e-ISSN 1983-4063 - *www.agro.ufg.br/pat* - Pesq. Agropec. Trop., Goiânia, v. 55, e81998, 2025

Review Article

Typological classification of bamboo: from the advent of microscopy to artificial intelligence[1]

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ABSTRACT

Many bamboo species are used as lignocellulosic raw materials for different purposes; therefore, their correct classification is necessary. A bibliographic survey on the stem anatomy of various bamboo species was carried out to better characterize their anatomical structural differences, with special attention to the description of the evolutionary process of the vascular bundles typological classification. Analyzes carried out since the emergence of electron microscopy to the innovative use of artificial intelligence were considered, as well as collected information on the morphological characterization and anatomy of species, with emphasis on the classification patterns of fibers, parenchyma cells, sclerenchyma sheath and conducting/vascular channels (xylem and phloem), which can be used by artificial intelligence tools to speed up and qualify the correct identification of genera and species. Anatomical differences make it possible to classify the material, with the most relevant aspects being the shape of the vascular bundle, as well as the fibers distribution and content.

KEYWORDS: Monocotyledons, fibrovascular bundles, lignocellulose.

RESUMO

Classificação tipológica de bambu: do advento da microscopia à inteligência artificial

Muitas espécies de bambu são utilizadas como materiais primários lignocelulósicos para diferentes fins, o que requer a sua correta classificação. Uma revisão bibliográfica da anatomia de caules de variadas espécies de bambu foi efetuada para melhor caracterizar as suas diferenças estruturais anatômicas, com especial atenção para a descrição do processo evolutivo da classificação tipológica dos feixes vasculares. Foram consideradas análises realizadas desde o surgimento da microscopia eletrônica até o uso inovador da inteligência artificial, bem como coletadas informações sobre a caracterização morfológica e anatomia de espécies, com ênfase nos padrões de classificação de fibras, células de parênquima, bainha de esclerênquima e canais condutores/vasculares (xilema e floema), que podem ser utilizadas por ferramentas de inteligência artificial para agilizar e qualificar a correta identificação de gêneros e espécies. Diferenças anatômicas permitem classificar o material, sendo os aspetos mais relevantes a forma do feixe vascular e a distribuição e o teor de fibras.

PALAVRAS-CHAVE: Monocotiledôneas, feixes fibrovasculares, lignocelulose.

INTRODUCTION

Bamboos belong to the angiosperm group, which includes monocotyledonous plants classified in the Poaceae (Gramineae) family, Bambusoideae subfamily, and is divided into two tribes: Olyreae (herbaceous) and Bambuseae (lignified) (Silveira et al. 2017).

It is a significant non-timber forest product (Ma et al. 2023), which has in its stem bast-woody bundles, that is, vascular bundles of primary phloem (bast) and vascular tissue of primary xylem, surrounded by parenchyma cells (Rusch et al. 2018, Depuydt et al. 2019). Some authors consider bamboos to be natural nanocomposites, formed by multinodes and different functional structures at the microscopic and macroscopic levels, with internodal cells growing in a defined arrangement from end to end (Imadi et al. 2014, Akinlabi et al. 2017, Mousavi et al. 2022, Amjad 2024). They have also been

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[1] Received: Mar. 03, 2025. Accepted: Apr. 28, 2025. Published: June 16, 2025. DOI: 10.1590/1983-40632025v5581998.

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Editor: Luis Carlos Cunha Junior

defined as a biocomposite material reinforced with fibers, formed mainly by cells with thick and highly dense walls, arranged in a unidirectional direction, an essential condition for its resistance capacity (Gao et al. 2022).

In morpho-anatomical terms, bamboo is a biocomposite comprised of three fundamental tissues: epidermis, vascular bundles surrounded by supporting fibers and parenchyma cells (Youssefian & Rahbar 2015).

The characterization and classification of the bamboo anatomical structures began in the 1950s, with the renowned researcher Walter Liese, who was a pioneer in electron microscopy, initially focusing on fine structural details of cell walls in woody tissue of different wood species, and, later, of varying bamboo species (IAWS 2023). Its diagnostic description is restricted to the cross section, since no specific characteristics exist in the radial and tangential sections (Grosser & Liese 1971). This anatomical characterization made it possible to determine that most of it consists of vascular bundles embedded in a matrix of parenchyma cells. Vascular bundles are tissues arranged in a longitudinal direction and comprise metaxylematic vessels (responsible for transporting nutrients and water) and sclerenchyma fiber sheaths, constituting the central supporting element determining its mechanical characteristics (Rusch et al. 2018). Parenchyma cells occupy the remaining space, a filling tissue, which assumes the function of a matrix, providing stability to the fibers and transmitting load among them (Akinbade & Harries 2021).

According to Xu et al. (2022), bamboo vascular bundles are the reinforcement and transfusion tissues in the longitudinal direction of the plant formed by the primary phloem, cambium and primary xylem, which provide rigidity to the material. In contrast, the parenchyma is made up of thin-walled cells, with the function of a composite matrix, which contributes little to the rigidity of the stem. The bamboo stem's mechanical properties depend on its components' volumetric fraction and the distribution of the sclerenchyma fibers, in addition to the interface properties of its various components. The development of computer technology, computer vision and digital image processing makes it possible to intelligently identify and classify plants by extracting morphological or anatomical characteristics of plants (Sun et al. 2017, Kaya et al. 2019, Wang et al. 2023). Due to the rapid progress of computational and processing technology, deep learning algorithms have emerged for application in recognition and classification in the field of wood science (Yusof et al. 2013, Kobayashi et al. 2015, Kobayashi et al. 2017, Hwang et al. 2018, Hwang et al. 2020, Xu et al. 2021), which have evolved for application in different bamboo species (Li et al. 2021, Xu et al. 2021, Xu et al. 2022, Li et al. 2023, Wang et al. 2023).

The thickness of the fibers' cell wall varies along the height of the bamboo stem, and, as a result, their physical and mechanical properties differ from one extreme to the other, what can cause additional difficulties when using this material. Thus, this study aimed to compile information from the literature regarding the morphological characterization and anatomy, i.e., the classification of fibers, parenchyma cells, sclerenchyma sheath and conducting/vascular channels (xylem and phloem), of bamboo species, considering mainly the historical evolution of the typological classification process of vascular bundles, from the emergence of electron microscopy to the innovative use of artificial intelligence.

