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Study on the anatomical structure and chemical characteristics of several common bamboo rhizomes

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Abstract: With the promotion of eco-friendly initiatives such as "replacing plastic with bamboo," bamboo rhizomes – traditionally discarded as underground byproducts – have recently gained increasing attention as renewable and sustainable materials. To better understand their characteristics and potential applications, this study systematically investigated the anatomical structures and chemical compositions of five representative bamboo rhizomes (Moso, Golden, Water, Purple, and Spotted bamboo) through microscopic observation and chemical analysis, using bamboo culms as a reference. Results showed that rhizomes shared similar structural frameworks with culms but exhibited unique internal features. Their vessel diameters (120–150 µm) were located toward the higher end of the typical range for bamboo culms (50–200 µm), and the proportion of vascular tissues (13.6–19.7 %) was also higher, reflecting stronger functions in water conduction and storage. Fibers in rhizomes were shorter, thicker, and contained lower cellulose but higher lignin contents, resulting in reduced mechanical strength yet enhanced durability. Species-specific differences were evident: Water bamboo and Moso bamboo rhizomes had longer, thicker-walled fibers with higher cellulose content. Spotted bamboo rhizome contained more vessels, while Purple bamboo and Golden bamboo rhizomes had shorter, thinner-walled fibers. These findings clarify the structural diversity and structure–property relationships of bamboo rhizomes, providing a scientific basis for their high-value utilization in sustainable material development.

Keywords: bamboo rhizome; high-value utilization; anatomical characteristics; chemical composition; computer vision techniques

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1 Introduction

The bamboo rhizome, or underground stem, works with the culm, or above-ground stem, to create the plant's complex biological structure (Figure 1a) (Guo et al. 2020; Wang 2024). Bamboo rhizomes possess strong reproductive capabilities. While underground rhizomes root and sprout into new rhizomes and bamboo shoots, those growing on the surface do not produce shoots. Instead, they consume nutrients and negatively impact the growth of the bamboo forest. During forest harvesting and renewal, a large number of rhizomes are abandoned due to aging or mechanical damage. Besides, the rapid growth of bamboo and its tendency to encroach upon neighboring ecosystems pose a threat to agricultural land and can lead to a decrease in biodiversity and an increase in landslides (Ai et al. 2024; Ito et al. 2014). Therefore, the regular removal of bamboo rhizomes is crucial for maintaining ecological safety. Unfortunately, discarded rhizomes are often left to decay or are incinerated, which not only wastes valuable resources but also contributes to environmental burden by releasing greenhouse gases and pollutants (Wu et al. 2019). In recent years, with the increasing severity of plastic pollution, the International Bamboo and Rattan Organization has issued the "bamboo for plastic" initiative. This call has accelerated the transformation of bamboo utilization from extensive to holistic and high-value utilization. Against this backdrop, bamboo rhizomes, as an important part of bamboo, have gradually attracted attention due to their similar biological structure to bamboo culms and their unique morphology and properties. Currently, bamboo rhizomes are used to produce certain handicrafts and decorative materials, such as handbag handles, tea sets, and round fans (Figure 1c). The

