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BOTANICAL AND TECHNOLOGICAL CHARACTERIZATION OF *Dendrocalamus strictus* AND *Chusquea bambusoides* SPECIES

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Resumo

Caracterização botânica e tecnológica das espécies Dendrocalamus strictus e Chusquea bambusoides. O bambu vem se estabelecendo como um recurso natural de excepcional relevância no contexto da bioeconomia sustentável, sendo os bambus de colmo maciço de particular interesse tecnológico. Portanto, este estudo teve como objetivo realizar uma caracterização botânica morfológica, complementada por análise densitométrica de raios X, dos colmos de *Dendrocalamus strictus* e *Chusquea bambusoides*, gerando dados comparativos que sirvam de referência para a identificação botânica e para a avaliação de seu potencial de utilização. A caracterização morfológica das espécies de bambu seguiu um protocolo de identificação baseado em uma análise detalhada das partes vegetativas, enquanto a densitometria de raios X foi realizada em amostras da base, do meio e do topo do colmo. *D. strictus* apresentou hábito entouceirante, colmos rígidos com padrão em ziguezague, ramificação agrupada dominante e folhas pilosas. *C. bambusoides* apresentou ramificação aracnoide, folhas glabras e ápice escandente. A densidade aparente transversal média de D. strictus (0,597 g/cm³) foi significativamente superior à de *C. bambusoides* (0,308 g/cm³). Conclui-se que as espécies possuem finalidades distintas*:* *D. strictus* é adequada para aplicações estruturais, enquanto *C. bambusoides* é indicada para painéis leves, artesanato e biomassa, reforçando a complementaridade entre espécies exóticas e nativas no cultivo sustentável de bambu.

Palavras-chave: Bambu maciço, Densitometria de raios X, Morfologia.

Abstract

Bamboo is establishing itself as a natural resource of exceptional relevance within the context of the sustainable bioeconomy, with solid-culm bamboos holding particular technological interest. Therefore, this study aimed to perform a morphological botanical characterization, complemented by X-ray densitometric analysis, of the culms of *Dendrocalamus strictus* and *Chusquea bambusoides*, generating comparative data to serve as a reference for botanical identification and for the evaluation of their utilization potential. The morphological characterization of the bamboo species followed an identification protocol based on a detailed analysis of the vegetative part, while X-ray densitometry was performed on samples from the base, middle, and top of the culm. *D. strictus* exhibited a clumping habit, rigid culms with a zigzag pattern, dominant clustered branches, and pilose leaves. *C. bambusoides* displayed arachnoid branching, glabrous leaves, and a scandent apex. The mean transverse apparent density of *D. strictus* (0.597 g/cm³) was significantly higher than that of *C. bambusoides* (0.308 g/cm³). It is concluded that the species have distinct purposes: *D. strictus* is suitable for structural applications, while *C. bambusoides* is indicated for lightweight panels, crafts, and biomass, reinforcing the complementarity between exotic and native species in the sustainable bamboo cultivation.

Keywords: Solid bamboo, X-ray densitometry, Morphology.

INTRODUCTION

Bamboos belong to the Bambusoideae subfamily, within the Poaceae family, and are classified into three tribes: Arundinarieae, 32 genera (temperate woody bamboos, occurring in the tropics at high altitudes), Bambuseae, 69 genera (tropical woody bamboos, occurring outside the tropics), and Olyreae, 22 genera (herbaceous bamboos) (CLARK *et al.*, 2015).

Bamboo is establishing itself as a natural resource of exceptional relevance within the context of the sustainable bioeconomy. Its cultivation aligns directly with sustainability principles, since, when properly implemented and exploited in the field, it takes advantage of the rapid growth and annual production of culms characteristic of the plant. When managed correctly, the bamboo clump can be used productively for long periods

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in the same location, constituting a renewable source of raw material (PEREIRA *et al*., 2017). To this end, the application of sustainable management techniques is imperative (MACIEL; AFONSO; MIRANDA, 2016).

In the internodes of most bamboos there is the culm wall, which varies in thickness, with very few species having solid internodes, among which *Dendrocalamus strictus* (Roxb.) Nees, *Chusquea* spp., and certain species of the genera *Merostachys* and *Guadua* may be cited (LIESE, 1998; LIESE; KÖHL, 2015. ZHANG *et al*., 2018). Among the species with notable potential, the solid bamboo *Dendrocalamus strictus*, although exotic, exhibits great economic importance in several tropical regions owing to its physical and mechanical characteristics. However, it is essential to equally value native species. In this scenario, the genus *Chusquea* takes on particular relevance in the Brazilian flora, representing about 40% of the neotropical woody bamboo species, with the species *Chusquea bambusoides* Hack., of solid culm, being a native representative with potential that is still little explored (BFG, 2021; SILVA *et al*., 2020).