TAXONOMY AND DISTRIBUTION

Bamboos present distinct sizes among different species, from non-lignified herbaceous plants, a few centimeters in height, to medium and large woody bamboos, which can reach more than 20 cm in diameter and 30 m in height (Miranda et al. 2017). According to records from the Royal Botanic Gardens of Kew (RBGK 2024), there are 139 genera, with 1,821 species scattered worldwide. They are classified into three tribes: i) Arundinarieae (37 genera and 618 species) - temperate bamboos, although some occur at high elevations in the tropics; ii) Bambuseae (79 genera and 1,058 species) - tropical bamboos, although some occur outside the tropics; iii) Olyreae (23 genera and 145 species) - herbaceous bamboos.

With a large occurrence area, bamboos are found in temperate, subtropical and tropical regions of Africa, America, Asia and Oceania, in a latitudinal range from 51ºN in Japan to 47ºS in Argentina, from sea level to 4,000 m above the sea level. Interestingly, herbaceous bamboos are not observed at altitudes above 1,500 m (Yeasmin et al. 2015). In Latin America, more than 400 species have been identified, a diversity lower than the estimates in Asia, but higher than that in Africa (Canavan et al. 2017). In Brazil, 258 native species have been described to date (of which 175 species in 12 genera are considered endemic) and are divided into two tribes: i) Olyreae (herbaceous) in 17 genera and 93 species; ii) Bambuseae (woody with lignified culms) in 18 genera and 165 species (Filgueiras & Viana 2017). For Canavan et al. (2017), the total number of species, considering native, introduced and invasive species, is over 400 in Brazil; whereas, for Kadivar et al. (2024), there are 316 species from 52 genera. However, the most remarkable bamboo diversity in a country is found in China, with almost 700 species, although the occurrence area tends to increase, since many species are quickly introduced into other regions, occupying various ecological niches (Panda 2011, Hakeem et al. 2015).

MORPHOLOGICAL CHARACTERISTICS OF BAMBOOS

Unlike most lignocellulosic plants, bamboo does not have a trunk, but rather a set of stacked culms that form a stem (Rusch et al. 2018). The most important structural components are the roots, rhizomes, culms, branches and leaves, being rhizomes and culms the most studied ones. Rhizomes are the underground stems of bamboo, with the function of anchoring and capturing, transporting and storing nutrients (Li et al. 2024), in addition to enabling its vegetative reproduction, being able to convert into a new rhizome or lateral sprouting. The composition of its tissues comprises, on average, 18 % of conductive tissues forming xylem and phloem, 20 % of fibers and 62 % of parenchyma cells. When well developed, the rhizomes are quite branched, having a structural function. Anatomically, they are different from culms; however, they are similar in their subdivision into nodes and internodes, although they are shorter and have a smaller diameter (Nayak & Mishra 2016).

For Long et al. (2023), the root system is categorized into four main types, due to the position of development: i) primary, resulting from the embryonic roots; ii) derived from knots of the rhizome; iii) derived from the stalk, which occur at the base of the stalk; and iv) derived from the shoot, at the stem nodes or branch bases. The importance of rhizomes is related to the type of growth, with the two central branching systems/patterns being called pachymorphic (sympodial or clumping) or leptomorphic (monopodial or spreading). Leptomorphic species often present tyloses in vascular bundles in the intercellular space between the two metaxylem vessels, whereas this does not occur in pachymorphic species. Thus, tyloses can be a diagnostic characteristic (Grosser & Liese 1971).

The most noteworthy and remarkable structure in bamboo plants is the above-ground culm, characterized as a cylindrical and hollow tube, with an erect, semi-arched or arched shape (Chaowana 2013, Liese & Tang 2015). The number of culms found in a single bamboo stem is varied, and there is also variation in the length of the internode depending on the species, generally being more significant in the intermediate portion (Rusch et al. 2018). An important characteristic is the thickness of the walls, as they significantly impact the mechanical properties (Banik 2015, Nayak & Mishra 2016). In the culm wall, the parenchyma fraction of the tissue decreases with increasing stem height, while the number of vascular bundles undergoes slight variations (Banik 2015, Nayak & Mishra 2016). Thus, from the base to the top, a reduction in both the diameter and wall thickness of the culm is noticeable, resulting from the lower proportion of parenchyma cells, which provides an increase in density in the most apical regions (Liese & Tang 2015, Okahisa et al. 2018). Although the anatomical structure of bamboo culms is generally uniform, there are minor variations among species, indicating different uses.

Bamboo plants have a structure completed by the shoot system, composed of branches and leaves. According to Banik (2015) and Nayak & Mishra (2016), there are two types of leaves: i) culm sheath, or cauline leaf, which is a modified, provisional, large and rigid leaf, which falls off as the bamboo transforms into a mature individual; and ii) green leaf, which has a covering structure, occurs in adult individuals that have already lost their cauline leaves. The cauline leaf protects the bamboo shoot from its initial growth until adulthood.

To aid in species identification, it is recommended to analyze the region around the fifth node of the culm, or between 150 and 200 cm above the ground level (Banik 2015). This location contains typical characteristics, such as combinations involving the auricle, bristles and ligules, essential traits for species identification, like colors. Auricles and bristles may or may not be present. If present, these structures are located on each side of the edges, both in stem sheaths and in the green foliage of adult bamboos. The ligule is located internally between the auricles and bristles on each side of the sheath.

ANATOMICAL CHARACTERISTICS OF CULMS AND STRUCTURES OF BAMBOO FIBER

Bamboos have remarkable characteristics, such as exclusive primary growth, elongated structures, dimensional stability and high mechanical strength. The external anatomical structure of bamboo culms consists of a layer of cutin (rich in silica) and wax, protecting against animal attacks (Habibi & Lu 2014). Silica is predominantly concentrated in the superficial layer of the outer epidermis of bamboo culms (Yin et al. 2016). The epidermis is the outer wall of the bamboo that has the function of environmental protection for the plant, and is formed by a thin, dense, smooth, waxy layer rich in silica (Sá et al. 2023). Internally, the structure of its tissues is organized into fibrovascular bundles and parenchymal cells (Liese 1980, Liese 1985, Liese 1998, Nayak & Mishra 2016, Rusch et al. 2018, Kalali et al. 2019, Li et al. 2021, Sun et al. 2022), and the fibers and sclerenchyma cells hinder the lateral movement of liquids, but allow for increased resistance. The chemical composition of bamboo fibers is a mixture of lignin, cellulose and hemicellulose (Mousavi et al. 2022). In most species, 10-15 % of the fibers are concentrated in the inner area of the culm wall, and 60 % in the region close to the outer layer (Janssen 2000, Akinbade & Harries 2021).