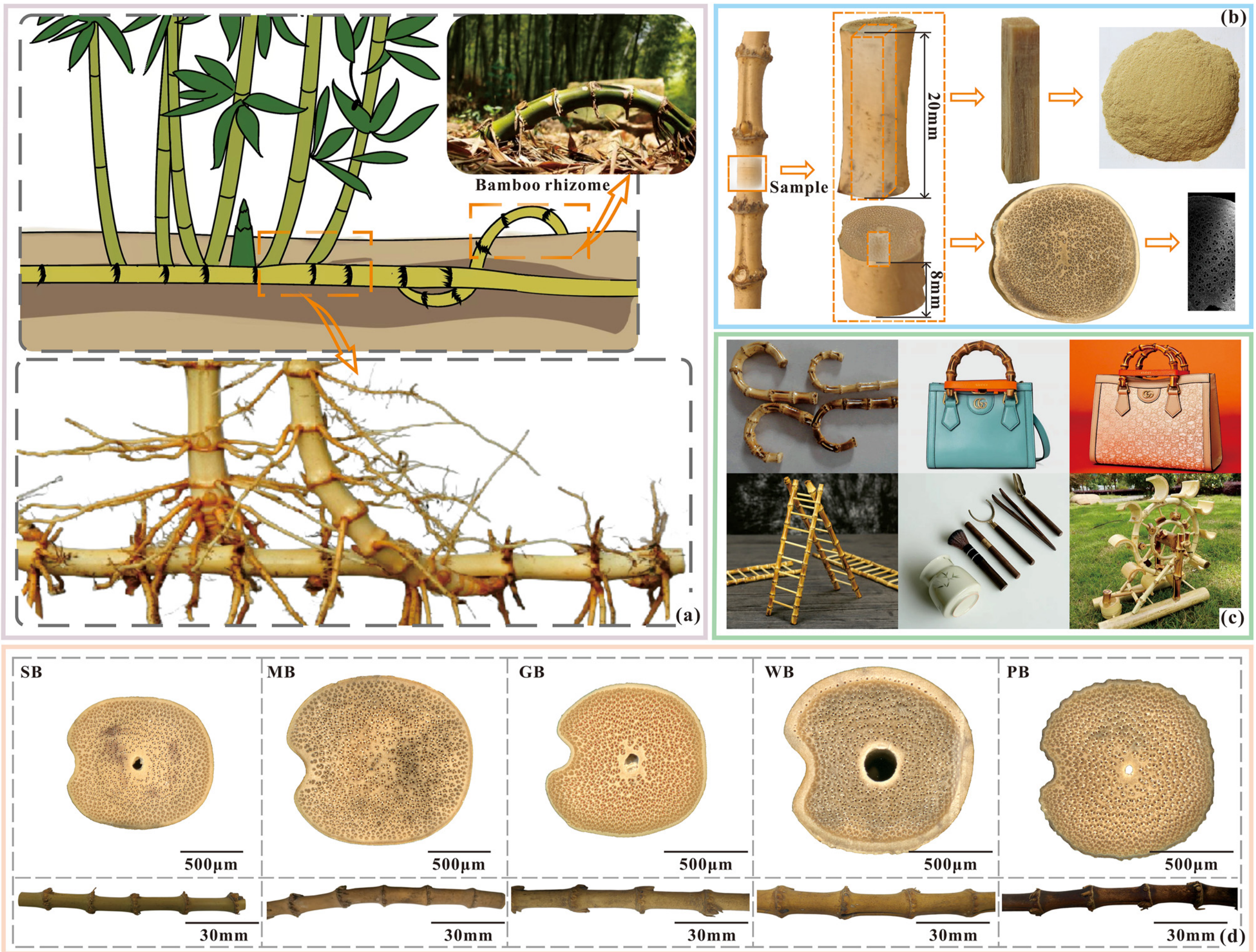

Figure 1: Bamboo rhizome and its application and sample preparation. (a) Bamboo forest system, (b) rhizome sample preparation, (c) bamboo rhizome application, (d) bamboo rhizome and their cross-section. SB: spotted bamboo, MB: moso bamboo, GB: golden bamboo, WB: water bamboo, PB: purple bamboo.

raw materials for these products are primarily sourced from *Phyllostachys aurea* Rivière & C. Rivière (Golden bamboo, GB), *Phyllostachys bambusoides* Siebold & Zucc. (Purple bamboo, PB), *Phyllostachys nigra* (Lodd. ex Lindl.) Munro (Spotted bamboo, SB), *Phyllostachys edulis* (Carrière) J. Houz. (Moso bamboo, MB), *Phyllostachys heteroclada* Oliv. (Water bamboo, WB) rhizomes (Figure 1d). Despite the growing utilization of bamboo rhizomes, research on their structure and properties remains relatively limited. Most existing studies focus on bamboo forest cultivation and ecological applications. However, the anatomical structure and chemical composition of bamboo rhizomes are crucial factors that determine their material properties and applications. These two aspects collectively define their mechanical properties, durability, processability, and application potential. A deeper understanding of the anatomical and chemical properties of bamboo rhizomes will not only enrich fundamental data but also provide theoretical support for their refined utilization, thereby enhancing the added value of the bamboo industry.