The anatomical variability among the different bamboo species is a determining factor for their final applications. The dimensions and proportions of structural elements such as fibers, vessels, and parenchyma directly influence the physical and mechanical properties, defining the suitability of the raw material for specific uses (RUSCH; CEOLIN; HILLIG, 2019). Therefore, detailed studies of anatomy and physical properties—such as apparent density—are fundamental to characterize the material and define its technological potential (PRATES *et al.,* 2018).

Given the need to expand knowledge about native species such as *C. bambusoides*, and considering the scarcity of detailed information about its anatomy and physical properties compared with the exotic *D. strictus*, the hypothesis of this study is that the two species, despite sharing the characteristic of solid culms, possess significant morpho-anatomical and densitometric differences that direct their technological applications toward distinct purposes. Thus, the objective was to carry out a morphological botanical characterization, complemented by X-ray densitometric analysis, of the culms of *D. strictus* and *C. bambusoides*, in order to generate comparative data to serve as a reference for botanical identification and for the evaluation of their technological utilization potential.

MATERIAL AND METHODS

Collection area

The samples of *C. bambusoides* were collected on a rural property located in the Bela Vista do Sul District, in the municipality of Mafra, in Santa Catarina (Figure 1 B). The region's climate is of the humid subtropical type, with a mean annual temperature ranging from 16 °C to 18 °C and mean rainfall of 1600 to 1700 millimeters; the local altitude varies between 800 and 900 m above sea level and the relief is formed by slightly excavated valleys and gently undulating surfaces (INMET, 2021; EPAGRI, 2003).

The samples of *D. strictus* were collected in the vegetable garden of the Campus of the Federal University of Acre, Rio Branco, Acre (Figure 1 A). A region of humid tropical climate, according to the Köeppen classification, with a mean annual temperature between 26 and 27 °C (INMET, 2021; ALVES; MARENGO, 2010). The relief of the municipality of Rio Branco, Acre is considered quite homogeneous, without major altimetric variations, ranging from 200 m to 300 m in altitude. The soils vary in fertility, with predominance of Ultisols (Argissolos) (BRASIL, 2018 and ACRE, 2010).

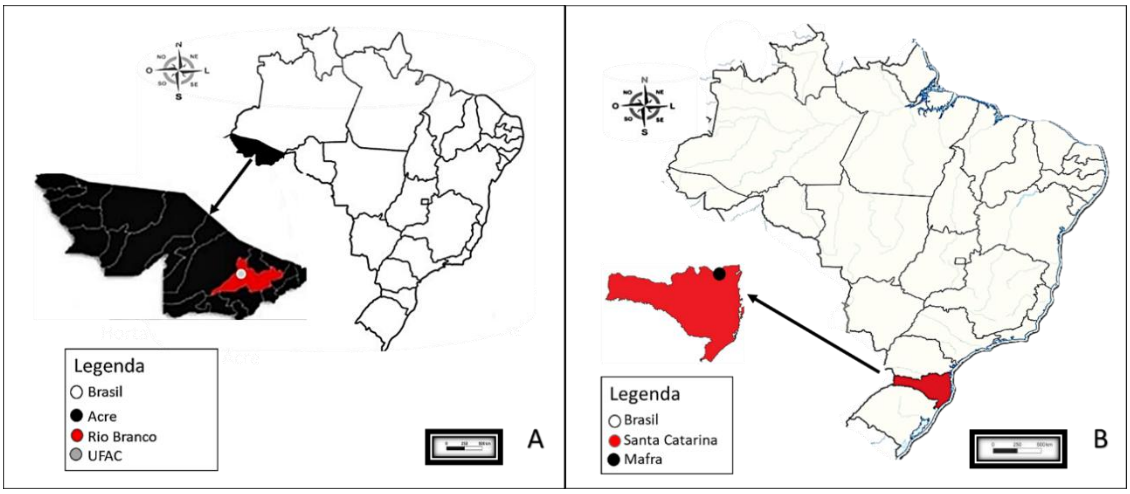

Figure 1 - Collection site of the samples of *Chusquea bambusoides* (A) and *Dendrocalamus Strictus* (B).
Figura 1 - Local de coleta das amostras de *Chusquea bambusoides* (A) e de *Dendrocalamus Strictus* (B).

Taxonomic Identification and Collection Procedures

The taxonomic identification of the individuals of *C. bambusoides* and *D. strictus* was carried out through a comparative analysis of vegetative botanical characters, using specialized identification keys: Shirasuna; Oliveira (2016) and Clark *et al*. (2020) for the first species; and BFG (2021) and Filgueiras (2015) for the latter. For documentation and the creation of a reference database, digital photographic records of the vegetative structures were made, aiming to support the botanical morphological confirmation of the species.