The fiber cell wall has a direct influence on its mechanical performance. In these fibers' structure, cellulose microfibrils are found in a matrix of intertwined hemicellulose and lignin called lignin-carbohydrate complex (Youssefian & Rahbar 2015). For Amjad (2024), the constituent's cellulose, hemicellulose and lignin represent between 60-70, 20-30 and 20-30 %, respectively. Rusch et al. (2018) emphasize that the fibers can be considered light, rigid and resistant, characteristics that positively influence the physical-mechanical resistance of materials produced from bamboo fibers. An in-depth review of the multi-scale structures of bamboo fiber (cell wall layers and microfibrils) is presented in Gao et al. (2022), considering studies by Preston & Singh (1950), Parameswaran & Liese (1976), Wai et al. (1985) and Liu (2008). Preston & Singh (1950) determined, using polarizing microscopy and X-ray images, that the bamboo cell wall is composed of alternating layers of thin and thick microfibrils, with the average angle of the thin microfibril decreasing from 35º in the outermost layer to 20º in the intermediate layer, reaching 10º in the internal cell cavity, while the angle of the thick microfibril is 5-6º.

Parameswaran & Liese (1976) proposed a schematic model of the bamboo cell wall, in which the intercellular layer from outside to inside is composed of the primary wall, followed by the transition layer (S0) of the secondary wall and other thin and thick layers (S1, S2, S3, S4, S5, S6, S7 and S8) arranged alternately. Wai et al. (1985) proposed a structural model in which O indicates the outermost wall layer of the secondary wall, and the entire secondary wall is composed of thin (N1, N2 and N3) and thick (L1, L2, L3 and L4) layers arranged alternately. Liu (2008) proposed a model consisting of the following layers: i) thin: S1 (20º/30º), S3 (45º/60º), S5 [80º/90º and S7 (±90º)]; and, ii) thick: S2, S4, S6 and S8, all between 0 and 5º. Considering the differences in the described models, Gao et al. (2022) suggest that they may derive from biological variations, related to bamboo types, growth environments and sampling times.

For Wang et al. (2012), there are two types of microfibril orientation: thin lamellae that align with a fibrillar angle of 80-90º, concerning the vertical axis, and thick lamellae that align with a fibrillar angle of 2-20º, and can be considered almost parallel to the longitudinal axis. Comparatively, in tree species, the orientation of most microfibrils in the S2 layer of the cell wall is aligned practically parallel to the axial axis. In addition to differentiation within and between vascular bundles, there is variation in the dimensions of the fibers in the stems (Chaowana 2013, Dixon & Gibson 2014, Liese & Tang 2015), both in length and thickness, due to their position in the stem, which can reduce or increase resistance in compression and traction (Pereira 2012). The fibers are present at the ends of the vascular bundles as "sclerenchyma sheaths". They are elongated and tapered, often bifurcated at the ends and aligned in the longitudinal direction of the culm (Nayak & Mishra 2016).

On the other hand, according to Parameswaran & Liese (1976), the length of the fibers varies from 2 to 4 mm, serving as protection for the vascular bundles, composing the mechanical tissue of the plant, whose essential function is to give resistance to the individual. Although they represent approximately 40-50 % of the total area of its tissue, they constitute 60-70 % of its mass, considering total weight (Liese 1980, Nayak & Mishra 2016). In the longitudinal direction of the stalk, there is an increase in the length of the fiber up to approximately 60 % of the distance between the region close to the lower and upper nodes, reversing this trend mainly in the final 10 % of the internode (Liese 1985). The density in the cross section of the bamboo varies throughout its thickness, as a function of the increase in the percentage of fibers from the inside to the outside, whereas the parenchyma content decreases. In the region of the inner or middle layer, the size of the vascular bundle is larger, tending to be smaller and denser in the outer layer (Chaowana 2013, Chaowana et al. 2014). In the longitudinal direction, the longest fibers are located in the median part and the shortest ones at the ends, close to the nodes (Tomazello Filho & Azzini 1987).

The upper portion of the bamboo's stem has a higher proportion of fibers, resulting in greater slenderness of the material, when compared to its basal part, which contains more parenchyma (Grosser & Liese 1971). These variations in fiber content decisively interfere with the density and properties that must be considered for its use. Generally, the percentage distribution of the constituent elements of bamboo (parenchyma, fibers and conductive cells) shows a defined pattern. In addition, the external part (cortex) consists of epidermal cells covered with a waxy layer that prevents moisture loss from the culm (Chaowana 2013, Nayak & Mishra 2016).

Parenchyma and conductive cells are more frequent in the lower third of the stem, whereas, in the upper third, the percentage of fibers is higher. Thus, the common practice of not using the upper portion of bamboo cut in the forest is wasteful, regarding cellulose content (Grosser & Liese 1971, Liese 1980). In general, bamboo has small amounts of secondary chemical constituents, such as waxes, resins, tannins, proteins and soluble ash (Chaowana 2013, Vena et al. 2013, Liese & Tang 2015, Nayak & Mishra 2016, Rusch et al. 2018, Amjad 2024), thus constituting a suitable raw material for various industrial activities.

