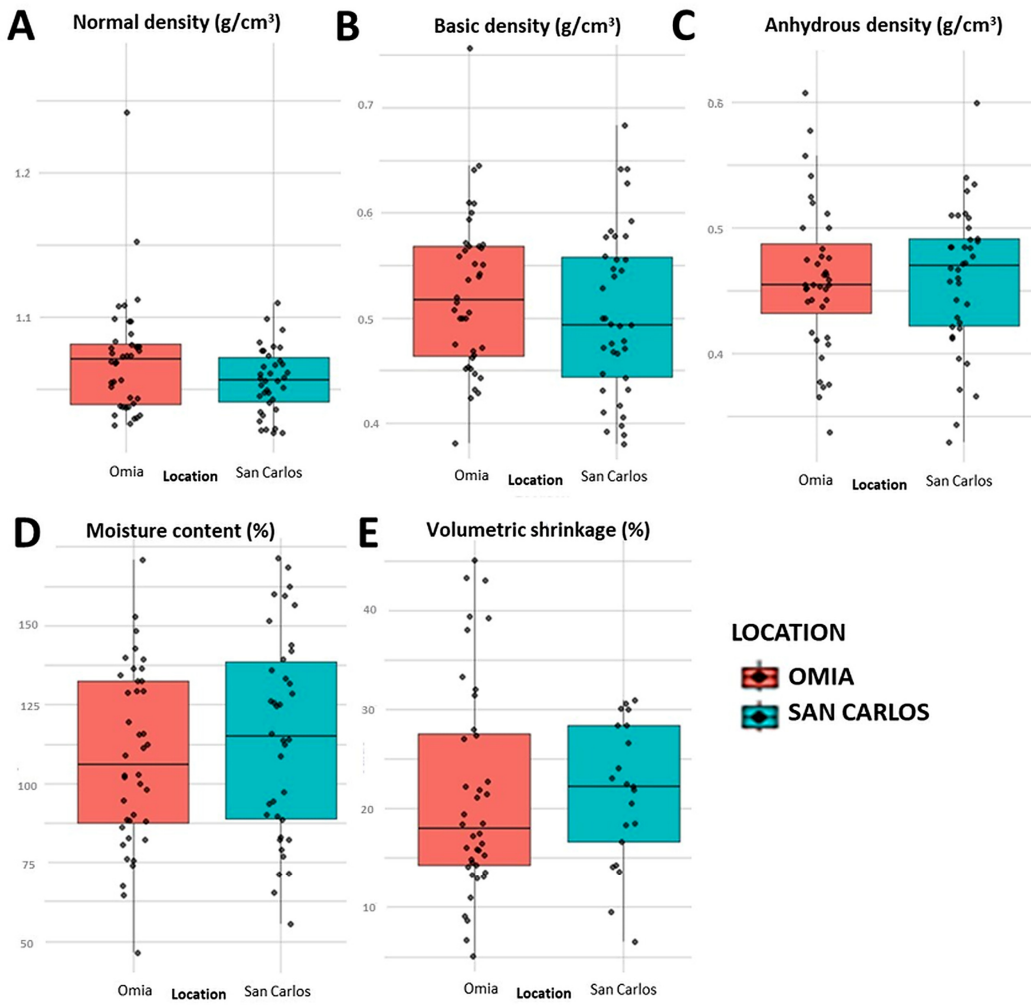

Figure 5. Box plot of mean values for the physical properties of *Cedrela* sp. wood from the Omia and San Carlos districts. (**A**) Normal density. (**B**) Basic density. (**C**) Anhydrous density. (**D**) Moisture content. (**E**) Volumetric shrinkage.

Similarly, in San Carlos, the moisture content averaged 115.02 ± 32.11%, while basic density (0.50 g/cm^3) classifies it as medium-density wood [34], and anhydrous density (0.46 g/cm^3) were nearly identical to those observed in Omia. Volumetric shrinkage was comparable (21.47), indicating very high volumetric shrinkage (Figure 5).