Existing research on the structure and composition of bamboo rhizomes has largely focused on Moso bamboo. Studies have shown that Moso bamboo rhizomes have the same basic composition as Moso bamboo culms, including the epidermis, pith, and vascular tissue (Ito et al. 2015). Their vascular bundles are also composed of vessels, sieve tubes, and fiber sheaths. Furthermore, the fiber morphology of Moso bamboo rhizomes was similar to that of the culm, with a fusiform shape. However, according to Liu (2015), the fiber length of the rhizomes ranged from approximately 620–920 μm, which was notably shorter than that of mature Moso bamboo culms (almost all of which are greater than 2000 μm). The fiber width (about 20–25 μm) is similar to the culm, but the lumen diameter (about 11–16 μm) is slightly larger. The cell wall to lumen ratio is 0.67–1.08, which is smaller than that of the culm (about 1.18–2.98). These indicated that the fibers in

Moso bamboo rhizomes were shorter, with thinner walls and larger lumens, compared to those in the culm (Liu 2015; Ming et al. 2018). In addition, the chemical composition of Moso bamboo rhizomes is similar to that of the culms, mainly consisting of cellulose and lignin (Ito et al. 2015). Xu et al. (2024) reported that the lignin content of Moso bamboo rhizomes is around 24.70 %, with holocellulose ranging from 66.7 % to 68.3 % and cellulose from 37.8 % to 38.4 %. The content of these components is comparable to that of Moso bamboo culms (Liu 2015; Xu et al. 2024). In general, the interpretation of the structure and chemical composition of Moso bamboo rhizomes has essentially clarified the similarities between bamboo rhizomes and bamboo culms, which undoubtedly lays the foundation for understanding and developing bamboo rhizome resources. However, with the vast diversity of bamboo species, whether there are differences in structure and composition among the rhizomes of different bamboo species, and how these differences affect their utilization, remain scientific questions that need to be further explored in depth.

To address this gap, this study has comprehensively characterized the anatomical and chemical properties of five commonly used bamboo rhizome species – Golden, Spotted, Purple, Moso, and Water bamboo – aged 2–3 years. These species are widely utilized as raw materials for handicrafts. A detailed analysis has been presented on their structural features, including vascular bundle morphology and distribution, tissue proportions, vessel size distribution, fiber cell parameters, and chemical composition. Furthermore, the shared anatomical and chemical characteristics among these bamboo rhizomes have been summarized, while distinct interspecies differences have also been highlighted through comparative analysis with common bamboo culms. These findings provide valuable insights for developing targeted applications and maximizing the comprehensive utilization of bamboo resources.

2 Materials and methods

2.1 Sample preparation

Five types of bamboo rhizome samples (Golden, Spotted, Purple, Moso, and Water bamboo) were all collected from disease-free and pest-free 2–3 year-old healthy bamboo rhizome in Sichuan, China (107.20°E, 30.74°N). Two types of inter node bamboo blocks, B_1 (8 mm) and B_2 (20 mm), were respectively cut from the middle section of the bamboo rhizome (Figure 1b). It was used for testing after standardized pretreatment at a constant temperature of 20 ± 1 °C and a equilibrium moisture content of 65 ± 5 % (Li et al. 2023). In all experiments, 6 replicates were used to ensure statistical reliability.

2.2 Observation of vascular bundle morphology and distribution

The B_1 sample was sliced and made into 8 mm high samples (Figure 1b). After drying at 103 °C, the samples were placed in the bell jar of the vacuum coating machine and gold films were sprayed respectively by sputtering coating method (Wang and Cheng 2020). Photographs were taken using a scanning electron microscope (Quanta 200, FEI, US) at an acceleration voltage of 7.5 kV (Lian et al. 2022). The morphology and distribution of the vascular bundles were observed.