THE PARENCHYMAL MATRIX IN THE ANATOMICAL STRUCTURE OF THE STEMS

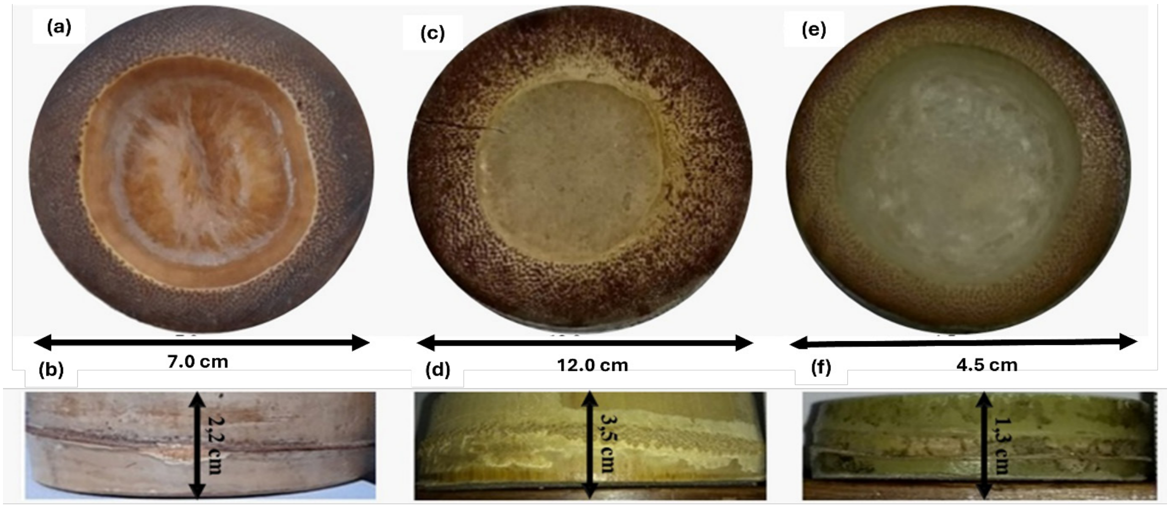
Parenchyma cells are the tissue that occurs in the most significant proportion in bamboo, assuming the function of a filling matrix, in which the fibrovascular bundles are incorporated, allowing both elements to contribute together to its stability and flexibility (Liese & Tang 2015). The primary function of parenchyma is to store nutrients and water, enabling the storage of a significant amount of starch (Beraldo & Azzini 2004). These cells are commonly minor in the external portion of the bamboo wall and gradually grow in the opposite direction (internal region), representing between 40 and 60 % of its composition. In the longitudinal direction, there is a reduction in the concentration of parenchyma in the base-to-top direction, with an average of 60 % at the base and 40 % at the apical part (Liese & Tang 2015).

Considering the aforementioned points, the percentage of parenchyma increases from the external region to the interior of the bamboo wall, while the opposite occurs for the fibrovascular bundles, being more numerous in external layers. This gives the darker coloration of the culms, in the outermost portion, when compared to the inner one (Darwis et al. 2020). As a rule, bamboo culms are formed by 10 % of vascular bundles, 40 % of fibers and 50 % of parenchyma cells (Liese 1980, Liese 1998, Liese & Tang 2015, Nayak & Mishra 2016). For Parameswaran & Liese (1976) and Nayak & Mishra (2016), these cells can present two patterns: i) shorter cells, with denser cytoplasm, which remain primarily non-lignified, even in mature culms; ii) longer cells that have a poly-laminated structure, consisting of several lamellae with alternating fibril orientation, similar to what occurs in the cell wall of fibers, which gradually become lignified as the individual ages.

In bamboo culms, the anatomical structure consists of fibers with a cell wall thicker than in wood. In the cross section of a node, there is variation in the organization of its tissues, with numerous curved fibrovascular bundles (which connect to the internal septa of the node) surrounded by parenchyma cells rich in reserve substances in the form of starch (Liese 1980, Liese 1985, Tomazello Filho & Azzini 1988). In the internodes, these bundles follow a longitudinal trend and are composed of metaxylem vessel elements, phloem, protoxylem fiber sheath and additional fiber bundles, depending on the species (Liese 1998). Figure 1 shows the cross section of the culm of bamboo species. The greatest concentration of fiber bundles occurs in the external region, giving the material a higher resistance in this region. In contrast, on the opposite side, close to the center of the stem, there is a greater concentration of parenchyma cells, with less resistance (Janssen 2000). The fibrovascular bundles, with their clusters of fibers within the parenchyma tissue, contribute enough to the structural character (Liese & Tang 2015).

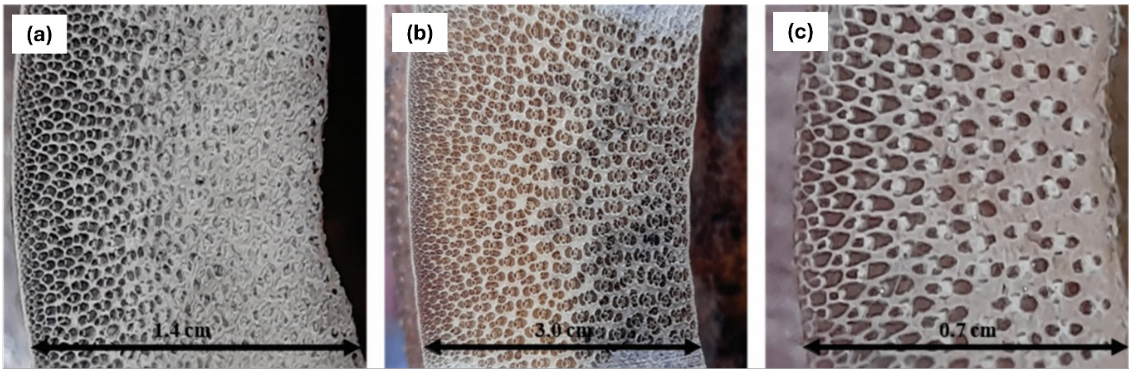
Figure 2 shows the fibrovascular bundles in the transverse direction of the stem wall of the *Dendrocalamus asper*, *Bambusa vulgaris* and *Phyllostachys aurea* species.

In the anatomical structure of bamboo internodes, the cells are arranged in a longitudinal direction, with no cells arranged in a radial direction (Liese 1980). In the node's cross section, numerous fibrovascular bundles are surrounded by parenchyma cells, with an epidermis consisting of epithelial and sclerenchyma cells. The vascular bundles incorporated in the parenchymal tissue influence the flexibility and stability of the culm (Nayak & Mishra 2016). The fibrovascular bundles of the nodal region run directly and indirectly from one internode to another, that is, within the node there



Photos by F. Rusch and E. de Paula

Figure 1. Transverse and axial representation of the culm node of three bamboo species: transverse section of *Bambusa vulgaris* (a), *Dendrocalamus asper* (c) and *Phyllostachys aurea* (e); axial section of *B. vulgaris* (b), *D. asper* (d) and *P. aurea* (f).