These results demonstrate a high degree of consistency in physical properties across sites, with *Cedrela* sp. characteristics as medium-density, lightweight timber exhibiting high volumetric contraction values during complete dehydration. The observed moisture content values exceeding 100% are typical of freshly cut tropical timber, reflecting water mass relative to dry wood mass.

3.4. Correlation Analysis

Pearson correlation analysis (Figure 6) revealed that wood density was associated with several anatomical and physical traits. Basic density exhibited a moderate positive association (r = 0.38) with ray width, suggesting that increased radial parenchyma development contributes to higher wood density through enhanced structural packing. Conversely, moisture content showed a nearly perfect negative correlation (r = −0.96) with basic density, indicating that denser wood structures tended to retain lower amounts of water within the cellular network.

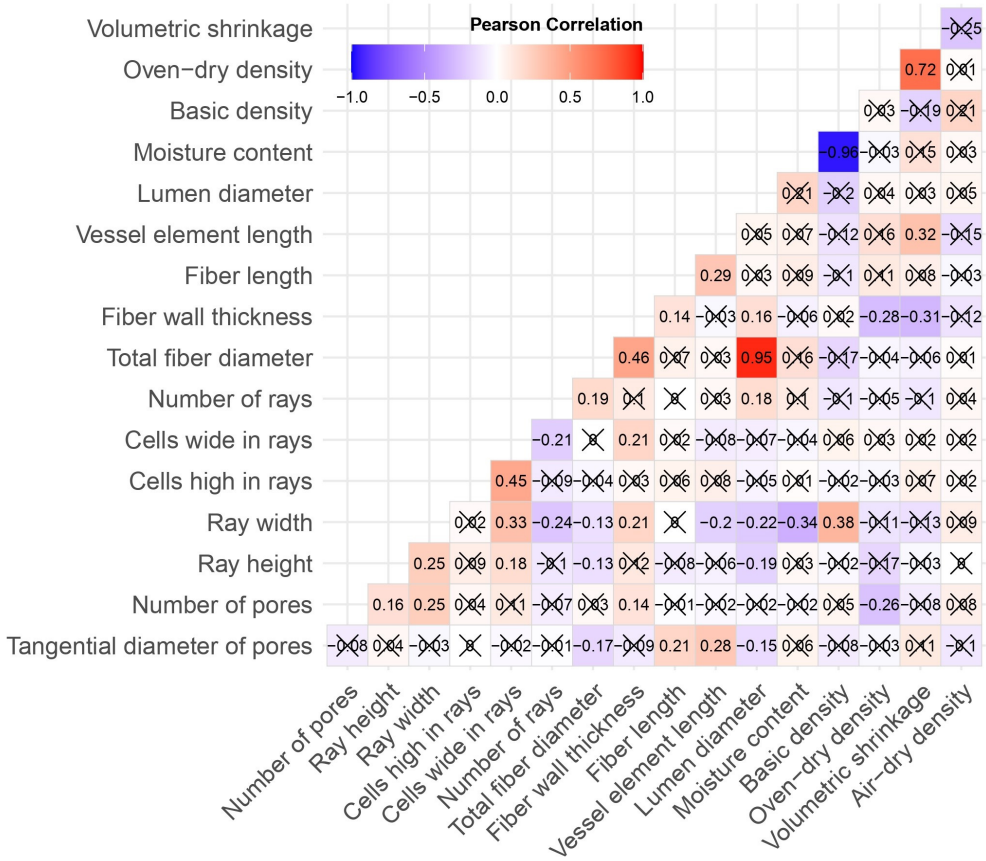

Figure 6. Correlation matrix between microscopic anatomical features and physical properties of *Cedrela* sp.

Regarding shrinkage performance, oven-dry density displayed a strong positive correlation (r = 0.72) with volumetric shrinkage, indicating that wood with higher mass per unit volume undergoes greater dimensional changes during complete dehydration. Interestingly, anatomical traits also influenced shrinkage patterns: vessel element length showed a positive correlation (r = 0.32) with volumetric shrinkage, while fiber wall thickness exhibited a negative relationship (r = −0.31). This suggests that thinner-walled fibers and longer vessel elements may create a more collapsible structural framework during drying.