The collection of mature culms (> 3 years) was carried out with a Japanese saw, adopting specific criteria for each species. For *D. strictus*, culms with a yellowish-green coloration were chosen, located in the interior of the clump, devoid of culm leaves and with the presence of lichens on the epidermis of the culm. For *C. bambusoides*, maturity was determined by the tonality of the culm epidermis, of a grayish olive-green color, the absence of culm sheaths, and the incidence of lichens.

The botanical material (leaves and branches) was herborized according to standard techniques, involving field pressing and drying in a forced-ventilation oven to obtain dehydrated exsiccate free from deformations. Each sample was labeled with complete metadata: collector identification, date, georeferencing, municipality, state, phytophysiognomy, substrate, habit, and life form, for subsequent incorporation into the collection of the UFAC Herbarium; the *Chusquea bambusoides* species under the number UFACPZ 29911 and the *Dendrocalamus Strictus* species under the number UFACPZ 36809. The mature culms were sectioned for the preparation of test specimens, which were destined for X-ray densitometry analyses, subsequent.

X-ray densitometry

The culms of each species were collected and taken to the Wood Anatomy Laboratory - LabMad, of the Center for Biological and Natural Sciences - CCBN, at the Federal University of Acre – UFAC, where they were cut in their cross section with an approximate dimension of 5 cm in length and with a culm diameter corresponding to the position from which it was taken, totaling 27 test specimens from 3 culms of the bamboo *C. bambusoides* and of *D. strictus* at adult age, taken from the base (9 test specimens), middle (9 test specimens), and top (9 test specimens) sections.

The samples were sent to the Laboratory of Wood Anatomy and Identification – LAIM, of the Luiz de Queiroz College of Agriculture (ESALQ/USP), where they were subjected to a precision metallographic cutting machine intended for sectioning the samples, using diamond cutting discs that provide low deformation of the samples, cut in the transverse direction, generating test specimens with a final dimension of approximately 1 mm in thickness. For more accurate results, the test specimens were subjected to thickness measurement with a caliper.

The cross sections of the culm were conditioned in a climate-controlled chamber for 24 hours, at a temperature of 20 °C and relative humidity of 60% until they reached a moisture content of 12% (TOMAZELLO FILHO *et al.*, 2018). After acclimatization, the samples were scanned in the Faxitron MX20-DC12 equipment (Faxintron X-Ray, Illinois, USA), in which they were irradiated for 3 seconds, to obtain the radial profile of the apparent density of the transverse part of the culm, according to the X-ray densitometry method. For this technique, it was necessary to perform a calibration, which consists of inserting, together with the samples, a cellulose acetate calibration wedge into the X-ray equipment, to start the operation and automatic reading (30Kv/19 seconds) of the samples together with the wedge, generating the digital images, which were saved in TIFF (Tagged Image File Format).

The images saved in TIFF format were analyzed in the WinDRENDRO© software, where, based on the analysis of the images, it was possible to obtain information about the transverse variation profile and the mean apparent densities (Figures 2 A - B). Immediately afterward, the specific values of apparent microdensity were determined in the transverse direction of the culm (inner, intermediate, and outer areas) and at three positions in the longitudinal direction of the culm (base, middle, and top).

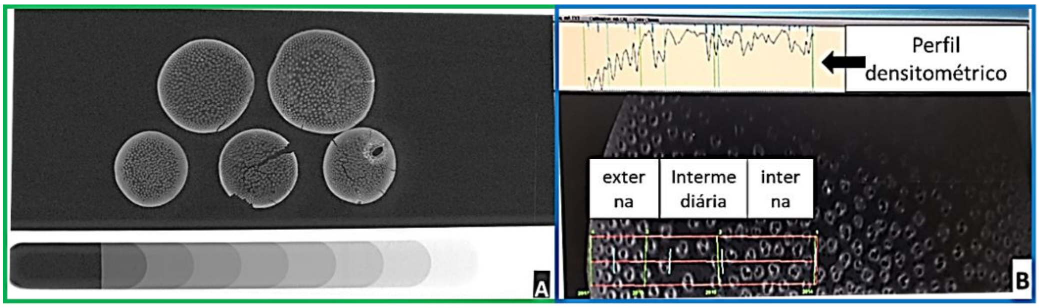

Figure 2 - Images TIFF-format depicting the cellulose acetate calibration wedge (A) and the bamboo culm radiograph analyzed using WinDENDRO software, showing the transverse profile of mean apparent density variation (B)

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Figura 2 –Imagens em formato TIFF mostrando a cunha de calibração de acetato de celulose (A) e a radiografia do colmo de bambu analisada no software WinDRENDRO exibindo o perfil de variação transversal das densidades aparentes médias (B)

Statistical analysis

Before applying the ANOVA, the assumptions of normality of the residuals were verified by the Shapiro-Wilk test ($p > 0.05$), the homogeneity of variances was assessed by the Levene test ($p > 0.05$), and the independence of observations was ensured by the completely randomized design, with samples collected from different culms and longitudinal positions of the bamboo. All assumptions were met, allowing the use of parametric tests, and the means were compared by the Tukey test ($p < 0.05$), using the R software version 3.5.1 (R CORE TEAM, 2018).