2.3 Measurement of radial distribution of tissue proportions

A SEM image depicting bamboo cortex (BC), bamboo middle (BM), and bamboo pith ring (BP) was chosen for statistical analysis. Initially, a representative arc slices was selected from each of the three regions.

Following this, the measurement tools in Digimizer were employed to measure the areas of fiber cells, parenchyma cells, and conducting tissue within the selected slices, as well as the total area of each slice. Moreover, the proportion of each tissue was calculated, and the variation of these parameters in the radial direction was analyzed.

All fiber and parenchyma cell data were analyzed and processed using Origin 2024 and IBM SPSS Statistics 30 software. The double-wall thickness, aspect ratio, and wall-to-lumen ratio of fiber cells were calculated.

2.4 Separation and morphological measurement of fiber cells

Sample preparation was carried out by the Franklin impregnation method (Lian et al. 2022a, b). The 20 mm segment from the middle part of each bamboo rhizome internode (B_2) (Figure 1b) was taken and soaked in a 1:1 (v/v) mixture of glacial acetic acid and 30 % hydrogen peroxide. Six samples were collected from each type of bamboo rhizome. The samples were then heated in a constant-temperature water bath at 60 °C until they softened and could be separated into individual fibers (Niu et al. 2023). After rinsing with deionized water 5 to 8 times, mechanically break up the fibers with a glass rod. Draw the fiber impregnation solution and place it on a glass slide. Observe under an optical microscope and randomly select 100 fibers to measure their length, wall width and cell diameter parameters.

2.5 Determination of vessel size and distribution

The cross-sections of the samples were scanned in 64-bit color mode using a scanner (V850 PRO, EPSON, Japan) with a resolution of 12,800 ppi. The obtained images were used for the extraction of vessels features. Subsequently, a digital vessels detection model was used to extract the positions and dimensions of all vessels in the rhizome samples. The wrongly identified vessels (foreign substances such as dust and particles in the scanned images) were manually removed. Then, the Matpoltlib model was used to draw the vessels scatter plot. Finally, the axial and radial distribution of the vessels was characterized based on the curve fitting technique of Numpy (Xu et al. 2024).

2.6 Determination of cellulose, hemicellulose, and lignin in bamboo rhizome

After cleaning, drying and crushing the B_2 sample, pass it through a 60-mesh sieve (Figure 1b). Weigh 0.3000 ± 0.001 g of the completely dried sample and place it in a hydrolysis bottle. Add 3.00 ± 0.01 mL of 72 % sulfuric acid and keep it in a water bath at 30 ± 3 °C for 60 ± 5 min. Then, 84 ± 0.04 mL of deionized water was added to dilute it to 4 % sulfuric acid, and it was placed in a 121 °C sterilizer and kept for 1 h. At the same time, prepare the sugar recovery standard solution (SRS) and treat it together with the sample. The samples after acid hydrolysis were vacuum filtered. 50 mL of the filtrate was taken to determine the contents of acid-soluble lignin, cellulose and xylan. The residue was washed, dried and weighed. Finally, the lignin content was calculated according to the formula for acid-insoluble lignin content, and the sugar loss during the acid hydrolysis process was corrected by using the sugar recovery standard solution (Sluter et al. 2012).

3 Results and discussion

3.1 Tissue proportions of bamboo rhizomes

The cross-section of the bamboo rhizoms internodes is irregularly elliptical (Figure 1d), with a smaller central cavity, contrasting sharply with the hollow structure of bamboo culms. In comparison, WB-rhizome exhibits the largest cavities, while GB -rhizome, SB-rhizome, and PB-rhizome have smaller ones. MB-rhizomes lack cavities altogether. Furthermore, Figure 2a reveals the microscopic structure of the bamboo rhizome cross-section, which is mainly composed of thin-walled basic tissue and vascular bundles (Ji 2024). The vascular bundles are distributed within the thin-walled basic tissue and mainly consist of fiber tissue and vascular tissue (vessels and sieve tubes). The tissue composition of bamboo material refers to the proportions of fiber tissue, basic tissue, and vascular tissue within the entire structure (Xiang et al. 2019). As shown, the tissue proportions of fiber, thin-walled, and vascular tissue in different radial regions of several bamboo rhizomes were calculated (Figure 2b and c).