Furthermore, ray width was negatively associated with moisture content (r = −0.34), implying that the volume occupied by ray parenchyma might displace potential space for free water. Finally, a strong intrinsic correlation (r = 0.95) persisted between total fiber diameter and lumen diameter, although this geometric dependence does not appear to be directly related to basic density. These findings suggest that while anatomical traits are internally coordinated, their influence on physical properties is selective, with density and shrinkage being the most sensitive to cellular variations.

3.5. Principal Component Analysis (PCA)

The PCA (Figure 7) revealed substantial overlap between Omia and San Carlos for both anatomical and physical datasets, indicating broadly similar structural and functional characteristics. For microscopic traits (Figure 7A), the San Carlos samples exhibited a wider dispersion and a shift toward positive values along the first principal component, indicating higher homogeneity. For physical properties (Figure 7B), both sites showed considerable overlap, although San Carlos displayed slightly reduced dispersion, suggesting more uniform physical behavior.

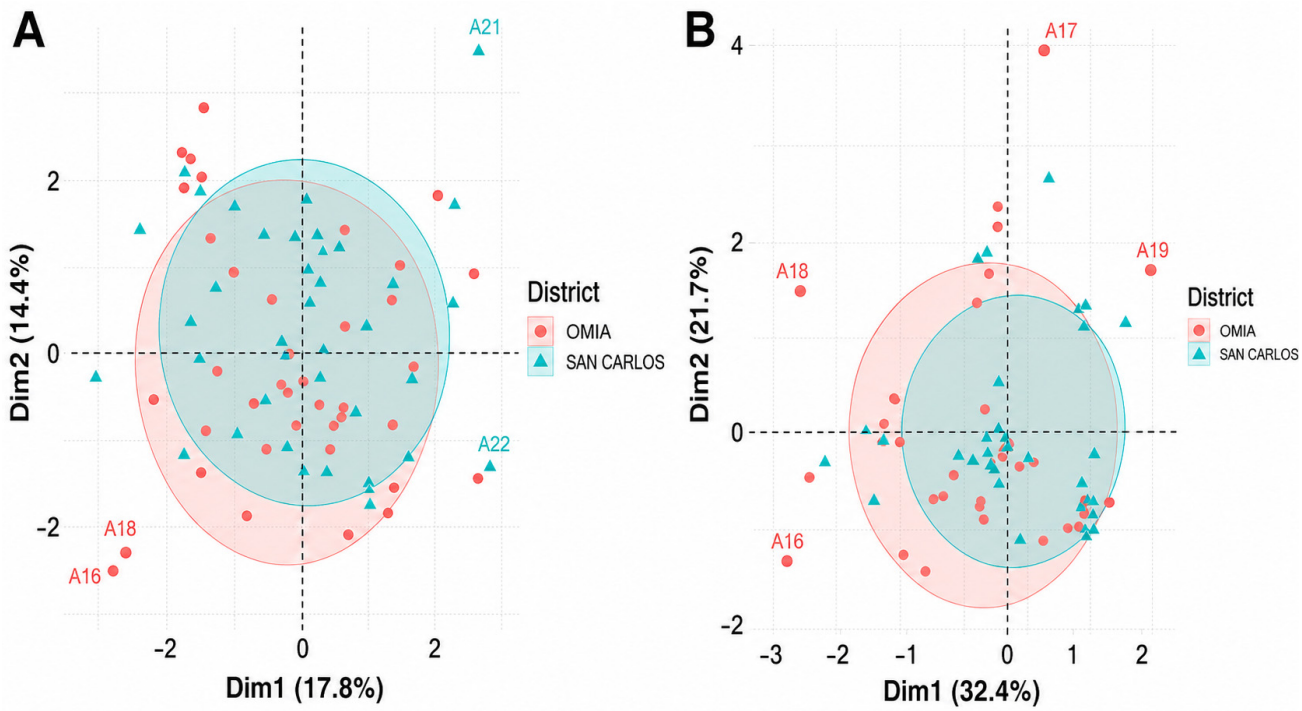

Figure 7. Principal Component Analysis (PCA) of (**A**) microscopic characteristics and (**B**) physical properties of *Cedrela* sp. wood from the Omia and San Carlos districts in the Amazonas department.