RESULTS

Morphological characterization

C. bambusoides presented a pachymorph rhizome and culms 2-10 m high, with a scandent apex. The internodes are cylindrical and solid (22-33 cm). The branching is infravaginal, with complementary branches arranged in an arachnoid pattern (Figures 3(1) A). The sheaths are persistent, glabrous, and the leaves are oblong-lanceolate and glabrous on both faces, with an inner ligule length of 0.4 to 0.6 mm, membranous with a ciliolate apex; outer ligule absent (Figures 3(1) A-F). The culms measure 2-10 m in height, with a scandent apex, and the internodes are cylindrical and solid with thin walls (Figures 3(1) G and H).

Figure 3 - Morphological characterization of *Chusquea bambusoides* (1). *Dendrocalamus strictus* (2)
Figura 3 – Caracterização morfológica de *Chusquea bambusoides* (1) e *Dendrocalamus strictus* (2).
Legend (1) - A- Branch with an arachnoid appearance; B- Culm sheath; C – Detail of the color and roughness of the sheath, D - Leaves and pseudopetiole, E- Lanceolate to oblong-lanceolate leaf blade F- Detail of the inner ligule (green arrow and white circle), G – culm size and H – diameter and thickness of the culm wall.
Legend (2): A- length of the sheaths, B – Details of the rigid hairs on the back of the sheath; C- detail of the ligule with a triangular, awl-shaped blade; D – Grouped branches with a larger dominant branch; E Details of the roughness of the leaf tip. F – Detail of the leaf ligule. G – zigzag of the culm and H – aerial roots and I- diameter and thickness of the culm wall.

D. strictus exhibited a clumping habit, with variable culm sheaths, the lower ones shorter, measuring 8 to 30 cm in length with rigid golden-brown hairs on the back, sometimes glabrous, striated, rounded at the top, with a pilose margin; ligule 2 to 3 mm high, dentate; small auricles, triangular, awl-shaped blade, pilose on both sides

(Figures 3 (2) A-C). Leaf branching occurs at multiple nodes, with grouped branches and a dominant one. Small linear-lanceolate leaves up to 25 cm long and 3 cm wide, rounded at the base into a short petiole, sharply acuminate tip with a twisted point, rough and often pilose above and softly pilose beneath; very short ligule (Figures 3 (2) D-F). Its culms measure from 8 to 20 m tall and 2.5 to 8 cm in diameter. The internodes are 30 to 45 cm long and have thick, almost-solid walls. The culms may present a slight zigzag and aerial roots (Figures 3 (2) G-I).

X-ray densitometry

The mean transverse apparent density of *C. bambusoides* was 0.308 g/cm³, significantly lower than that of *D. strictus*, which was 0.597 g/cm³. The results showed mean apparent density values of 0.302, 0.288, and 0.335 g/cm³ for *C. bambusoides*, and of 0.537, 0.576, and 0.678 g/cm³ for *D. strictus*, respectively, in the longitudinal direction of the base, middle, and top of its culm (Figure 4).

For *C. bambusoides*, the apparent density in the outer region of the culm was significantly higher ($p<0.05$) than those of the inner and intermediate regions in all longitudinal positions analyzed (base, middle, and top), as illustrated by the transverse densitometric profile (Figure 5A).