Micrographs by F. Rusch and E. de Paula

Figure 2. Cross-sectional micrographs of fibrovascular bundles of *Bambusa vulgaris* (a), *Dendrocalamus asper* (b) and *Phyllostachys aurea* (c).

are several branches of the vessels, which allow their connection to both the upper and lower internodes (Liese 1980, Liese 1985). In addition, secondary bifurcations of smaller thickness are responsible for connecting with the nodal diaphragms, linking the peripheral and internal parts of the node (Pereira 2012). In other words, in this region, part of these bundles bifurcates, connecting with: the peripheral zone or external part of the epidermis, constituted by the nodular ring or sheath ring or with the dormant bud; or with the internal zone or vessels of the node diaphragm (Figure 3B).

Vascular bundles constitute the main empty spaces, the point of least mechanical resistance. These bundles, which comprise the xylem and primary phloem, are smaller and more numerous on the periphery of the culm and larger and fewer in their internal part (Beraldo & Azzini 2004). Li et al. (2021) and Xu et al. (2022) found that, in the radial direction of bamboo, the number of vascular bundles decreases from the outer layer to the inner layer, whereas their size increases. From the base to the top of the bamboo, the number of vascular bundles decreases. For Fujii (1985), the highest concentration of vascular bundles was found in the upper outer part of the bamboo stem (3 bundles mm^{-2}), being lower (0.5 bundles mm^{-2}) in the internal part of the base. Regarding the distribution of vascular bundles, the same author found that 50-80 % are located in the outer third of the wall, 10-35 % in the middle and only 10-20 % in the inner third. Thus, to determine the number and density, the average size is an essential factor, and the larger the bundles, the smaller the number present in a given area. The phloem, metaxylem vessels and intercellular spaces derived from the protoxylem elements of a vascular bundle are surrounded by fiber sheaths, sclerenchyma cord and parenchyma cells, differing in size and shape according to the bamboo species and their position within the culm.

The conducting tissues, both metaxylem and phloem vessels, are surrounded by sclerenchyma sheaths. In addition, fibers occur inside and outside the vascular bundle, which differ considerably in size, shape and location, according to the height position and the thickness of the culm, characteristics that are influenced by the bamboo species (Liese 1980, Liese 1985). Some species present a combination of different types of fibrovascular bundles, mainly depending on the height position of the culm and its wall thickness (Grosser & Liese 1971). Regarding shape, in the internal part of the culm, the vascular bundles are almost circular or rounded (more oval and larger), gradually changing to an elliptical shape (longer and smaller) as they approach the external region of the wall. The variation in these microscopic characteristics of bamboo directly affects its physical and mechanical properties, interfering with its processing and use (Grosser & Liese 1971, Liese 1985, Chaowana et al. 2014).

TYPOLOGICAL CLASSIFICATION OF VASCULAR BUNDLES

Between the 1950s and 2000s, several researchers, such as Dietger Grosser, Walter Liese, Narayan Parameswaran, T. Sekar and A. Balasubramanian, carefully examined the parenchyma and vascular bundles in several bamboo species, considering the emergence of electron microscopy. Grosser & Liese (1971) characterized the anatomical structure of adult stems of different bamboo genera and species using culm samples collected in several Asian countries. Thus, 1,200 internodes of 250 culms of 52 species belonging to 14 genera were evaluated, allowing the characterization of various anatomical aspects and classifying the species according to their vascular bundles.

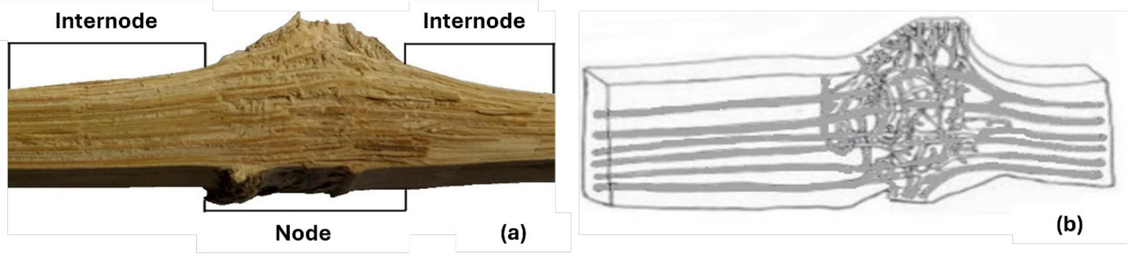


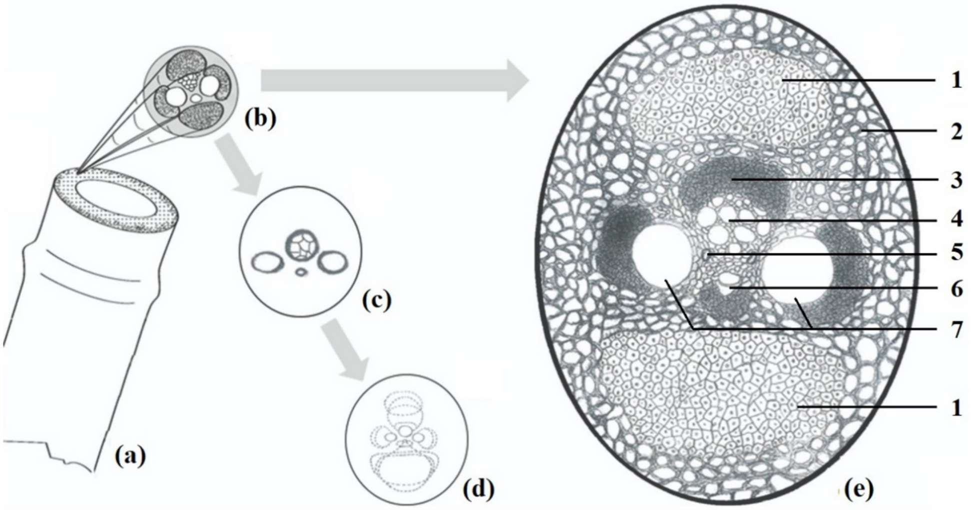
Figure 3. Fibrovascular bundles of the node and internode regions: node and internode regions in bamboos (a); representation of the internal structure of the bundles inside the culm (b).