Overall, except for SB-rhizome, the area ratio of fiber cell in several bamboo rhizomes is the highest, followed by parenchyma cells, and finally, vascular tissue. The fiber ratio is approximately between 42.0 and 49.4 %, parenchyma cells between 35.5 and 39.2 %, and vascular tissue between 13.6 and 18.9 % (Figure 2b and c). This differs from previous studies on mature bamboo culms, where the content of thin-walled cells exceeds that of fiber cells (Liese and Köhl 2015). Parenchyma cells, also known as basic tissue, play storage and support roles in bamboo material. They are the most abundant cell type in bamboo, typically occupying 40 %–60 % of the cross-sectional area of bamboo culms (Sun et al. 2022; Wu et al. 2021). Fiber cells, which are structural cells, provide strength and toughness, and they occupy 30 %–50 % of the cross-sectional area of bamboo (Li et al. 2013). The differing proportion of these two cell types in bamboo rhizomes is influenced by the content of vascular tissue. As shown in Figure 2b and c, the area ratio of vascular tissue in bamboo rhizomes is significantly higher than in common bamboo culms (about 8–10 %) (Kamthai and Vaivudh 2012). It is the increase in conducting tissue that results in a decrease in the proportion of thin-walled cells. Bamboo rhizomes, as underground stems of bamboo, play a crucial role in the transport and distribution of nutrients and water (Kotangale et al. 2025). They are responsible for transporting organic nutrients (mainly sucrose) produced through photosynthesis from the leaves downward and storing them for the growth of bamboo shoots in the following year. At the same time, they absorb water and inorganic salts from the soil and transport them to the above-ground bamboo culms and leaves (Hu et al. 2024; Luo et al. 2020; Pan et al. 2025). To efficiently perform these functions, bamboo rhizomes require a well-developed conducting system. This phenomenon applies even to SB-rhizome, which has a lower fiber content. Thus, the higher content of conducting tissue in