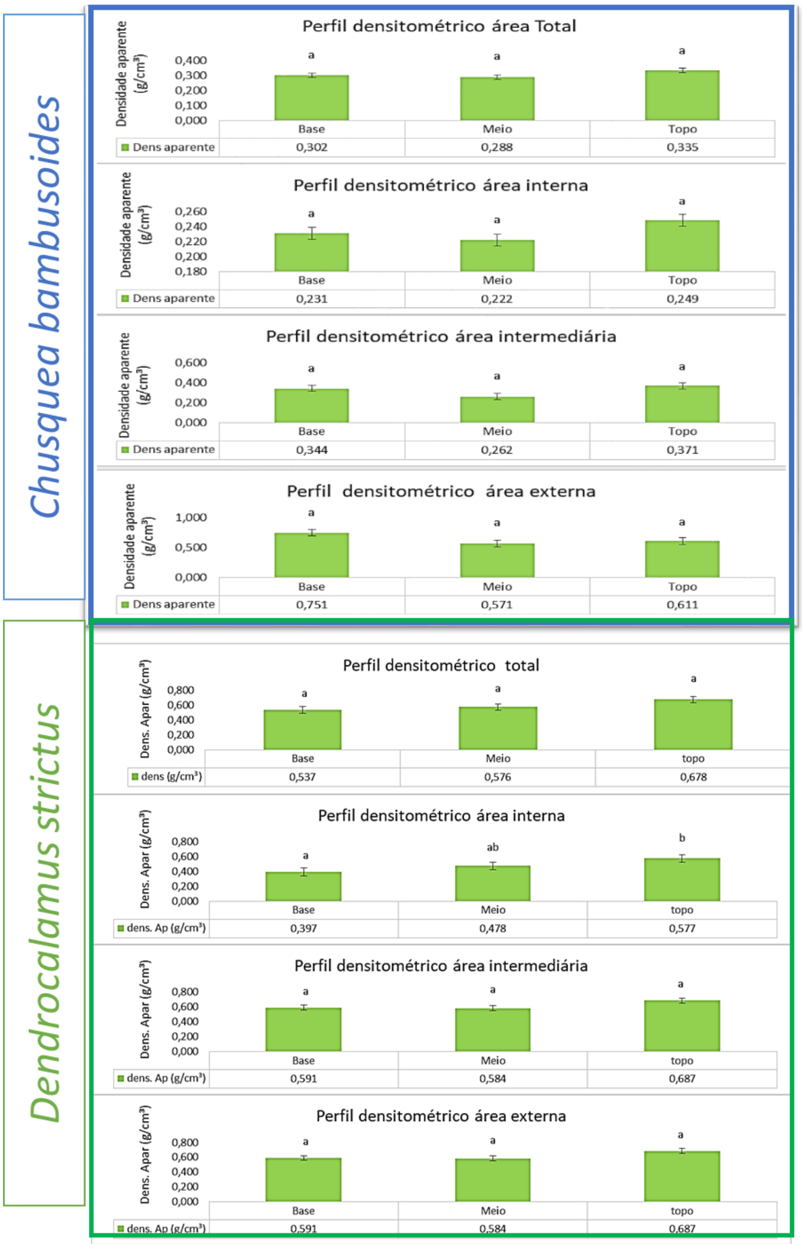

Figure 4 – Transverse densitometric profile of *Chusquea bambusoides* and *Dendrocalamus strictus* culm samples at the different longitudinal positions of their culm (base, middle and top).
Figura 4 – Perfil densitométrico transversal das amostras do colmo de *Chusquea bambusoides e Dendrocalamus strictus* nas diferentes posições longitudinais do seu colmo (base, meio e topo).

