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Scientific Article

ANATOMICAL AND PHYSICAL ANALYSIS OF THE BARK OF THREE AMAZONIAN TREE SPECIES AS A TOOL FOR SPECIES IDENTIFICATION

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ABSTRACT

Accurate species identification is crucial for conservation efforts and combating illegal logging. This study analyzes the anatomical characteristics and physical properties of the bark of three tropical species: *Bertholletia excelsa*, *Cedrela odorata*, and *Eschweilera coriacea*, to assess their potential for rapid species identification. The hypothesis proposed was that anatomical and physical differences in the bark would allow for effective identification. The study was conducted in the southeastern region of Peru, in the department of Madre de Dios, where nine trees from the three species were randomly selected. Bark samples were collected at breast height (DBH) from the trees. The samples were analyzed macroscopically, microscopically, and for physical properties such as moisture content, basic density, and volumetric shrinkage. The results showed that *B. excelsa* had the thickest (14.11 cm) and most fibrous bark, while *C. odorata* had thinner bark (9.33 cm), with a more regular organization. *E. coriacea* had the thinnest (8.83 cm) and most flexible bark. Regarding physical properties, *B. excelsa* exhibited the highest moisture content (68.71%), while *C. odorata* showed the highest basic density (740 kg/m³). This study demonstrates that anatomical and physical characteristics of bark are effective tools for the identification of tree species, contributing to conservation and the prevention of illegal logging.

Keywords: Illegal logging; Identification of phloem; Timber species

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ANÁLISE ANATÔMICA E FÍSICA DA CASCA DE TRÊS ESPÉCIES DE ÁRVORES AMAZÔNICAS COMO UMA FERRAMENTA PARA IDENTIFICAÇÃO DE ESPÉCIES

RESUMO A identificação precisa das espécies é crucial para os esforços de conservação e combate ao desmatamento ilegal. Este estudo analisa as características anatômicas e as propriedades físicas da casca de três espécies tropicais: *Bertholletia excelsa*, *Cedrela odorata* e *Eschweilera coriacea*, a fim de avaliar seu potencial para identificação rápida de espécies. A hipótese proposta foi a de que as diferenças anatômicas e físicas na casca permitiriam uma identificação eficaz. O estudo foi conduzido na região sudeste do Peru, no departamento de Madre de Dios, onde nove árvores das três espécies foram selecionadas aleatoriamente. Amostras de casca foram coletadas na altura do peito (DAP) das árvores. As amostras foram analisadas macroscopicamente, microscopicamente e quanto às propriedades físicas, como teor de umidade, densidade básica e encolhimento volumétrico. Os resultados mostraram que *B. excelsa* tinha a casca mais espessa (14,11 cm) e mais fibrosa, enquanto *C. odorata* tinha casca mais fina (9,33 cm), com uma organização mais regular. *E. coriacea* tinha a casca mais fina (8,83 cm) e mais flexível. Em relação às propriedades físicas, *B. excelsa* apresentou o maior teor de umidade (68,71%), enquanto *C. odorata* mostrou a maior densidade básica (740 kg/m³). Este estudo demonstra que as características anatômicas e físicas da casca são ferramentas eficazes para a identificação de espécies de árvores, contribuindo para a conservação e prevenção do desmatamento ilegal.

Palavras-Chave: Desmatamento ilegal; Espécies de madeira; Identificação de floema

1. INTRODUCTION

Tropical forests play a fundamental role in global climate regulation, biodiversity conservation, and the provision of crucial ecosystem services such as carbon capture and the regulation of hydrological cycles (Marengo et al., 2018). However, the accelerating process of deforestation and illegal resource exploitation in many tropical regions are creating a serious ecological problem (Chuquibala, 2022). Illegal logging of forest species threatens biodiversity and disrupts the balance of ecosystems, ultimately compromising the sustainability of natural resources. In this context, the accurate and rapid identification of forest species has become an essential tool in the fight against illegal logging and for the sustainable management of forest resources (Carmo et al., 2016a; Elias et al., 2024). Given the urgency of addressing illegal logging, identifying forest species accurately and efficiently has become even more critical. While traditional taxonomic methods have often relied on morphological characteristics, there has been growing interest in alternative tools that allow for faster and more reliable identification. Among these, the anatomical characteristics of tree bark have emerged as a promising and practical solution, particularly in field conditions.

The taxonomic identification of forest species has historically relied on visible morphological characteristics and, in recent years, molecular techniques. However, the anatomical characteristics of tree bark have emerged as a promising tool for species identification due to its high intraspecific variability and availability in the field. The bark acts as an external protective structure and presents a wide range of adaptations that reflect both environmental conditions and biotic pressures such as herbivory and competition for resources (Franceschi et al., 2005; Li et al., 2024). Features such as rays, fibers, crystals, and other anatomical structures of the bark serve defensive functions and provide distinctive characteristics that facilitate species differentiation. Additionally, the physical properties of the bark, such as its moisture content, basic density, and volumetric shrinkage, provide valuable information about the ecological adaptations of each species and are useful for rapid field identification (Baptista et al., 2013; Mota et al., 2021).

This study focuses on the bark anatomy of three key tropical forest species: *Bertholletia excelsa*, *Cedrela odorata*, and *Eschweilera coriacea*, which are of significant ecological and economic importance. Accurate identification of these species is essential for their sustainable management and for combating illegal logging. The bark anatomy and its physical properties were analyzed with the aim of exploring how these characteristics can be used to differentiate these species, both in taxonomic studies and in forest monitoring (Carmo et al., 2016b; Garlant et al., 2002). The motivation for this work arises from the need for accessible and effective tools for species identification in forest monitoring and protection contexts, where species may be difficult to differentiate through visual observations or traditional molecular techniques.

The objective of this research was to analyze the anatomical structure and physical properties of the bark of *B. excelsa*, *C. odorata*, and *E. coriacea*, in order to assess their potential for taxonomic identification of these species. The key research questions were: How do the anatomical characteristics of the bark vary between these species? Can these characteristics be used to effectively differentiate the species? The hypothesis proposed was that anatomical and physical differences in the bark would allow for effective identification.

This study contributes to the taxonomic knowledge of the species studied and provides a practical tool for monitoring and controlling illegal logging. Additionally, the results offer a foundation for future research on the use of bark anatomy in the sustainable management and conservation of forest resources, emphasizing the importance of anatomical features as an efficient means of identifying and protecting forest species of economic and ecological value (Nie et al., 2023).

2. MATERIAL AND METHODS

2.1 Study area

The study area is located in the southeastern region of Peru, in the department of Madre de Dios, an area recognized for its exceptional biodiversity (Myers et al., 2000). This department is part of the Madre de Dios River basin, a major tributary of the Beni River, which connects with the Amazon River. Additionally, it is situated at the border between Peru, Brazil, and Bolivia, highlighting its geostrategic significance in the Amazon region. The study focused on the "El Bosque" farm, owned by the National Amazonian University of Madre de Dios (UNAMAD), located 16.5 km southwest of Puerto Maldonado, in the Las Piedras district, Tambopata province, along the Southern Interoceanic Highway.

The farm spans an area of approximately 428 hectares, divided into 27 blocks. The land is classified as a high terrace forest, with an average elevation of 250 meters above sea level. The climate in the area is tropical humid, with an average annual temperature of 27.8°C. Monthly temperatures range from 26.6°C in May and June, reaching a peak of 28.8°C during the hottest months (January, February, and October). These values show slight seasonal variability, but in general, temperatures remain relatively constant throughout the year (Portal-Cahuana et al., 2023; Zepner et al., 2021).