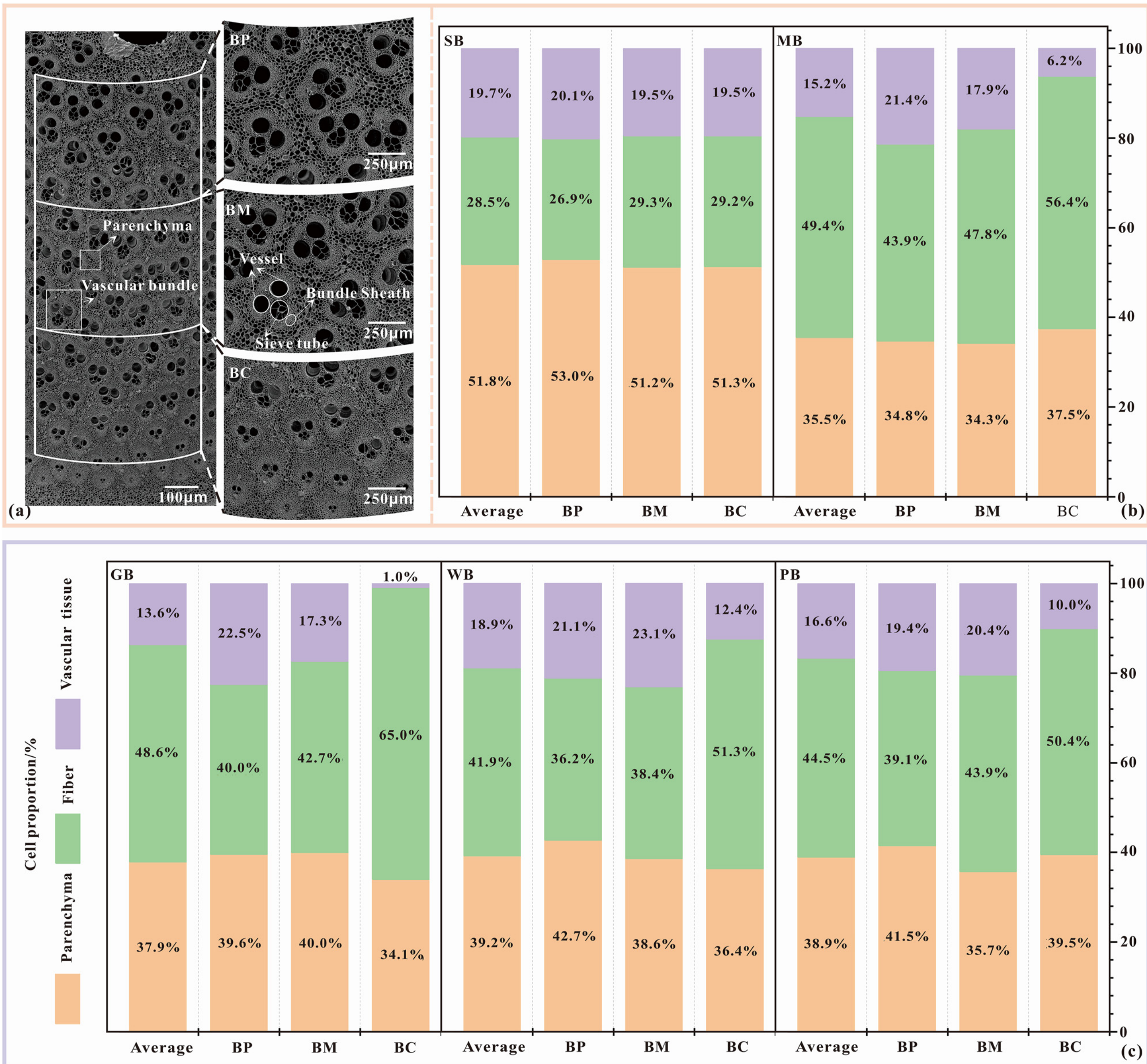

Figure 2: Cell proportions. (a) Cross-section appearance of bamboo rhizome; (b, c) area ratio of each tissue. SB: spotted bamboo, MB: moso bamboo, GB: golden bamboo, WB: water bamboo, PB: purple bamboo.

bamboo rhizomes is a major distinguishing feature from bamboo culms.

After comparing and analyzing the tissue composition of the five bamboo rhizomes, it can be observed that the SB-rhizome has the highest proportions of vascular tissue (19.7 %) and parenchyma cells (51.8 %), while its fiber content is the lowest (28.5 %) (Figure 2b). This characteristic suggests that the SB-rhizome is more specialized for water transport and storage functions, but relatively lacks in mechanical support (Liese and Köhl 2015). In contrast, the MB-rhizome exhibits a completely different pattern, with the highest fiber proportion (49.3 %) and the lowest parenchyma cell proportion (35.5 %), along with a relatively low proportion of vascular tissue (15.2 %) (Figure 2b). This indicates that its structure is more suited for mechanical loading and stability, but may have limitations in transport efficiency and storage capacity (Li et al. 2013). Both the GB-rhizome and WB-rhizome show relatively high fiber contents (48.6 % and 49.9 %, respectively) (Figure 2c), but there are significant differences in their vascular tissue proportions. The GB-rhizome has the lowest vascular tissue proportion (13.6 %) (Figure 2c), which may lead to weaker transport functions, while the WB-rhizome has a higher vascular tissue proportion (18.9 %)(Figure 2c), maintaining a good balance between mechanical support and water transport, resulting in more coordinated overall performance (Kamthai and Vaivudh 2012). The PB-rhizome has a relatively balanced distribution of the three tissue types, with vascular tissue accounting for 16.6 %, fibers 44.5 %, and parenchyma cells 38.9 %. (Amada and Untao 2001).