From the study by Grosser & Liese (1971), it became possible to classify, in a generic way, the vascular bundle in the bamboo culm as being composed of two larger metaxylem vessels (40-120 µm) with one or two protoxylem elements, with the phloem as thin-walled sieve tubes, unconnected and connected with companion cells. This conducting tissue functions throughout the bamboo's life without adding any new conducting tissue, unlike coniferous and dicotyledonous woods, which have cambial activity (Rusch et al.2018). In older (senile) bamboos, the vessels and sieve tubes sometimes become impermeable due to the deposition of slime-like substances (Liese & Tang 2015). Blockage of sieve tubes also occurs by tylose-like expansions (Liese 1980). Figure 4 illustrates and describes the structures of a bamboo fibrovascular bundle.

Although there is a similar tissue pattern in each internode, there are anatomical differences in the shape, quantity and size of the vascular bundles, which are also influenced by the height of the stem and their wall thickness (progressively minor in the base-to-top direction), making it possible to establish a classification of different types of bamboo. Thus, due to these variations in the vascular bundles, an internode at the base of the culm may exhibit a different structure than the middle part, which, in turn, may also differ from the upper part of the culm. Grosser & Liese (1971) confirm this pattern, having found that, in all investigated bamboo species, the size of the vascular bundles decreases steadily from the base to the top, with this tendency being more pronounced in species with large bundles at the base. For Liese (1980, 1985), there is a strict correlation between the morphological and histological characteristics, and the more the wall thickness is reduced, the greater the anatomical differences.

In this context, the anatomical variations identified in the vascular bundles made it possible to group the bamboo genera into different types. Grosser & Liese (1971) initially described the four basic types (I, II, III and IV) of vascular bundles by observing the structure compared to the sclerenchyma sheath. Type I encompasses all leptomorphs (spreading species), which exhibit similarity in the structure of their vascular bundles, whereas the anatomical types II, III and IV are represented by pachymorphs, which are clumping species. Table 1 compiles and describes the research on classification of the kinds of basic vascular bundles in bamboos up to the beginning of the 1980s.

Years later, Liese (1985) deepened the studies on bamboo vascular bundles, proposing a new typology with new descriptions and adding a type,



Schematic representations by F. Rusch and E. de Paula

Figure 4. Schematic representation of a bamboo fibrovascular bundle: cross-section of the culm (a), structure of a fibrovascular bundle (b), basic structure of the elements of a vascular bundle (c), variations of the fiber sheaths and fiber strands that occur in different types of vascular bundles (d), fibrovascular bundle embedded in parenchyma tissue with detailing the elements (e) fiber sheath (1), parenchyma cells (2), sclerenchyma sheath (3), phloem (4), small metaxylem elements (5), intercellular space derived from protoxylem (6) and metaxylem vessels (7). Source: adapted from Grosser & Liese (1971, 1973), Liese (1980, 1985) and Rusch et al. (2018).

considering the bundles' size, shape and location (Table 2).

Liese (1985) also emphasizes that the leptomorph genera have only type I vascular bundle, whereas the pachymorph genera have types II, III and IV. The size and shape of the vascular bundles vary along the internode, but also with the height of the stem. In 1994, an analysis developed by Sekar and Balasubramanian in *Bambusa vulgaris* Schrad. proposed adding the subtype IIa (Sekar & Balasubramanian 1994). These studies were refined, and Liese & Grosser (2000) added two new subtypes for an expanded typology (Table 3).

The aforementioned studies emphasize the importance of the anatomical characteristics of the culm for the correct taxonomy of bamboos and highlight mainly the role of vascular bundles. Therefore, the use of artificial intelligence allows these characteristics to be considered quickly and accurately. In the current scenario, the importance of

Table 1. Classification of basic vascular bundle types in bamboos.

Type	Characteristics	Ocurrence
I	Formed by a single portion of central vascular thread, it presents only sclerenchyma sheaths as supporting tissue. In its intercellular space there are tyloses.	In species that present spreading rhizomes (leptomorphs), which develop from a complex network of underground rhizomes, with an intensely invasive habit, with emphasis on the *Arundinaria*, *Phyllostachys* and *Tetragonocalamus* genera.
II	Similar to the previous type (with central vascular thread and sclerenchyma sheath as supporting tissue); however, the intercellular space (protoxylem) is broader and there is no occurrence of tyloses.	Bamboos that have pachymorphic rhizomes in clumps or single culm formation. Subdivided into two groups: one formed by the *Melocanna*, *Schizostachyum* and *Teinostachyum* genera, in which vascular bundles of types II and III occur in the basal internodes, or also by the *Cephalostachyum* genus, in which only vascular bundles of type II occur, mainly in the middle and upper parts, but sometimes also at the base.
III	Composed of two parts: i) central vascular strand; ii) fiber strand. The fiber strand is inside the central strand. The separate fiber strands become smaller towards the outside and join the sclerenchyma sheaths. The sheaths in the intercellular space (protoxylem) are generally smaller than the others.	This bundle type occurs in clumping species (pachymorphs), mainly in the middle and upper part of the bamboo. In the *Bambusa*, *Dendrocalamus*, *Gigantochloa* and *Thyrsostachys* genera, in the internodes of the base, it may be combined with type IV. In *Melocanna*, *Schizostachyum* and *Teinostachyum*, combined with type II. In some *Oxytenanthera* spp. as the only type throughout the culm.
IV	Composed of three parts, namely, a central vascular thread and the fiber thread in two subdivisions: external to the central thread, and inside the central thread.	In species formed by pachymorphic, clumping rhizomes of the *Bambusa*, *Dendrocalamus*, *Gigantochloa* and *Thyrsostachys* genera, they always occur in combination with type III, mainly in the basal culms and rarely in the median ones. This type is almost entirely restricted to the thick-walled basal internodes and is later replaced by type III.

Source: adapted from Grosser & Liese (1971, 1973) and Liese (1980).