These patterns indicate that site-related differences are subtle and primarily reflected in intra-site variability rather than in distinct structural divergence. This pattern suggests that the data captures the broad natural variability inherent to the genus, within which individual phenotypic responses overlay any localized environmental gradients.

3.6. Potential Uses of Cedrela sp. Wood

It is important to note that *Cedrela* sp. is a CITES-regulated species, and any industrial or commercial use of its timber must comply with international trade regulations and national conservation guidelines.

The observed basic density (0.52 g/cm^3) provides a preliminary basis for considering *Cedrela* sp. wood for furniture, cabinetry, or lightweight components, although these potential uses require validation through standardized mechanical testing [35]. Its density characteristics also suggest a potential suitability for reconstituted wood panels/plywood and engineered wood products, and the medium-density range (0.41–0.60 g/cm^3) [34] renders it potentially appropriate for construction panels, suggesting a high theoretical structural efficiency as established by the Ministry of Housing, Construction, and Sanitation [37].

However, the very high volumetric shrinkage (21.46%) indicates a substantial potential for volume reduction during complete dehydration. While actual dimensional stability against warping or twisting is governed by directional anisotropy rather than volumetric

values alone, this high shrinkage suggests that its technological use should target conditions where dimensional variations can be technically managed [35].

Regarding its physical classification, the mean normal density and oven-dry density (0.46 g/cm^3) classify this timber as a lightweight to medium material, which is advantageous for manufacturing utility items requiring a low weight-to-volume ratio. Furthermore, its relatively uniform density may favor its use in advanced wood processing and machining, laminated products, and artisanal manufacturing, provided that appropriate drying protocols are applied to minimize deformation. Additionally, the initial moisture content values (averaging 108.20% in Omia and 115.02% in San Carlos) fall within the expected range for green tropical timber of medium-to-light density, representing typical values for freshly cut material that require standard conditioning protocols prior to industrial processing. These technological orientations are based strictly on physical properties, representing screening indicators for wood utilization.

4. Discussion

The present study provides an integrated anatomical and physical characterization of *Cedrela* sp. wood from two montane tropical sites in northeastern Peru, offering new insights into intra-specific variability under contrasting local conditions. The observed patterns indicate that wood structure and properties are influenced by the interaction between local environmental conditions and intrinsic species-level constraints. This interpretation is consistent with previous studies showing that wood density is shaped by genetic regulation, tree age, morphological traits, and environmental adaptability, while anatomical features such as vessel arrangement, fiber wall thickness, and parenchyma abundance contribute to species responses to climatic stressors [38,39].

These findings provide a scientific basis for sustainable forest management and optimized industrial utilization of high-value tropical timber under varying local conditions. The anatomical results reveal a high degree of qualitative consistency between sites, with variability primarily expressed in quantitative traits. This structural conservation is typical of the genus Cedrela, yet the subtle differences in fiber dimension and vessel characteristics suggest responses associated with local environmental conditions [8,40]. Specifically, the documentation of macroscopic and microscopic profiles within the genus highlights that features such as diffuse-to-semi-ring porosity, distinct growth rings delimited by marginal parenchyma, and medium-sized vessels are highly stable diagnostic markers across Neotropical populations [41]. Furthermore, the predominance of multiseriate heterocellular rays and thin-to-medium fiber walls provides a structural framework that may contribute to the relatively low-to-medium density of the timber [41]. In particular, the association between fiber-related traits and basic density supports the widely recognized role of cell wall proportion in determining wood density. This is consistent with [8], who documented how climate parameters act as strong anatomical predictors in the genus Cedrela, showing that water availability directly influences vessel frequency, lumen area, and fiber wall thickness. Similar relationships have been reported for tropical hardwoods, where adjustments in xylem structure reflect functional responses to variation in water availability and climatic variability. In this context, the medium basic density observed in both sites indicates a functional balance between mechanical support and hydraulic efficiency, consistent with species growing under seasonally variable moisture regimes. According to the basic density thresholds established by [34], the timber from both studied populations falls within the medium density category (0.41–0.60 g/cm^3). Concurrently, when evaluated under the classification proposed by [35], the wood is categorized as light (0.36–0.55 g/cm^3). This intermediate density value aligns closely with the global reference standards compiled in the CIRAD Tropical Timber Atlas, which classifies the genus Cedrela