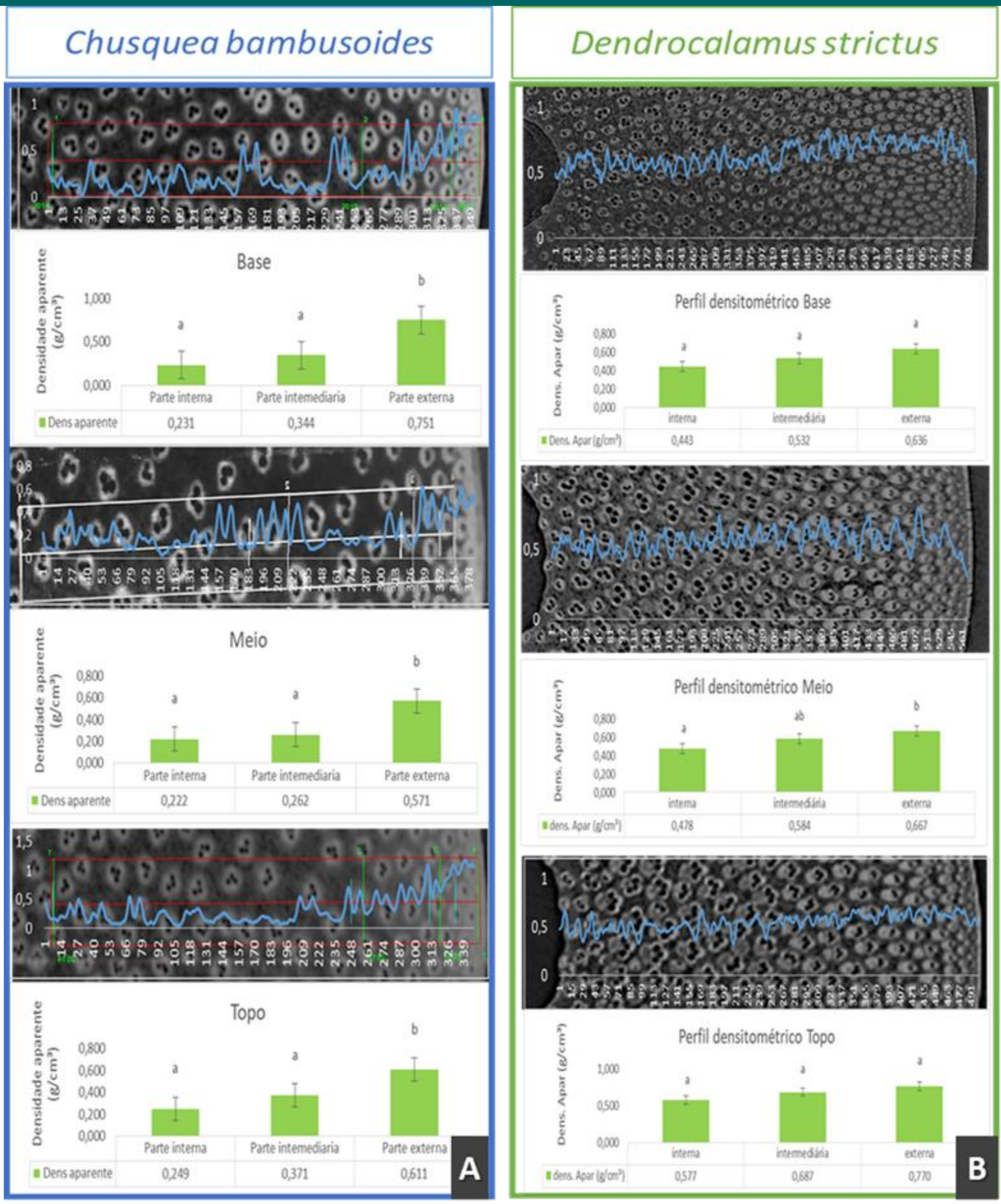

Figure 5 - Transverse densitometric profile of *Chusquea bambusoides* (A) and *Dendrocalamus strictus* (B) samples at the three longitudinal positions of their culm (base, middle and top).
Figura 5 – Perfil densitométrico transversal das amostras de *Chusquea bambusoides*(A) e *Dendrocalamus strictus* (B) nas três posições longitudinais do seu colmo (base, meio e topo).

Upon analyzing the densitometric profile in the transverse direction of *C. bambusoides* and *D. strictus* culms, we verified significant differences in the Tukey test ($p<0.05$) between the outer area, the inner area, and the intermediate area; only the outer area did not present a significant difference with the other positions (Figure 6).

Figure 6 – Comparison of the transverse densitometric profile of *Chusquea bambusoides* and *Dendrocalamus strictus* samples across the three transverse areas of their culms (inner, intermediate and outer) and across the entire transverse area.

Figura 6 – Comparação do perfil densitométrico transversal das amostras de *Chusquea bambusoides e Dendrocalamus strictus* nas três áreas do sentido transversal dos seus colmos (interna, intermediária e externa) e em toda a área transversal.

The observation of the transverse densitometric profiles revealed significant structural differences between the culms. The apparent density values of *C. bambusoides* were significantly lower than those of *D. strictus* in the inner (0.234 vs. 0.484 g/cm³) and intermediate (0.326 vs. 0.621 g/cm³) regions ($p<0.05$), indicating a greater proportion of parenchymatous tissue. However, in the outer region, the densities were statistically similar (0.644 vs. 0.687 g/cm³, $p>0.05$), reflecting a comparable concentration of fibrous elements in this layer (Figure 7).