Annual rainfall totals 2,260.4 mm, with a clearly seasonal precipitation pattern. The rainiest months are from January to March, when rainfall exceeds 350 mm per month, while the dry season, from June to September, is characterized by a marked decrease, with rainfall falling below 50 mm per month in the months with the least rainfall (Zepner et al., 2021).

This ecosystem exhibits characteristics of a degraded forest, where smaller and less commercially valuable species have been eliminated or reduced, primarily due to selective resource extraction. As a result, the forest shows a less dense structure, with larger trees dominating the canopy, while the lower layers display lower biodiversity.

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Despite this disturbance, the area remains rich in biodiversity and serves as an excellent location to study the anatomical characteristics of tree bark species.

2.2 Selected species

For this study, three species representatives of the high terrace forests of Madre de Dios were selected: *Bertholletia excelsa* Bonpl. (Brazil nut), *Cedrela odorata* L. (cedar), and *Eschweilera coriacea* (DC.) S.A. Mori (white misa). *B. excelsa*, highly valued for its seeds, is crucial for forest regeneration and seed dispersal through consumption by local fauna; its logging is prohibited in the department of Madre de Dios (Rockwell et al., 2017). *C. odorata*, prized for its wood, is listed on CITES Appendix II as a threatened species and is vital for the forest structure and the regeneration of other species (CITES, 2020). *E. coriacea*, although less well-known, is a timber species with high local use. These species were selected not only for their ecological and commercial importance but also for their potential to be identified through the anatomical characteristics of the bark, which could serve as an additional tool in the fight against illegal logging.

2.3 Sample collection

Bark samples were collected from 9 trees of three forest species. These trees naturally grew on the "El Bosque" farm (Figure 1). The selection of the trees was done randomly, following a probabilistic sampling approach, ensuring that all trees in the population had the same probability of being selected for the sample. The number of trees was determined in accordance with the Peruvian Technical Standard (NTP N°251.008, 2016), which stipulates a minimum of three trees per species.

Each tree was georeferenced (Table 1), and dasometric data such as diameter at breast height (DBH) and total tree height were recorded. Bark samples were taken at the DBH level, using two parallel cuts made with a manual saw. The bark was then extracted using a chisel and hammer, yielding pieces approximately 2.5 x 10 x 5 cm (Figure 1). Each sample was divided into three sections: one for macroscopic analysis, another for microscopic analysis, and a third for the measurement of physical properties (moisture content, basic density, and volumetric shrinkage).

To prevent future damage to the trees, the bark extraction area was treated with a hormonal healer and sealed with liquid silicone (Portal-Cahuana et al., 2023) (Figure 1). Below is the dasometric information of the selected trees, along with their respective geographic coordinates and characteristics.

2.4 Macroscopic characteristics

For the analysis of the macroscopic structure of the barks, representative samples of the three selected forest species were prepared. The samples were sanded and polished on the transverse plane using

Table 1. Selected trees of the three forest species with their respective coordinates and dasometric information
Tabela 1. Árvores selecionadas das três espécies florestais com suas respectivas coordenadas e informações dasométricas

N°	Scientific Name	Family	Common Name	DBH (cm)	East	North	Height (m)
1	*Bertholletia excelsa*	Lecythidaceae	Castaña	31.8	485051	86220136	23
2	*Bertholletia excelsa*	Lecythidaceae	Castaña	95.5	485116	8621957	27
3	*Bertholletia excelsa*	Lecythidaceae	Castaña	95.5	485485	8622041	30
4	*Cedrela odorata*	Meliaceae	Cedro	29.9	485150	8621949	25
5	*Cedrela odorata*	Meliaceae	Cedro	29.9	485578	8621608	22
6	*Cedrela odorata*	Meliaceae	Cedro	73.2	485340	8622022	26
7	*Eschweilera coriacea*	Lecythidaceae	Misa blanca	70.0	485098	8622036	26
8	*Eschweilera coriacea*	Lecythidaceae	Misa blanca	73.2	485202	8621977	28
9	*Eschweilera coriacea*	Lecythidaceae	Misa blanca	50.0	485370	8622067	25

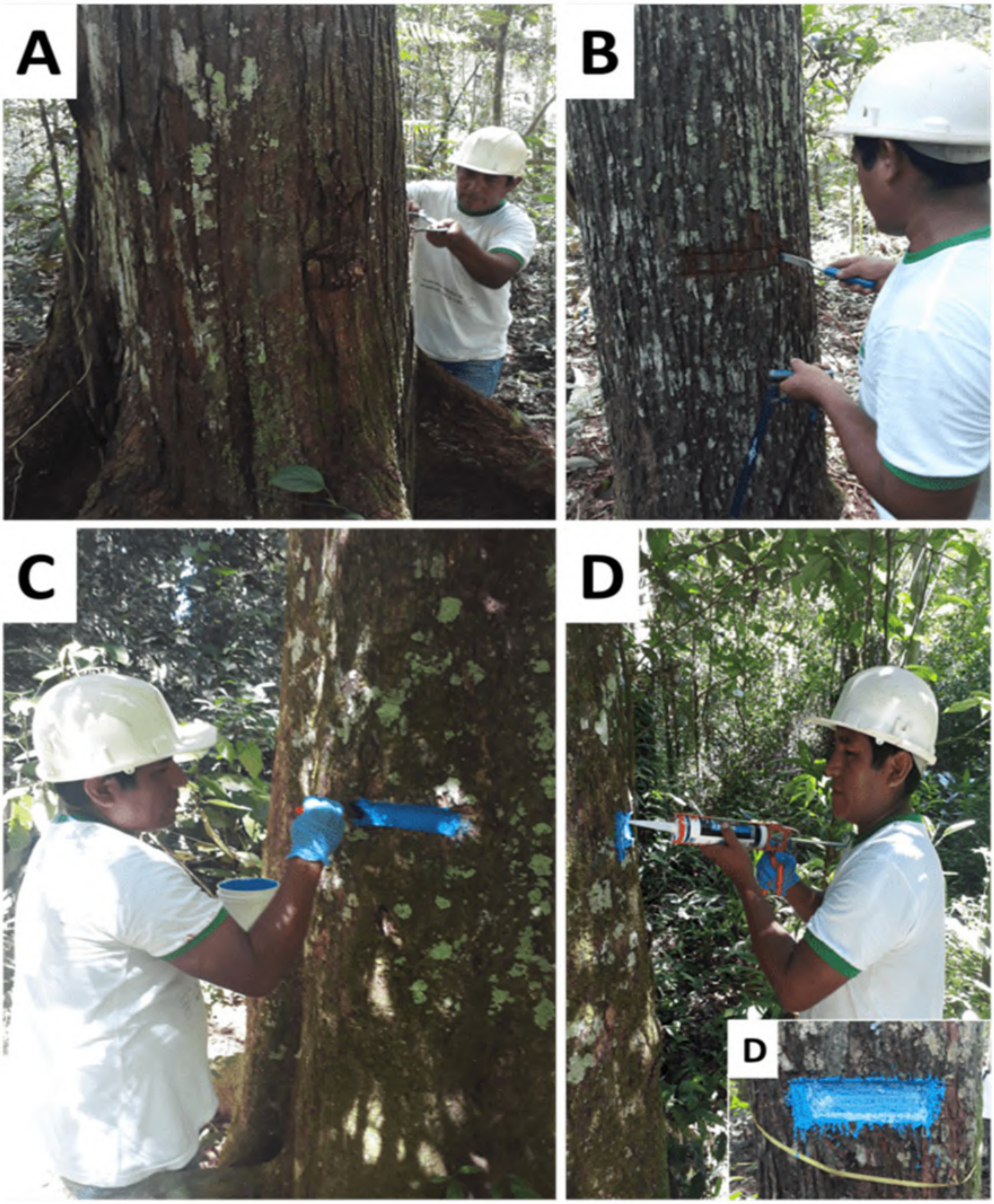

Figure 1. Field phase. A) Parallel cut made with a manual saw at breast height (DBH). B) Bark extracted using a chisel and hammer. C) Wound treated with a hormonal healer. D) Sealed with liquid silicone

Figura 1. Fase de campo. A) Corte paralelo realizado com serra manual na altura do peito (DAP). B) Casca extraída com formão e martelo. C) Ferida tratada com cicatrizante hormonal. D) Selada com silicone líquido

sandpaper of various grits (60-1200 grains/cm²). This process allowed for better visualization of macroscopic features, such as the layers that compose the bark and the differentiation of the various tissues present. The surface of the samples was observed under a Leica stereoscopic microscope, equipped with a built-in camera, to facilitate the detailed analysis of the observed structures.