(commercially referred to as "Cedro") as a light-to-medium weight timber with an average density of approximately 0.45 g/cm^3 at 12% moisture content [41]. The close convergence between our results and the CIRAD database suggests that, despite local environmental fluctuations, the wood density remains constrained within the characteristic genetic and functional boundaries of the genus.

Furthermore, its classification within the medium-density category has important implications for industrial applications, as traits such as durability and mechanical strength are essential for construction and high-end furniture manufacturing, as highlighted by [4].

The physical properties further reinforce this interpretation. Despite the environmental differences between Omia and San Carlos, both populations exhibited density values that constrain them within the same structural groups. In contrast, the volumetric shrinkage values obtained for both Omia and San Carlos (21.46%) place this timber in the very high shrinkage category (>15%), according to the classification criteria established by [35]. This result indicates a substantial potential for dimensional changes during drying and highlights the need for controlled seasoning protocols before industrial processing. However, because actual dimensional stability (such as warping, checking, or twisting) is strictly dictated by the anisotropy ratio between tangential and radial directions rather than volumetric shrinkage alone, further directional tests are required to definitively establish the structural stability of this timber under fluctuating hygroscopic regimes. This limitation has also been reported in prior studies on *Cedrela odorata* [42,43]. This pronounced volumetric shrinkage behavior, which might initially appear unusual when contrasted with the light-to-medium basic density of the wood, strongly corresponds with the intrinsic technological profile documented for the genus Cedrela. Broad geographic evaluations indicate that this timber group naturally exhibits a high potential for total volumetric contraction and a moderate-to-high susceptibility to cellular collapse or warping during initial water loss if early drying rates are not strictly monitored and controlled [41]. This trait is commonly associated with woods that possess a relatively high proportion of hygroscopic cell wall components, which respond markedly to changes in moisture content. Such behavior has been widely documented in tropical species subjected to pronounced seasonal fluctuations in humidity, where repeated cycles of swelling and shrinkage influence wood performance [5]. However, despite these dimensional stability constraints, the physical properties of Cedrela wood remain adequate for applications sheltered from drastic hygroscopic changes, such as fine furniture manufacturing [9,44], a recommendation that matches the primary end-uses certified by global databases for this genus [41].

From a technological standpoint, the combination of light-to-medium density and anatomical features observed in *Cedrela* sp. supports its potential use in value-added products where moderate strength, low weight, and good workability are desirable, such as furniture, cabinetry, interior joinery, decorative components, and other protected wood products [41–44]. This interpretation is consistent with previous studies on *C. odorata*, which have described the wood as suitable for light construction, interior design, ship decking and paneling, and general woodwork [42,43]. However, the very high volumetric shrinkage observed in the present study represents an important technological limitation, indicating that drying, conditioning, and moisture control are critical before industrial processing. Therefore, potential uses should be prioritized for indoor or sheltered applications, where dimensional changes can be technically managed. Applications in plywood, laminated components, or other engineered wood products should be considered preliminary and require further validation through mechanical testing, bonding performance, drying behavior, and dimensional stability assessments. In addition, because *Cedrela* spp. are CITES-regulated, any commercial use must comply with legal traceability, sustainable harvesting, and national conservation requirements.

From a functional perspective, *Cedrela* sp. wood exhibits a selective coordination between its cellular structure and physical properties, characterized by a trade-off between mechanical investment and dimensional stability. The strong positive correlation between oven-dry density and volumetric shrinkage (r = 0.72) demonstrates that a higher content of cell wall material directly leads to lower dimensional stability when hygroscopic water is lost. This pattern aligns with the "wood economics spectrum" described by [45], where density variations reflect a balance between biomass investment and hydraulic safety, a trend also observed by [7] in endemic species of the Peruvian Amazon, such as *Trichilia dazae*. These findings suggest that while the medium density of *Cedrela* sp. (averaging 0.50–0.52 g/cm^3), which is structurally determined by its intermediate fiber wall thickness, is favorable for workability, its high shrinkage rates necessitate careful seasoning for high-value applications.