Table 2. Current classification of basic vascular bundle types in bamboos.

Type	Characteristics	Ocurrence
I	Consisting of a central vascular cord; supporting tissue only as sclerenchyma sheath.	Exclusively in the *Arundinaria*, *Phyllostachys*, *Fargeria* and *Sinanundinaria* genera.
II	Constituted by a central vascular cord, supporting tissue only as sclerenchyma sheath; sheath in the intercellular space (protoxylem) notably more prominent than the other three.	Exclusively in the *Cephalostachyum* and *Pleioblastus* genera. It also occurs together with type III in the *Melocanna* and *Schizostachyum* genera.
III	Consisting of two parts, a central vascular cord with sclerenchyma sheaths and an isolated fiber bundle.	Exclusively in the *Oxytenanthera* genus, but also jointly with type III in the *Melocanna* and *Schizostachyum* genera.
IV	Composed of three parts, a central vascular cord with small sclerenchyma sheaths and two isolated fiber bundles outside and inside the central cord.	Together with type III in the *Bambusa*, *Dendrocalamus*, *Gigantochloa* and *Sinoclamus* genera.
V	A semi-open type that represents one more.	Not described.

Source: adapted from Grosser & Liese (1971, 1973), Wu & Wang (1976), Liese (1980), Jiang & Li (1982) and Liese (1985).

Table 3. Current typology of basic vascular bundles classification.

Types	Description	Subtypes
Asymmetric vascular bundles	Characterized by an uneven distribution of fiber and parenchyma tissues around the vascular elements (xylem and phloem). These variations influence the mechanical properties and the adaptation of bamboo to environmental conditions and structural functions.	Bundles with a greater concentration of fibers on the inner side of the stalk offer high resistance to internal compression.
		Bundles with a greater concentration of fibers on the outside, providing higher tensile strength.
Symmetrical vascular bundles	They are characterized by a uniform distribution of fiber and parenchyma tissues around the vascular elements. This provides a balanced and efficient structure for the conduction of water and nutrients and uniform mechanical resistance to the bamboo stem.	Characterized by a uniform distribution of fiber and parenchyma tissues around the vascular elements, providing a balanced and efficient structure for the conduction of water and nutrients and uniform mechanical resistance to the bamboo culm.
		Bundles with uniform parenchyma thickness around the vessels: it helps in the efficient conduction of resources and a stable structure.
Compound vascular bundles	Combining the characteristics of symmetrical and asymmetrical bundles, characterized by variation in fibers and parenchyma. Additionally, being adaptable and multifunctional, they contribute to the bamboo's structural and functional flexibility, allowing the plant to adapt to environments and growth demands.	They show a significant variation in the distribution of fibers and parenchyma around the vascular elements. This variation can be in both the quantity and location of the tissues. They can have different shapes and sizes, reflecting an adaptation to varied functions and environmental conditions.
Double vascular bundles	Characterized by two series of vascular elements, which are specialized, offering efficiency in the conduction of water and nutrients and mechanical resistance, being a vital adaptation to support structural loads and varied environmental conditions.	Two sets of vessels often arranged concentrically, with layers of fibers and parenchyma surrounding the vascular bundle.
Ringed vascular bundles	Presenting an arrangement of concentric rings of fibers and parenchyma around the vascular elements, which provide higher structural resistance and flexibility, being a vital adaptation to support types of loads and mechanical stresses.	Bundles with continuous rings: the rings of fibers and parenchyma form a continuous structure around the vessels.
		Bundles with discontinuous and interrupted rings, forming separate segments of fibers and parenchyma.

Source: adapted from Grosser & Liese (1971, 1973), Liese (1980), Wu & Wang (1976), Jiang & Li (1982), Liese (1985), Sekar & Balasubramanian (1994) and Liese & Grosser (2000).

the anatomical component "fiber" in the classification of bamboos is highlighted.

APPLICATIONS OF ARTIFICIAL INTELLIGENCE IN ANATOMICAL IDENTIFICATION

In a computer, an image is a combination of pixels, and different bamboo species present variations in the representation of their anatomical elements. In this context, the composition of the elements brings about differences in the intensity, arrangement and distribution of these pixels, which can be detected and learned by the computational neural network (Wang et al. 2023). In this context, the taxonomic advances in bamboo resulting from the classification of vascular bundle types, combined with the development of an innovative methodology, was presented by Li et al. (2021) to detect them in samples of moso bamboo [*Phyllostachys edulis* (Carr) H. de Lebaie] from the 12 main producing areas in China. This advance made it possible to apply/train the YOLO (You Only Look Once) algorithm, with the model parameters determined by repeated verification. As a result, a model for the automatic detection, positioning, counting and measurement of vascular bundles was proposed. Wang et al. (2023) emphasized that the YOLO algorithm recognizes vascular bundles, quantifies them and records the coordinates at this location, in addition to calculating their area, thus solving the problem of manual measurement that consumes time and generates work.

For Li et al. (2021), this was possible by evaluating a method for identifying vascular bundles considering high-definition scanning images, resulting in the survey of the coordinates of each vascular bundle. This model was applied to determine the vascular bundles from the base to the top of a culm at the breast height of the bamboo. In contrast, the vascular bundles at the top and bottom of the bamboo node were quantitatively characterized. In addition, the fiber volume fraction and the fiber sheath area in the cross section of the bamboo culm were calculated. Thus, it was established that the total number of vascular bundles of moso bamboo in the 12 evaluated areas was 7,196 ± 698, with a distribution density of 2.49 ± 0.58 mm^{-2}, and a fiber volume fraction of 23.68 ± 1.89 %. For the authors, the variations observed in the vascular bundles in the different areas result from the growth environment. Approximately 8,000 vascular bundles were found at the bamboo stem base, with a decrease to approximately 300 at the top, with a reduction mainly of the semi-open and open types. Concerning the total area of the fiber sheath, there was a linear decrease from the base to the top of the internodes, whereas the volumetric fraction of the fiber was 20-30 %.