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2.5 Microscopic characteristics

For microscopic characterization, the bark samples were cut with a Leica horizontal sliding microtome, following the transverse, radial, and tangential cutting planes at micrometer thicknesses. The traditional wood cutting procedure on the microtome was applied, adapted to avoid sample breakage, according to the protocols established by Carmo et al. (2016a) and Mota et al. (2017) in their studies on cutting techniques for wood and bark samples for microscopic observation.

Once the thin sections were obtained, they were stained with methylene blue and/or safranin to highlight the cellular structures. The sections were placed on slides and a small amount of glycerin was added to preserve the sample quality. Microphotographs were captured using a Leica microscope at different magnifications. The microscopic observations and descriptions of the barks were carried out according to the "IAWA List of Microscopic Bark Features" (Angyalossy et al., 2016), ensuring a detailed and systematic analysis.

2.6 Physical properties

The moisture content and volumetric shrinkage of the bark were determined using the formulas for the physical properties of wood from the Peruvian Technical Standards (NTP N°251.010, 2016; NTP N°251.012, 2016) (Eq. 1 and 2):

$$\mathrm{MC}\ (\%) = \frac{wh - wod}{wod} * 100 \qquad \text{(Eq. 1)}$$

$$\mathrm{CV}\ (\%) = \frac{Vs - Vsh}{Vs} * 100 \qquad \text{(Eq. 2)}$$

Where: wh = Wet mass of the test specimen (g), wod = mass of the oven-dry specimen (g), Vs = Saturated volume (cm^3), Vo = Oven-dry volume (cm^3).

2.6.1 Basic Density (DB)

The basic density of the bark (DB) was determined using the oven-dry weight (kg) and the wet volume (m^{-3}) by the water immersion method, as follows (Eq. 3):

$$\mathrm{DBc} = \frac{PSH}{VH}\ Kg\, m^{-3} \qquad \text{(Eq. 3)}$$

Where: DBc = Basic density of the bark, PSH = Mass of the sample (kg), VH = Volume of the sample (m^3).

The determination was performed on 3 trees per species (Carmo et al., 2016b; Carmo et al., 2016c).

2.7 Data analysis

The data obtained on the anatomy and physical properties of the bark from the three species were analyzed using R software, version 3.5.1 (R Core Team, 2019). For each element, 25 anatomical measurements were taken, which provided a representative set of the structural characteristics and physical properties of the barks. This statistical approach provided a solid foundation for the analysis and comparison of the studied species.

3. RESULTS

3.1 Macroscopic characteristics

For *Bertholletia excelsa*, the outer bark presents a fissured structure, with a color ranging from dark gray to blackish in the longitudinal section (Figure 2). The average bark thickness was 14.11 cm. In the transverse section, the bark takes on a reddish-brown cream tone. Due to the presence of a fibrous structure in the bark, its separation during handling is challenging.

Regarding the outer bark, it exhibits a sparse periderm, resulting in an underdeveloped rhytidome (Figure 2). The texture of the bark is fibrous, with thick rays that are clearly visible to the naked eye, but without noticeable ray expansions. The phloem, which appears dark reddish-brown, is thick and clearly delimited, showing a sharp contrast with the inner bark, which makes it easy to identify this transition.

For *Cedrela odorata*, the outer bark is characterized by a cracked structure, with a color ranging from light ash-brown in the longitudinal section, exhibiting cracks that are spaced apart. The rhytidomes, which are

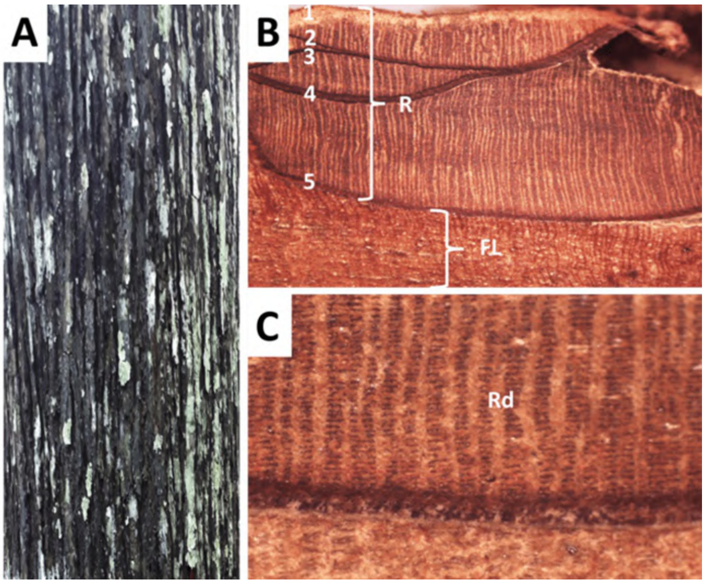

Figure 2. A) Longitudinal external bark, fissured design, gray to dark or blackish. B) Macroscopic transverse section of the bark. (R) Rhytidome, (FL) Phloem, and (Rd) Rays. (1, 2, 3, 4, 5) Successive periderm layers

Figura 2. A) Casca externa longitudinal, com design fissurado, de cor cinza a escura ou amarronzada. B) Seção transversal macroscópica da casca. (R) Rítidoma, (FL) Floema e (Rd) Raios. (1, 2, 3, 4, 5) Camadas sucessivas de periderme

sparse, form nearly rectangular plates (Figure 3). The average bark thickness was 9.33 cm. In the transverse section, the bark takes on a reddish-brown tone. The presence of a laminar structure allows the bark to separate easily during handling.

The outer bark has numerous periderm layers, resulting in a poorly developed rhytidome (Figure 3). Its texture is fibrous, though the rays are not visible to the naked eye, and the ray dilatation seems absent. A clear and abrupt difference between the outer and inner bark is observed, which facilitates identifying this transition.