Correlation analysis further reveals that moisture content presents a nearly perfect negative association with basic density (r = −0.96), indicating that water storage capacity is strictly constrained by the physical space occupied by the woody skeleton [46]. Interestingly, the moderate relationship between ray width and basic density (r = 0.38) highlights the structural contribution of radial parenchyma to wood compactness. According to [47], wood rays not only serve as storage tissues but also act as transverse reinforcements that influence the overall density and mechanical behavior of the xylem. This is reinforced by the negative association between ray width and moisture content (r = −0.34), suggesting that greater development of radial parenchyma displaces potential void space for free water, thereby influencing the hygroscopic equilibrium of the material.

The stability of *Cedrela* sp. is also dictated by microscopic traits, specifically the negative relationship between fiber wall thickness and volumetric shrinkage (r = −0.31). This observation aligns with [48], who identified that fiber wall and lumen fractions are the primary drivers of density and physical behavior in angiosperms. Furthermore, the strong geometric dependence between fiber diameter and lumen diameter (r = 0.95) reflects an intrinsic constraint that, while not solely determining density, confirms that wood quality results from the interaction of multiple anatomical components. Ultimately, evaluating the suitability of this timber based on density alone may lead to an overestimation of its performance; therefore, integrating shrinkage rates and fiber characteristics, as emphasized by [7], is imperative to optimize its industrial utilization under variable humidity conditions.

Multivariate analysis further supports the interpretation of limited but meaningful site-related variability. The substantial overlap observed in the PCA indicates that *Cedrela* sp. maintains a coherent anatomical and physical profile across sites, while the greater dispersion in San Carlos suggests higher intra-site heterogeneity. This variability may be linked to microenvironmental factors such as soil conditions, slope, or localized moisture availability that are not fully captured by broad climatic descriptors. Such heterogeneity is characteristic of montane tropical systems and may play a key role in shaping wood formation processes.

From an applied perspective, these findings have direct implications for timber utilization and forest management. The identified properties support the use of *Cedrela* sp. in applications requiring moderate strength, low weight, and good machinability, such as fine furniture, interior joinery, and engineered wood products. However, the pronounced shrinkage necessitates strict control of drying processes and end-use environments to minimize deformation and ensure product quality. This reinforces the need for site-specific management strategies that account for variability in wood properties, rather than assuming uniform performance across regions.

More broadly, the results highlight the importance of integrating anatomical and physical data into sustainable forest management frameworks. In tropical systems, where

environmental gradients are steep and highly heterogeneous, understanding intra-specific variability is essential for optimizing resource use and maintaining product quality. Moreover, the linkage between xylem structure and environmental conditions underscores the potential sensitivity of *Cedrela* sp. to ongoing climate change, particularly in relation to shifts in precipitation regimes and temperature patterns.

5. Conclusions

This study provides an integrated anatomical and physical characterization of *Cedrela* sp. wood from two montane tropical sites in the Amazonas department of northeastern Peru. The findings indicate that the species maintains a consistent qualitative anatomical pattern between Omia and San Carlos, while quantitative variation in fiber, vessel, and ray traits indicates moderate site-related variability within the natural range of the genus. Thus, the hypothesis of between-site variability is partially supported, mainly through quantitative anatomical traits rather than through marked structural differentiation. The physical characterization provides preliminary evidence of the technological potential of this wood for value-added applications where moderate weight and good workability are desirable. However, its behavior during drying should be carefully considered before industrial processing, particularly for products exposed to changes in moisture conditions. Overall, these results provide reference anatomical and physical data for unmanaged *Cedrela* sp. populations in montane Amazonian forests. By linking anatomical traits, physical properties, and local variability, this study contributes an initial framework for site-specific timber assessment and supports future research aimed at sustainable management and technological evaluation of this high-value tropical species.

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