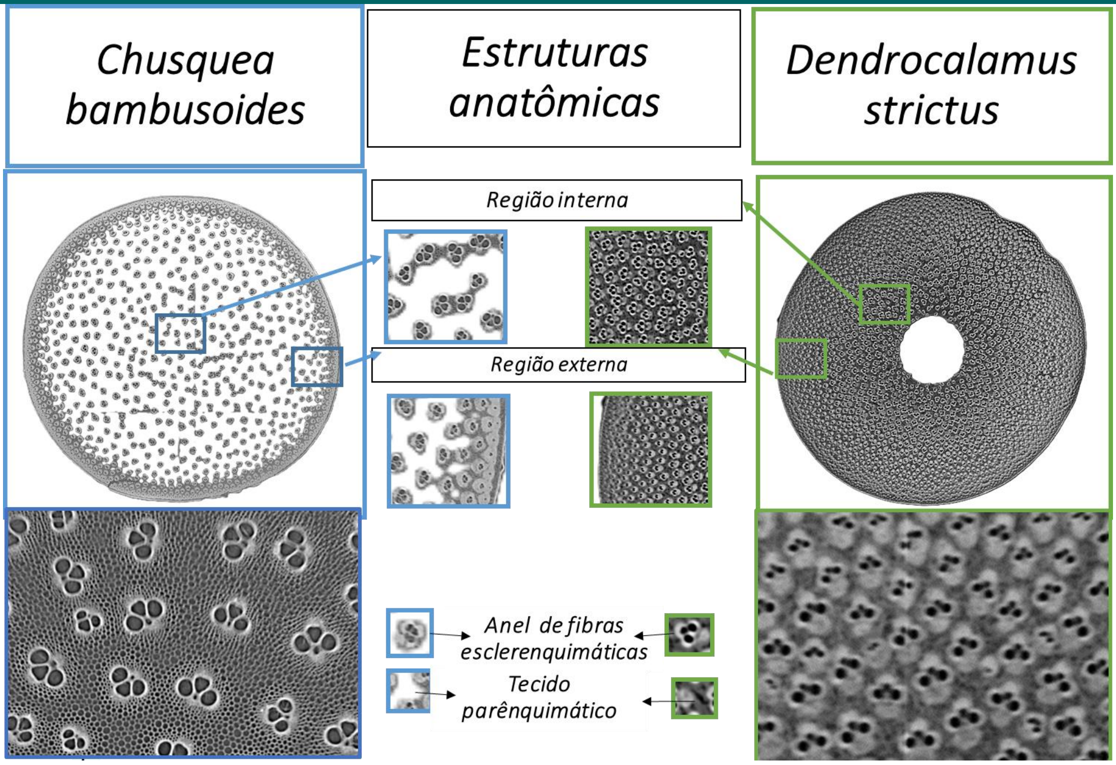

Figure 7 – Comparative analysis of the transverse radiographic images of *Chusquea bambusoides* and *Dendrocalamus strictus* culms, highlighting the distribution of anatomical structures

Figura 7 – Comparação das imagens radiográficas transversais dos colmos de *Chusquea bambusoides* e de *Dendrocalamus strictus* destacando a distribuição dos elementos anatômicos.

DISCUSSION

The comparative morphological analysis between *Chusquea bambusoides* and *Dendrocalamus strictus* reveals significant differences with important taxonomic and ecological implications. *D. strictus* presents a clumping habit, erect and rigid culms with occasional zigzag curvature, branches clustered under a dominant branch, and short, pilose lower sheaths (FILGUEIRAS; SANTOS-GONÇALVES, 2004; FILGUEIRAS, 2015), characteristics typical of woody bamboos adapted to seasonal tropical climates. In contrast, *C. bambusoides* exhibits culms with a scandent apex, a complementary arachnoid branching pattern, a diagnostic synapomorphy of the genus Chusquea, persistent and glabrous sheaths, and completely glabrous oblong-lanceolate leaves (SHIRASUNA; OLIVEIRA, 2016; CLARK *et al.*, 2020), reflecting adaptation to shaded and humid forest understories. From a taxonomic standpoint, these vegetative characters are diagnostic and consistent with the literature (FILGUEIRAS, 2015; SHIRASUNA; OLIVEIRA, 2016).

Functionally, the morphological differences guide distinct technological applications: the rigidity of *D. strictus* makes it suitable for construction and bioenergy, whereas the scandent habit of *C. bambusoides* suggests potential for slope bioengineering (PRATES *et al.*, 2018; RUSCH *et al.*, 2019). Thus, these distinctions are essential for the valorization of native species within the context of the bioeconomy (PEREIRA *et al.*, 2017; MACIEL *et al.*, 2016).

The densitometric results reveal a critical difference in the anatomical organization of the culms. The significantly higher density of *D. strictus* indicates a higher proportion of lignified vascular bundles (fibers), conferring upon it greater rigidity and mechanical resistance (LIESE, 1998; LIESE; KÖHL, 2015, CHAUDHARY *et al.*, 2019). This characteristic supports its consolidated uses in structural applications, such as civil construction and high-density composites (GHAVAMI; GARCIA, 2017; MACIEL *et al.*, 2016). This discrepancy is indicative of a higher parenchyma-to-fiber ratio within the inner cortex of *C. bambusoides*. Parenchyma, being a less dense filling tissue, compromises the strength and mechanical rigidity of the material (RUSCH *et al*., 2019). On the other hand, the high apparent density in *D. strictus* suggests a greater concentration of lignified vascular bundles, comprising dense sclerenchymatic fibers and vessel elements, which collectively confer superior rigidity and load-bearing capacity on the culm of this species (LIESE, 1998 CHAUDHARY *et al.*, 2019; MARASIGAN *et al.*, 2024).