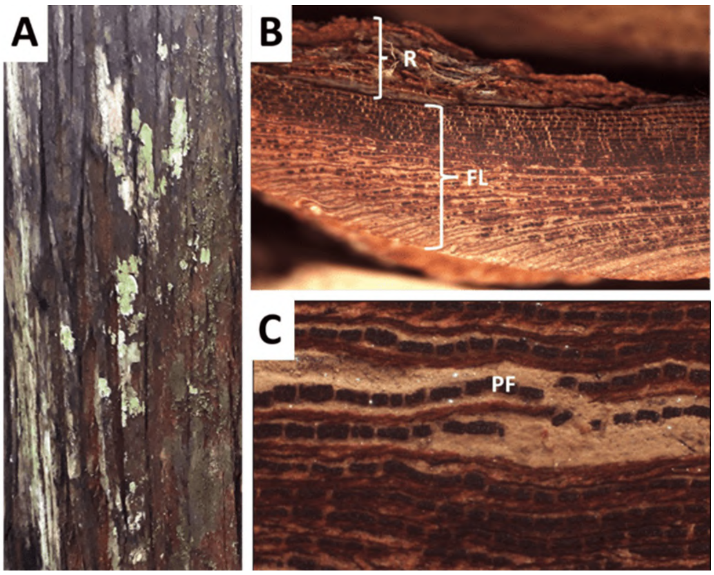

Figure 3. A) Longitudinal external bark, fissured design, straight longitudinal cracks. B) Macroscopic transverse section of the bark. (R) Rhytidome, (FL) Phloem, and (PF) Concentric plates of hard phloem

Figura 3. A) Casca externa longitudinal, com design fissurado, rachaduras longitudinais retas. B) Seção transversal macroscópica da casca. (R) Rítidoma, (FL) Floema e (PF) Placas concêntricas de floema duro

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For *Eschweilera coriacea*, the outer bark is characterized by a smooth surface, with scaly rhytidomes that peel off irregularly, presenting a dark grayish color in the longitudinal section (Figure 4). The average bark thickness was 8.83 cm. In the transverse section, the bark has a light brownish tan tone. Due to the presence of a fibrous structure, separating the bark during handling is difficult.

The outer bark shows few periderm layers, resulting in a very sparse rhytidome (Figure 4). Its texture is highly fibrous, with medium-sized rays clearly visible to the naked eye. The rays show a notable wedge-shaped dilation. The phloem, which has a dark brownish-cream color, is subtly contrasted and thin. A sharp difference is observed between the outer and inner bark, which facilitates identifying this transition.

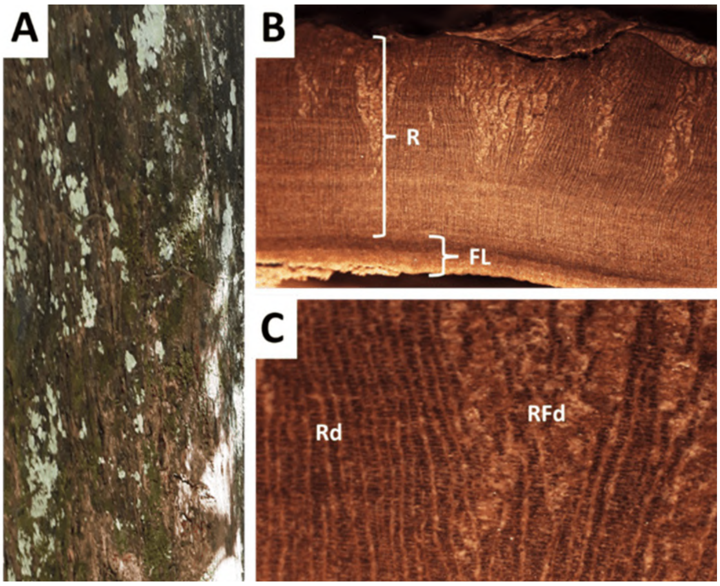

Figure 4. A) Longitudinal external bark, smooth with scaly rhytidomes that peel off irregularly, dark grayish coloration. B) Macroscopic transverse section of the bark. (R) Rhytidome, (FL) Phloem, (Rd) Rays, and (RFd) Dilated phloematic rays

Figura 4. A) Casca externa longitudinal, lisa, com rítidomas escamosos que se soltam de forma irregular, coloração cinza escura. B) Seção transversal macroscópica da casca. (R) Rítidoma, (FL) Floema, (Rd) Raios e (RFd) Raios floemáticos dilatados

3.2 Microscopic characteristics

For *Bertholletia excelsa*, at the microscopic level, the bark is characterized by a high content of lignified tissue, primarily composed of fibers, and scarce soft phloem. The hard phloem is composed exclusively of fibers arranged in rectangular columns that do not form continuous rings, making it easily identifiable.

In the middle zone of the bark, the structure is regular and non-stratified. The hard phloem, made up of fibers arranged in rectangular columns, is distinct from the rays, which are interrupted by structures that are 2, 3, and 4 cells wide (Figure 5). The rays in the radial section consist of procumbent phloem cells, with an average width of 20.8 (±2.87) µm and an average height of 141.9 (±35.31) µm. In terms of cellular composition, the rays have an average width of 3 (±1.12) cells and a height of 19 (±5.38) cells (Table 2, Figure 5). Additionally, a significant presence of rhomboid-shaped crystals is observed in the axial parenchyma cells.

Cedrela odorata, at the microscopic level, presents several layers of soft phloem (non-lignified phloem tissue) and hard

Table 2. Biometric Data of the Bark of Three Forest Species: Bertholletia excelsa, Cedrela odorata, and Eschweilera coriacea

Tabela 2. Dados biométricos da casca de três espécies florestais: Bertholletia excelsa, Cedrela odorata e Eschweilera coriacea

Species	Variable	Average	Std. Dev.	Min Value	Max Value	C.V
B. excelsa	Height of rays (µm)	141.90	35.31	67.88	2340961.00	25
	Width of rays (µm)	20.80	2.87	15.61	2615454.00	14
	Cells in rays (height)	18.60	5.38	9.00	28.00	29
	Cells in rays (width)	2.90	1.12	1.00	5.00	38
C. odorata	Height of rays (µm)	400.30	110.86	224.55	702.42	28
	Width of rays (µm)	44.70	7.90	32.19	68.11	18
	Cells in rays (height)	18.20	4.79	11.00	27.00	26
	Cells in rays (width)	2.50	0.51	2.00	3.00	20
E. coriacea	Height of rays (µm)	368.20	96.53	200.69	534.66	26
	Width of rays (µm)	32.10	5.27	22.90	43.51	16
	Cells in rays (height)	24.60	6.73	15.00	40.00	27
	Cells in rays (width)	2.00	0.20	2.00	3.00	10