Xu et al. (2022) applied the vascular bundle detection model as the source domain proposed by Li et al. (2021) to 29 types of *Phyllostachys* in cross-section, obtaining an accuracy rate of 96.97 % in the analysis of this model. In this way, they received the following characteristics: i) total number of vascular bundles; ii) distribution density of the vascular bundles; iii) total area of the fiber sheath; iv) volume fraction of the fiber; v) average value of the single fiber sheath area; vi) average value of the vascular bundle length; vii) average value of the vascular bundle width; and viii) average value of the length/width ratio of the vascular bundle. To this end, a transfer learning method (AI learning) was applied, saving computation and Graphics Processing Unit (GPU) time, to train models with similar characteristics, using only a small number of labeled vascular bundles (1/10 of the source domain, representing 2,000 vascular bundles per species) to build the universal detection model, enabling the automatic and simultaneous detection, positioning, counting and measurement of vascular bundles. To verify accuracy, the trained model was applied to the original digitized image and, for species with poor detection results, it is possible to reduce the error by increasing the number of labeled vascular bundles.

This universal transfer-learning model, built by Xu et al. (2021), determined parameters for quickly detecting vascular bundle characteristics in 29 species of the *Phyllostachys* genus, with accuracy of up to 96.97 %. Among the obtained results, the total number of vascular bundles, total area of the fiber sheath, and the length, width and area of the fiber sheath of individual vascular bundles within the entire cross section stand out. The analyzed parameters showed a strongly positive linear correlation with the bamboo culms' outer circumference and wall thickness. At the same time, the volume fraction of around 25.5 % of the fibers and the ratio of around 1.226 between the length and width of the vascular bundles were relatively constant. Furthermore, they finely stratified the cross section considering the wall thickness and counted the vascular bundle characteristics in each layer, thus finding that the radial distribution of the vascular bundle width increased linearly, the radial distribution of the length-to-width ratio of the vascular bundle decreased quadratically, and the radial distribution of the fiber volume fraction decreased exponentially. The trends of gradient change in the vascular bundle characteristics were highly consistent in the analyzed species.

To replace the traditional method of calculating the fiber volume fraction, Xu et al. (2021) proposed an image binarization method based on the K-means clustering algorithm, considering the bamboo rings at breast height and 50 internodes from the base to the top of moso bamboo [*Phyllostachys edulis* (Carr) H. de Lebaie] grown in 12 major producing areas in China. Through a layer model based on the WEB coordinate system, programmed via JavaScript, the homogeneous layer of the cross-section within the entire bamboo was accurately analyzed. This method improved the quality of cross-sectional image binarization, particularly the delimitation of fiber sheaths. As a result, excellent binarized bamboo cross-sectional images were generated, which revealed more accurate trends regarding the distribution and quantification of bamboo fiber volume fraction at the organizational level, which can guide the design and exploration of bamboo products.

It is believed that, due to the complex and cumbersome process of manual measurements of vascular bundles and their distribution, the variations between different bamboo genera and species are poorly understood. Li et al. (2023) used an artificial intelligence methodology to propose a universal model for fast, reliable and automatic detection of vascular bundle characteristics from cross sections of culms of 213 species in 23 genera of Chinese bamboo. For the authors, the outer circumference and wall thickness of the culm, respectively, present positive linear correlations with the number of vascular bundles and the area of the fiber sheath; the distribution density of the bundles showed a reduction in the exponential correlation with the outer circumference and wall thickness; and the average fiber volume fraction was 35.2 ± 7 %, with reduced relative variation among species.

The findings generated from the proposed model enabled a new bamboo classification system based on the morphology of vascular tissue. There are three categories based on the distribution pattern of the tangential and radial length of the vascular bundles in the direction from the endodermis to the epidermis, two categories considering the radial-tangential ratio and, finally, four categories of distribution pattern of the fiber sheath area. This classification of bamboo may have implications for structural and pulp/paper applications. For Wang et al. (2023), the development of computer technology in recent years has made the automatic classification of bamboo possible. To this end, the "neural architecture technology to design a new base network and extend it to obtain a family of models, called EfficientNets", proposed by Tan & Le (2019), demonstrated reliability and effectiveness for use in bamboo classification, by identifying the vascular bundles in the cross section of the bamboo culm. The application of this model improved the overall performance, and validation on bamboo images occurred through a data set with 8,000 for training, 2,000 for validation and another 2,000 for testing.

The bamboo classification model was trained using vascular bundles from the culm cross section of 10 species belonging to 10 bamboo genera. The authors emphasize that "fine-tuning with all layers is useful compared to fine-tuning with fully connected layer for bamboo identification", due to its better performance, identifying bamboo with an accuracy of 98.7 %. In this context, computer vision and deep learning are promising technologies for identifying bamboo considering its cross section. It is also worthwhile to emphasize that, although the morphological characteristics and anatomical parameters seem very stable, they are influenced by local conditions (Latif & Liese 2002). A higher fiber content may indeed occur in areas with drier climatic conditions and steep topography, possibly resulting in a material with greater density and increased resistance properties. Similarly, site conditions with high fertilization affect shoot production, fiber diameter and wall thickness, but not the anatomical composition (Abasolo et al. 2005).

FINAL CONSIDERATIONS

Despite following a relatively standardized structure, in terms of parenchyma, fiber and vascular bundle contents, adult bamboo stems' anatomy presents differences among the different genera. These differences allow this material to be classified into various groups. Parenchyma and conductive cells are more frequent in the inner third of the wall, whereas the percentage of fibers is higher in the outer third.

Regarding the variations in the main elements of bamboo, the upper portion of the stem has a higher proportion of fibers, when compared to the basal portion, which contains more parenchyma and larger vascular bundles. However, the most relevant aspects for classifying bamboo into different groups are related to the shape of the fibrovascular bundle and its fiber content, with the highest concentration in the upper portion and the outer third of the stem.

Over the last few decades, researchers have improved new classification typologies for bamboo, considering their vascular bundles. This way, standards are systematized to identify bamboo genera and species correctly.

Manual measurements of the dimensions and distribution of different bamboo genera and species' vascular bundles are difficult. In this context, artificial intelligence is a promising technology that can quickly, reliably and automatically identify bamboo genera and species.

ACKNOWLEDGMENTS

To the Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) and Fundação de Amparo e Promoção da Ciência, Tecnologia e Inovação do Rio Grande do Norte (FAPERN), for granting a postdoctoral scholarship to the first author.

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