In contrast, the outer radial region demonstrates a convergence in apparent density between the species *C. bambusoides* and *D. strictus*, with mean values of 0.68 g/cm³ and 0.70 g/cm³, respectively. This similarity is attributable to the presence of a peripheral ring of high-density sclerenchymatic fibers, an anatomical adaptation common in bamboos that serves as a primary structural reinforcement against bending and buckling stresses (ZHANG *et al*., 2018; CHAUDHARY *et al*., 2019). However, a critical morphological distinction lies in the relative thickness of this fibrous envelope. In *C. bambusoides*, this dense outer layer is narrower, thereby limiting its contribution to the overall mechanical integrity of the culm cross section in comparison with the more robust and wider fibrous zone in *D. strictus*.

The most revealing comparative metric is the mean transverse apparent density of the entire cross-sectional area; with a value of 0.308 g/cm³, *C. bambusoides* presents an apparent density 48% lower than that of *D. strictus* (0.597 g/cm³). This substantial difference quantitatively confirms the fundamental anatomical disparity between a species with a parenchyma-rich matrix and another with a predominantly fibrous structure (CHAUDHARY *et al*., 2019; PRATES *et al*., 2018; MARASIGAN *et al*., 2024). These divergent densitometric profiles have direct and significant implications for the practical use of both species, since density is a primary predictor for industrial applications. It exhibits strong positive correlations with mechanical properties, such as compressive and bending strength, modulus of elasticity, hardness, and natural durability, all of these being critical parameters for the performance of lignocellulosic materials in engineering applications (LIESE, 1985).

Consequently, applications for high-density bamboos, such as *D. strictus*, are well established in sectors that demand high performance. Its superior mechanical properties (density > 0.6 g/cm³) make it highly suitable for structural applications in civil construction, including columns, beams, and truss systems, and its apparent density and stability lend themselves to the production of high-durability flooring and cladding (GHAVAMI; GARCIA, 2017, CHAUDHARY *et al*., 2019). Beyond solid applications, *D. strictus* fibers serve as an excellent reinforcement in high-density composite materials, such as medium-density fiberboard (MDF) panels and other engineered panels, providing a sustainable alternative to traditional wood sources (MACIEL *et al*., 2016, GHAVAMI; GARCIA, 2017).

In stark contrast, the intrinsically low density of *C. bambusoides* (0.308 g/cm³) inherently restricts its use in high-strength and load-bearing applications where *D. strictus* excels. Therefore, its valorization must be strategically aligned with niches that leverage its specific characteristics. Its low density is advantageous for the manufacture of lightweight panels intended for non-structural purposes, such as interior partitions, furniture cores, and plywood, where minimizing weight is a priority (SULASTININGSIH *et al*., 2020). Its flexibility and workability make it an ideal resource for crafts, decorative items, and products (SHIRASUNA; OLIVEIRA. 2016). Additionally, its rapid growth cycle and low apparent density position it favorably for the production of energy biomass, including charcoal and fuel pellets (PEREIRA *et al*., 2017).

Although C. bambusoides cannot replace D. strictus in structural functions, its true potential lies in sustainable, context-specific niches that align with ecological and socioeconomic objectives. As a species endemic to the Atlantic Forest, *C. bambusoides* is already ecologically adapted to slopes and disturbed areas, making it a first-rate candidate for use in the rehabilitation of degraded land(ZAPPELINI, 2017). Moreover, its cultivation and transformation into low-impact, value-added products, such as handicrafts, can stimulate local economies and generate income for rural communities. This approach is perfectly aligned with the principles of a circular bioeconomy, promoting the sustainable use of local native biodiversity (MACIEL *et al*., 2016).

CONCLUSIONS

- Despite the morphological similarity of possessing solid culms, the densitometric analyses reveal profound anatomical differences: *D. strictus* is characterized by a dense, homogeneous matrix of lignified fibers, whereas *C. bambusoides* exhibits a predominantly parenchymatous structure. Thus, the industrial applications established for high mechanical performance bamboos of *D. strictus* in construction and advanced composites are not directly transferable to low-density species such as *C. bambusoides*.
- The effective use of native species, such as *C. bambusoides*, requires the identification and development of alternative applications that capitalize on their unique attributes: low density, flexibility, and local availability. This reinforces the need for management policies, forestry practices, and technological development pathways specific to each species within sustainable bamboo cultivation strategies.
- The complementarity between high-density exotic species for structural uses and low-density native species for lightweight and ecological applications underscores a holistic and diversified approach to the use of this renewable, ecological resource with great capacity for carbon accumulation from the atmosphere.

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