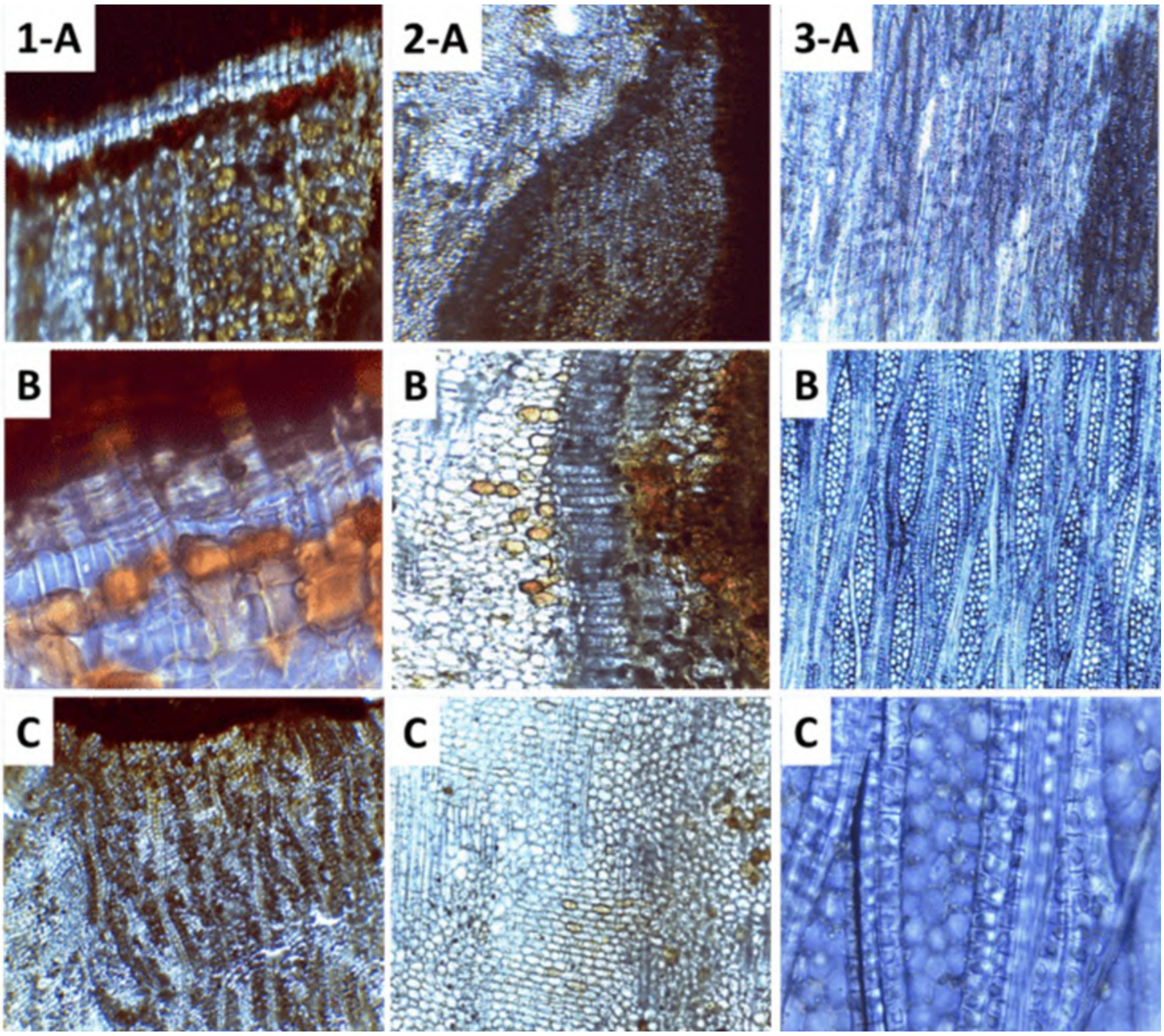

Figure 5. Microscopic photographs of the bark of *Bertholletia excelsa*: 1-A) Cross-sectional view. 2-A) Radial section. 3-A) Tangential section. Scale: A = 4x, B = 40x, C = 10x

Figura 5. Fotografias microscópicas da casca de *Bertholletia excelsa*: 1-A) Vista em seção transversal. 2-A) Seção radial. 3-A) Seção tangencial. Escala: A = 4x, B = 40x, C = 10x phloem (fibers), although the latter are relatively scarce. The hard phloem is represented exclusively by fibers arranged in rectangular plates that form continuous rings, which makes it easy to identify.

In the middle zone of the bark, the structure is clearly regular and stratified. The hard phloem (phloem fibers), arranged in rectangular plates, overlaps with the soft phloem (Figure 6) and is interrupted by biseriate and triseriate rays of cells, whose arrangement is deflected by the hard phloem plates. The rays in the radial section (Figure 6) are formed exclusively by procumbent phloem cells. The rays have an average width of 44.7 (±7.90) µm and an average height of 400.3 (±110.86) µm. In terms of cellular composition, the rays have an average width of 3 (±0.51) cells and an average height of 18 (±4.79) cells (Table 2, Figure 6). Additionally, a significant presence of rhomboid crystals and, to a lesser extent, styloid or elongated crystals, are found in the axial parenchyma cells.

Eschweilera coriacea, at the microscopic level, has a higher amount of lignified hard tissue (fibers) and a scarce presence of soft phloem (non-lignified phloem tissue). The hard phloem is represented exclusively by fibers arranged in rectangular plates, forming continuous rings with slight contrast.

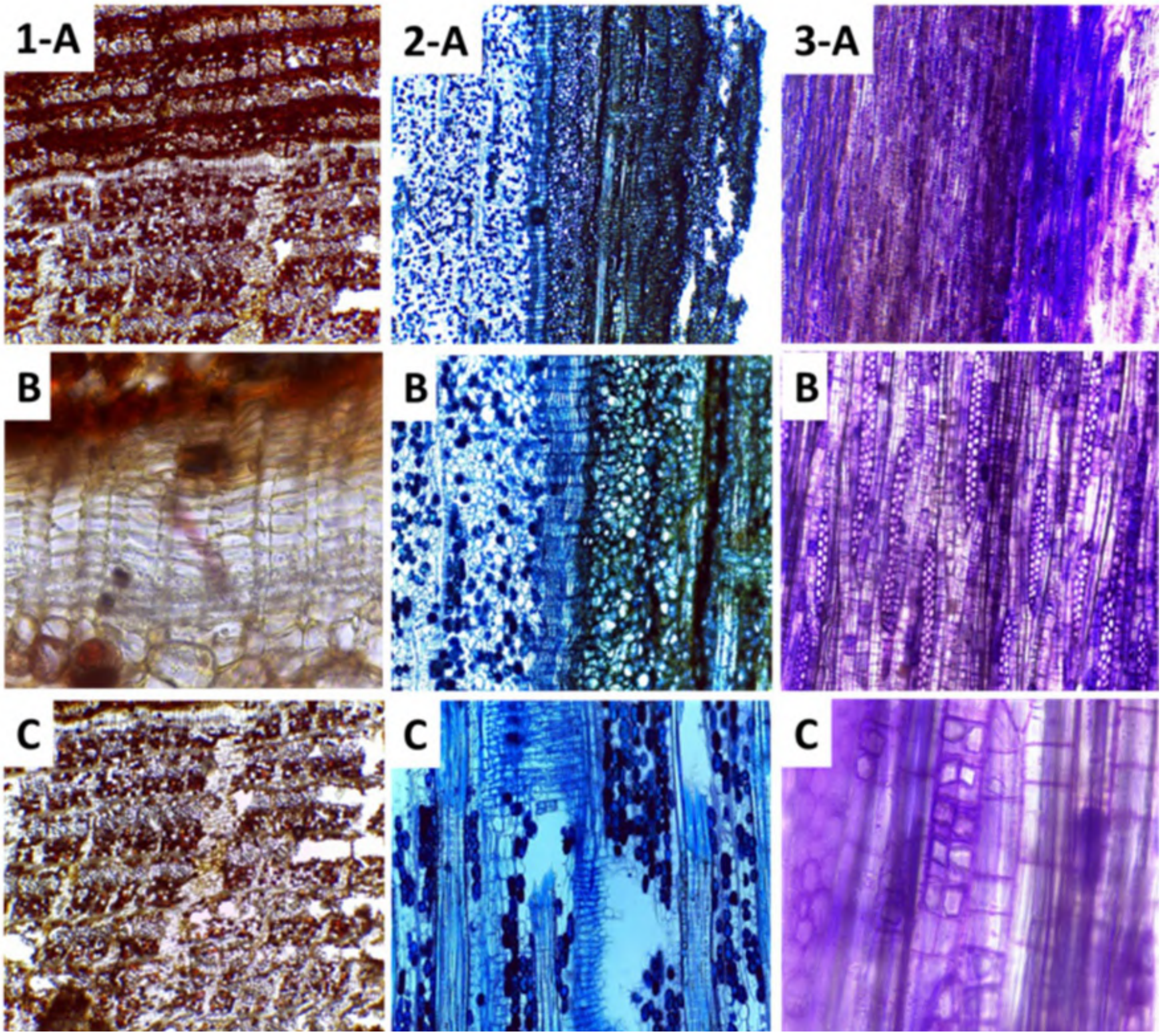

Figure 6. Microscopic photographs of the bark of *Cedrela odorata*: 1-A) Cross-sectional view. 2-A) Radial section. 3-A) Tangential section. Scale: A = 4x, B = 40x, C = 10x

Figura 6. Fotografias microscópicas da casca de *Cedrela odorata*: 1-A) Vista em seção transversal. 2-A) Seção radial. 3-A) Seção tangencial. Escala: A = 4x, B = 40x, C = 10x

In the middle zone of the bark, the structure is regular and non-stratified. The hard phloem (phloem fibers), arranged in rectangular plates, overlaps with the soft phloem (Figure 7) and is interrupted by uniseriate and biseriate rays of cells. In the radial section, the rays are composed of square-shaped phloem cells (Figure 7). The rays have an average width of 32.1 (±5.27) µm and an average height of 368.2 (±96.53) µm. In terms of cellular composition, they have an average of 2 (±0.20) cells in width and 25 (±6.73) cells in height (Table 2, Figure 7). Additionally, a significant presence of rhomboid crystals was observed in the axial parenchyma cells.

3.3 Physical properties

The species with the lowest moisture content was *C. odorata*, with an average of 19.29%, while *B. excelsa* showed the highest moisture content, with an average of 68.71% (Table 3). Regarding basic density, *E. coriacea* recorded the lowest density, with an average of 510 kg/m³, while *C. odorata* exhibited the highest basic density, with an average of 740 kg/m³ (Table 3). For volumetric shrinkage, *C. odorata* showed the least shrinkage, with an average of 14.29%, while *E. coriacea* presented the greatest volumetric shrinkage, with an average of 28.57% (Table 3).

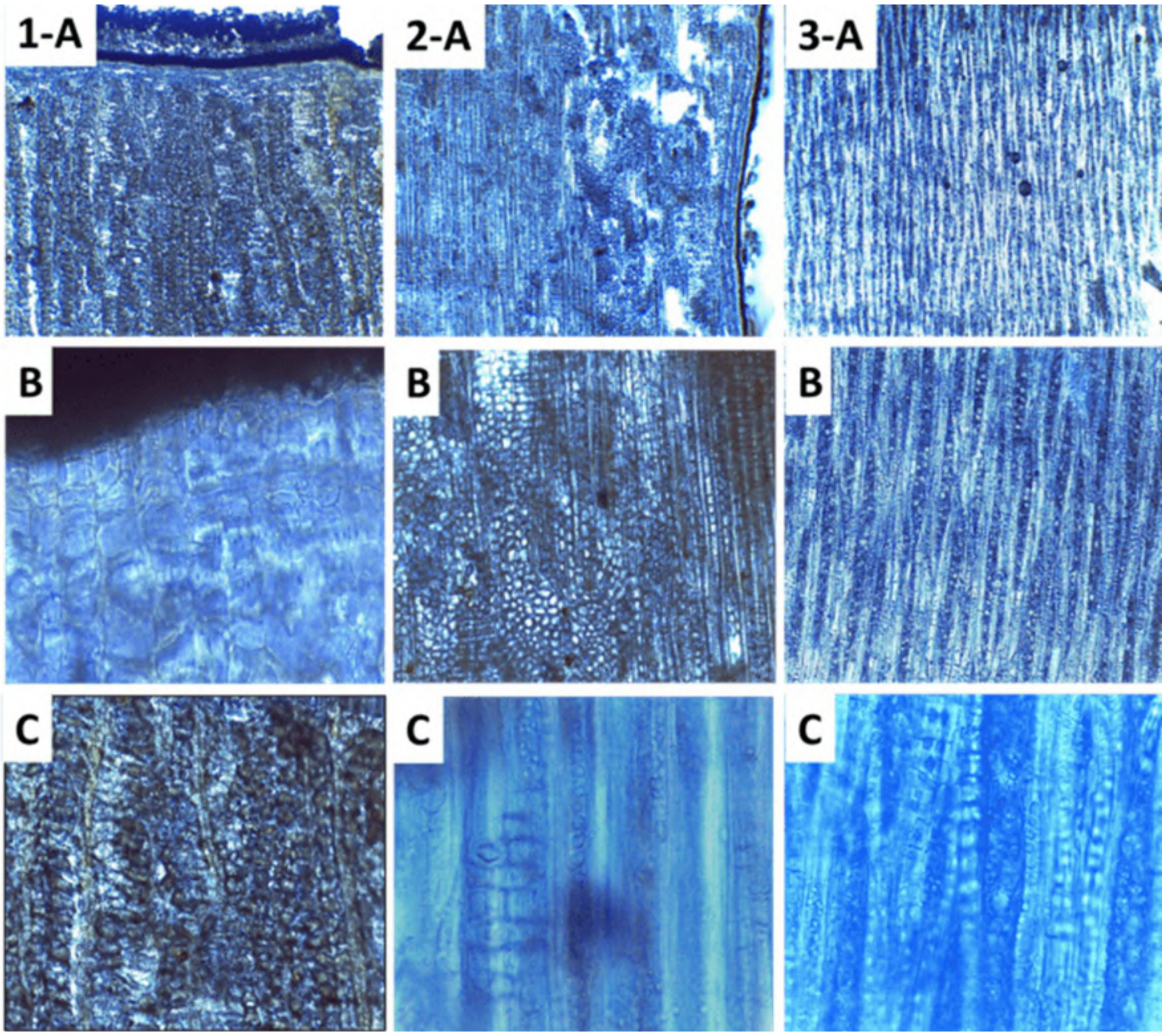

Figure 7. Microscopic photographs of the bark of the species *Eschweilera coriacea*: 1-A) Transverse section. 2-A) Radial section. 3-A) Tangential section. Scale: A = 4x, B = 40x, C = 10x

Figura 7. Fotografias microscópicas da casca da espécie *Eschweilera coriacea*: 1-A) Seção transversal. 2-A) Seção radial. 3-A) Seção tangencial. Escala: A = 4x, B = 40x, C = 10x

Table 3. Physical Properties (Moisture content, basic density, and volumetric shrinkage) of the bark of the studied species
Tabela 3. Propriedades físicas (teor de umidade, densidade básica e encolhimento volumétrico) da casca das espécies estudadas

Species	Tree N°	Moisture content (%)	Basic density (kg/m³)	Volumetric Shrinkage (%)
B. excelsa	5	65.377	520	20
	2	68.713	670	20
	3	38.591	780	23
	Average	57.560	657	21
C. odorata	5	30.033	660	14
	4	19.289	740	25
	3	23.851	670	17
	Average	24.390	690	19
E. coriacea	7	10.337	710	23
	5	27.899	650	29
	2	85.667	510	28
	Average	41.300	623	26

These densities are compared with available data from other species in the scientific literature (Figure 8). In previous studies, such as those of *Betula pubescens* (Bhat, 1982) with a density of 517.7 kg/m³ and *Betula pendula* (Bhat, 1982) with 559.3 kg/m³, species with lower densities are found. Other species, such as *Eucalyptus globulus* (Quilhó and Pereira, 2001) with 600 kg/m³ and *Albizia niopoides* (Carmo et al., 2016c) with 605.5 kg/m³, show intermediate densities. At the other end of the spectrum, species like *Goupia glabra* (Carmo et al., 2016b) (690.1 kg/m³) and *Copaifera langsdorffii* (Carmo et al., 2016a) (781.4 kg/m³) have higher densities.

This analysis reveals that the three species studied (*Bertholletia excelsa*, *Cedrela odorata* and *Eschweilera coriacea*) exhibit relatively high densities compared to other species, which may have implications for their mechanical properties and their ability to resist decomposition. Therefore, these values highlight the importance of the basic density of bark as a relevant factor in the ecology and forest management of these species.

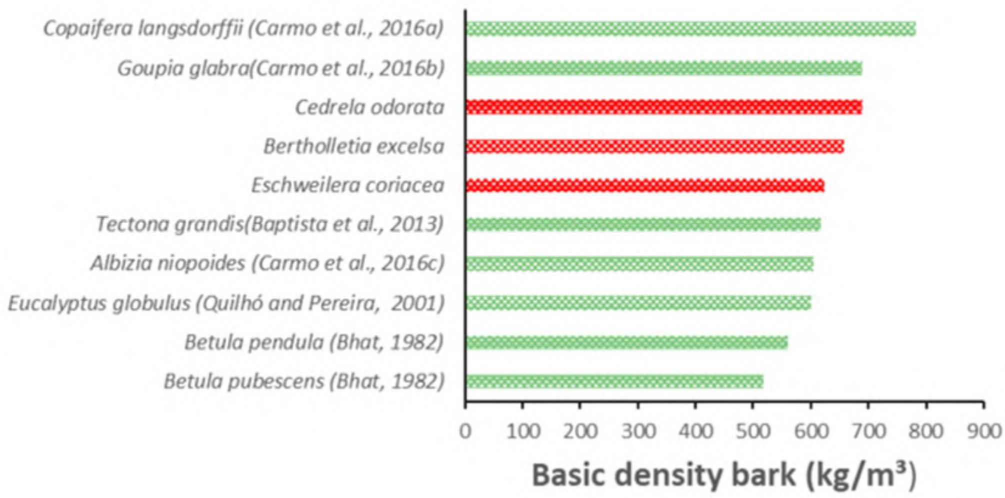

Figure 8. Comparison of the basic bark density with other species
Figura 8. Comparação da densidade básica da casca com outras espécies

4. DISCUSSION

4.1 Anatomy of the bark

This study investigated the bark anatomy of three forest species: *Bertholletia excelsa*, *Cedrela odorata*, and *Eschweilera coriacea*, highlighting their macroscopic, microscopic, and physical properties, with the aim of assisting in the identification process of these species. The results showed significant variability in bark thickness, phloem organization, and the presence of defensive structures, suggesting that each species has developed specific characteristics to face their respective environments and biotic pressures.

The bark of *B. excelsa* exhibits a fissured ritidome ranging from dark gray to black, with an average thickness of 14.11 cm. This thick and fibrous bark is characterized by the presence of thick and clearly visible rays, indicating a robust mechanical defense, likely adapted to withstand herbivore attacks. The lignified structure of the bark, with hard phloem fibers arranged in rectangular columns, provides significant structural strength (Elias et al., 2024). These findings align with previous studies, such as Franceschi et al. (2005), which highlight that species with thick, well-lignified bark are usually less susceptible to decay and herbivore attacks. The presence of rhomboid crystals in the axial parenchyma is another feature that may act as a chemical defense against pathogens and herbivores (Carmo et al., 2016a).

The design of *B. excelsa* bark reinforces the hypothesis that species with thick and fibrous bark have active defense strategies against herbivory, a phenomenon also observed in other Amazonian species, such as in the study conducted by Garlant et al. (2002) on species from the Meliaceae family. In this case, the bark thickness seems to be associated with a mechanical defense strategy, contrasting with other more flexible species that develop chemical defenses, such as *C. odorata*.

The bark of *C. odorata* is characterized by a cracked structure and a light ash-brown coloration in the longitudinal section, with an average thickness of 9.33 cm. Although thinner than that of *B. excelsa*, this bark still exhibits effective structural defense, with hard phloem formed by fibers arranged in rectangular plates. This organization is consistent with the findings of Li et al. (2024), who observed that hard phloem composed of fibers in rectangular plates is a common characteristic in species that develop structural defenses.

Microscopically, *C. odorata* shows a clear difference from *B. excelsa* in the stratified organization of its bark, with a higher content of soft phloem and a thinner ray structure compared to *B. excelsa* (Garlant et al., 2002). This more flexible structure may be advantageous in habitats where herbivore pressure is lower, and where the plant can opt for chemical defense or rapid bark renewal, instead of developing thick bark as a physical barrier. Additionally, the absence of exudates and the low number of crystals in *C. odorata* may suggest a reduced reliance on physical or chemical deterrents, favoring other strategies for defense.

The bark of *E. coriacea* has an average thickness of 8.83 cm, making it the thinnest of the three species studied. This bark is characterized by a smooth surface with scaly ritidomes that shed irregularly, suggesting a more adaptable bark that may be easier to renew. The phloem fibers are present, although the bark is less dense than those of *B. excelsa* and *C. odorata*, which may indicate a lighter defensive strategy (Mota et al., 2021).

The structure of the rays, which are observed to be dilated in a wedge-like shape, is a notable feature that indicates a growth response to herbivore pressure or mechanical factors. Microscopically, *E. coriacea* presents thinner and more dilated phloem rays than those of *B. excelsa* and *C. odorata*, which could be an adaptation for greater flexibility and response to changes in environmental conditions. This is consistent with what Nie et al. (2023) describe, observing that species with thinner bark tend to focus their defenses on adaptability and flexibility in response to environmental

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stress, rather than a fixed mechanical barrier.

Moreover, recent studies on bark anatomy across different tropical species highlight additional ecological and anatomical insights that could enrich our understanding. For instance, Lehnebach et al. (2020) found that species with fibrous bark structures and significant sclereids, like those observed in the Meliaceae family, often exhibit significant longitudinal traction stresses. These species, such as *Swietenia macrophylla*, show a remarkable correlation between bark density and stress resistance. Their findings suggest that species with fibrous bark in a reticular pattern exhibit higher resistance to environmental stress, providing a useful comparative point for species like *C. odorata* and *B. excelsa*, which also show fibrous elements in their bark. This additional perspective helps deepen our understanding of the mechanical and functional roles of bark across different families, offering a broader context for the defensive strategies observed in the species studied here.

4.2 Physical properties of the bark

The moisture content in the bark of the studied species varied considerably, with *B. excelsa* showing the highest value (68.71%), suggesting a greater capacity for water absorption and retention. This high moisture content could be related to its fibrous and thick structure, adapted to environments with high water availability, as observed in species with similar bark in the Amazon, such as *Goupia glabra* (Carmo et al., 2016c). In contrast, *C. odorata*, with only 19.29% moisture, has drier bark, suggesting an adaptation to conditions of lower humidity or greater exposure to decomposition. This aligns with the findings of Quilhó and Pereira (2001), who found that species with drier bark tend to better resist decomposition in drier climates. *E. coriacea* shows an intermediate value, reflecting an adaptation between the two previous species.

Volumetric shrinkage shows that *E. coriacea* has the greatest capacity for volume change (28.57%), indicating that its bark is more susceptible to changes in environmental humidity and probably more flexible in response to water fluctuations. This behavior is also observed in species like *Eucalyptus globulus*, which showed a tendency for bark expansion in response to environmental changes, as reported in studies by Miranda et al. (2013). On the other hand, *C. odorata* exhibits less volumetric shrinkage (14.29%), which could suggest that its bark is more stable and adapted to environments with fewer moisture fluctuations. *B. excelsa*, with an intermediate contraction value, likely develops a bark more resistant to sudden changes, similar to species like *Tectona grandis*, which has similar bark characteristics in terms of stability against moisture fluctuations (Baptista et al., 2013).

The basic density varied significantly between species, with *C. odorata* showing the highest density (740 kg/m³), reflecting denser and more resistant bark. This characteristic is also observed in species with more lignified bark, such as *Tectona grandis* (Baptista et al., 2013), which develops dense bark to resist deterioration and herbivory. In contrast, *E. coriacea* has a lower density (510 kg/m³), suggesting that its bark is less dense and more flexible, probably adapted to an environment with lower herbivore pressure and less need for mechanical defense, similar to observations in Myrtaceae family species like *Eucalyptus globulus*, which showed lower densities (Quilhó and Pereira, 2001). *B. excelsa*, with a density of 520 kg/m³, falls in an intermediate range, suggesting that its bark is robust but not as rigid as that of *C. odorata*.

Finally, the anatomy of the bark is presented as a valuable tool for the identification of forest species, as it provides a set of morphological and structural characteristics that are specific to each species. In this study, it was observed that the three species investigated *B. excelsa*, *C. odorata*, and *E. coriacea* show significant differences in the macroscopic and microscopic organization of their barks, which facilitates their differentiation. These anatomical characteristics are essential not just for taxonomic identification, but equally for understanding the functional and ecological adaptations of each species.

However, recent literature highlights that, despite its significant potential in plant systematics, ecology, and conservation, bark anatomy presents notable challenges that limit its broader application. As noted by Li et al. (2024), the fragile nature of bark tissues and the technical difficulties in obtaining high-quality anatomical sections can hinder the generation of reliable data, requiring specialized techniques such as tissue maceration to observe rare features like simple sieve plates. Likewise, Shtein et al. (2023) emphasize that bark anatomy remains less studied than other plant tissues due to methodological gaps and a lack of standardized terminology, calling for advances in both sampling and analytical approaches, as well as greater attention to the ecological and physiological roles of the bark under environmental stress.

In light of these perspectives, our study contributes to a growing body of work that not only demonstrates the usefulness of bark anatomical traits in species identification, but also recognizes the need for methodological refinement and broader ecological integration to enhance the reliability and applicability of such data in forest management and conservation contexts.

4.3 Practical applications for field guides and environmental inspection protocols

Given the valuable insights provided by this study on the anatomical characteristics of tree bark, we propose the following practical approach for utilizing these findings in the field, particularly in combating illegal logging.

In the case of illegal logging activities, it would be beneficial for trained personnel, such as forestry experts and inspectors, to extract bark samples from the stump of a felled tree. These samples should then be transported to a laboratory or carpentry workshop, where the bark can be air-dried. After drying, the cross-sectional surface of the bark should be sanded to obtain a clear macroscopic image. This image can then be compared to the images of bark anatomy from the species studied in this research.

To facilitate the identification process, it would be crucial to develop a database of bark images from commercially important tree species. This database could serve as a reference for field personnel, enabling them to quickly identify the species of a tree based on its bark characteristics. By integrating this bark identification method into existing environmental inspection protocols, it would provide an additional tool for inspectors to confirm the species involved in illegal logging activities.

Incorporating bark anatomical features into field guides and environmental inspection procedures can enhance the effectiveness of monitoring efforts and contribute to the fight against illegal logging. This approach offers a non-invasive and efficient way to identify tree species, particularly in situations where traditional identification methods may be challenging or impractical.

4.4 Limitations of the study

This study focused on the bark anatomy of only three species, which, although providing valuable insights, limits the broader applicability of the findings to other species within the Meliaceae and Lecythidaceae families, or other tropical species in general. Additionally, the sample size was relatively small, and the study did not account for potential variability due to environmental factors or ontogenetic stages, which could affect bark anatomy. Furthermore, as noted in the IAWA List of Microscopic Bark Features (Angyalossy et al., 2016), bark anatomy is inherently challenging due to the combination of both soft and hard tissues within the bark, which complicates preservation, sectioning, and observation. These challenges are particularly notable when dealing with species exhibiting fibrous or dense bark, which can require specific preparation methods, such as maceration, to obtain high-quality anatomical sections.

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Moreover, while the IAWA list offers a comprehensive framework for the study of bark anatomy, it acknowledges that there is still significant variation in the structural details of barks across different species, which has not yet been fully described or coded. Therefore, this list should be viewed as a practical starting point for comparative bark anatomy, and it encourages further research to explore the diversity of bark structures in more detail. The integration of both microscopic and macroscopic bark features would enhance the understanding of the functional and phylogenetic significance of bark anatomy, an area that remains underexplored.

4.5 Future approaches in bark anatomy research

While this study provides valuable insights into the anatomical characteristics of the bark of tropical species, there are several areas that warrant further exploration to enhance our understanding and broaden the applicability of bark anatomical studies.

One important direction for future research is to investigate seasonal variability in bark anatomy. Seasonal changes in environmental factors such as temperature, moisture, and light intensity may influence bark growth, structure, and chemical composition, which could lead to variations in anatomical characteristics across different times of the year. Studies like those by Shtein et al. (2023) emphasize the need to consider environmental stresses and their impact on bark structure, particularly in terms of dilatation and adaptation mechanisms during seasonal transitions.

Another promising avenue is to explore ontogenetic differences in bark structure. As plants mature, significant changes in bark morphology and anatomy can occur. For example, the bark of young plants may differ substantially from that of older individuals due to developmental constraints and functional adaptations over time. Shtein et al. (2023) highlight the need to examine these differences, as bark ontogeny can provide insights into plant growth patterns, mechanical defense strategies, and ecological adaptations.

Additionally, complementary chemical analyses of bark components could provide a more comprehensive understanding of its functional roles. For instance, studies on sesquiterpenoids and other bioactive compounds found in bark tissues, such as those in the Meliaceae family, have revealed their antimicrobial, antioxidant, and antidiabetic properties, which could play a crucial role in the ecological functions of the bark. By combining anatomical data with chemical profiling, future research could establish deeper links between bark structure and its chemical defenses, leading to a more holistic view of the role of bark in species identification and forest management.

Incorporating these approaches will not only deepen our knowledge of bark anatomy but also expand its practical applications in areas such as ecological monitoring, conservation, and the fight against illegal logging.

5. CONCLUSION

In conclusion, the research on the anatomy and physical properties of the bark of *Bertholletia excelsa*, *Cedrela odorata*, and *Eschweilera coriacea* has revealed key differences in their structure and ecological adaptations. While it may seem predictable that different species exhibit distinct characteristics, these specific differences can be crucial for reliable species identification in the field. The observed variability in bark thickness, the presence of fibers and crystals in the phloem, and physical properties like basic density and moisture content are not just taxonomically significant; they also reflect the species' responses to environmental pressures. These anatomical markers can be used as practical tools for species identification, especially in contexts where traditional identification methods are time-consuming or difficult to apply. By providing distinctive and easily recognizable traits, bark anatomy can contribute to the rapid detection of illegal logging activities, ensuring more effective monitoring and enforcement. Moreover, these findings open new avenues for promoting sustainable forest management, as they offer a non-invasive means of assessing the health and status of forest species, facilitating better-informed decisions for conservation and resource management. Therefore, the anatomical study of bark not only enhances our understanding of forest species but also plays a critical role in combating illegal logging and ensuring the sustainability of forest ecosystems.

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AUTHOR CONTRIBUTIONS

L.A.PC.: Conceptualization, Investigation, Data curation, Formal analysis, Writing – original draft, Writing – review & editing. Read and approved the final manuscript; N.MM.: Investigation, Methodology, Validation, Writing – review & editing. Read and approved the final manuscript.

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