Next, the tissue composition across different radial regions (BP, BM, BC) from the center to the outer side of the bamboo rhizomes was analyzed. It was found that, except for the SB-rhizome, where no significant variation in tissue proportions was observed across the three regions from the pith to the outer layer, the tissue proportions in the other four bamboo rhizomes exhibited a distinct gradient change. Specifically, the fiber tissue proportion increased gradually from the pith to the outer layer in all four bamboo rhizomes. On the other hand, the proportion of vascular tissue was significantly smaller on the outer layer side than in the pith and middle regions. No clear trend was observed in the distribution of parenchyma cells. These trends are generally consistent with the radial variation of tissue proportions in bamboo culms. Chaowana et al. (2015) used digital image analysis to examine the changes in fiber volume fraction and microstructure in the cross-section of *Dendrocalamus asper* bamboo culms. They found that the fiber distribution followed a specific pattern, decreasing from the outer to the inner layers, while parenchyma and vascular tissues were more prevalent in the inner third of the bamboo wall. They suggested that this distribution effectively disperses and resists bending stress caused by wind load. Similarly, Ray et al. (2005) observed a gradient in fiber distribution in bamboo culms: in the outermost layer, there are approximately 8 fibers per square millimeter, while in the innermost layer, only 2 fibers are present in the same area. Furthermore, regarding vascular tissues, Li et al. (2024) demonstrated that the cross-sectional area of vascular bundles decreases exponentially from the inner to the outer layers. Although the total number of vascular bundles is greater in the outer layers, the individual vascular bundles in the inner layers are larger, particularly with larger conduits in the post-formed xylem. This also supports the finding that vascular tissue occupies a larger area in the inner layers, gradually decreasing towards the outer layers.

A comparison of the radial tissue composition gradients in the bamboo rhizomes reveals that the SB-rhizome exhibits the smallest gradient, followed by the PB-rhizome. The WB-rhizome, MB-rhizome, and GB-rhizome show a more distinct gradient, especially the GB-rhizome. This pronounced fiber gradient structure may suggest the excellent bending strength of the bamboo rhizomes.

3.2 The morphology and distribution of vascular bundles of bamboo rhizome

Figure 3 shows the morphology and distribution of vascular bundles in the five bamboo rhizomes from the outer layer to the pith. The vascular bundles in bamboo culms are primarily composed of vessels, sieve tubes, fiber sheaths, and a small amount of parenchyma cells (Abdul-Latif, 1992). The vascular bundles are classified into several types, including undifferentiated, semi-differentiated, double-belted, belt-shaped, tightly-belted, open, and semi-open types (Wen and Chou 1984). Figure 3c–l compare the types and sizes of vascular bundles in different radial regions (BC, BM, and BP) of the bamboo rhizomes and mature moso bamboo culms across their cross-sections. The five bamboo rhizomes contain four types of vascular bundles: undifferentiated, semi-differentiated (Figure 3g and h), semi-open (Figure 3i and j), and opentypes (Figure 3k and l). Specifically, the vascular bundles closest to the outer layer are mostly undifferentiated and semi-differentiated. Most of the vessels and sieve tubes within these vascular bundles are not fully developed (Li et al. 2018), and the vascular bundles are mainly composed of fiber cells (Figure 3g). As the distance from the bamboo wall increases, the vascular bundles in the BC region gradually transition to a semi-open structure, and the area occupied by the vascular bundles steadily increases (Figure 3i). From the BC to BM regions, the number of semi-open vascular bundles slightly decreases, while the number of open vascular bundles gradually increases. Meanwhile, the vascular bundle area at the BM region increases slowly (Figure 3a). At the BP region, the vascular bundles are predominantly of the open type, with a small amount of semi-open vascular bundles. The area of the vascular bundles here increases slowly, stabilizes, and even slightly decreases.

Additionally, as shown in Figure 3g–l, the vascular bundles in the bamboo rhizomes are significantly smaller than those in mature moso bamboo culms. For the bamboo rhizomes, the size of the vascular bundles increases initially and then stabilizes as one moves from the outer layer to the pith.

As shown in Figure 3f, the total vascular bundle area ratio in the cross-section of the bamboo rhizomes is similar to that in common bamboo culms, ranging from approximately 50 %–70 %. However, the vascular bundle area ratio in bamboo rhizomes does not show a clear radial gradient,

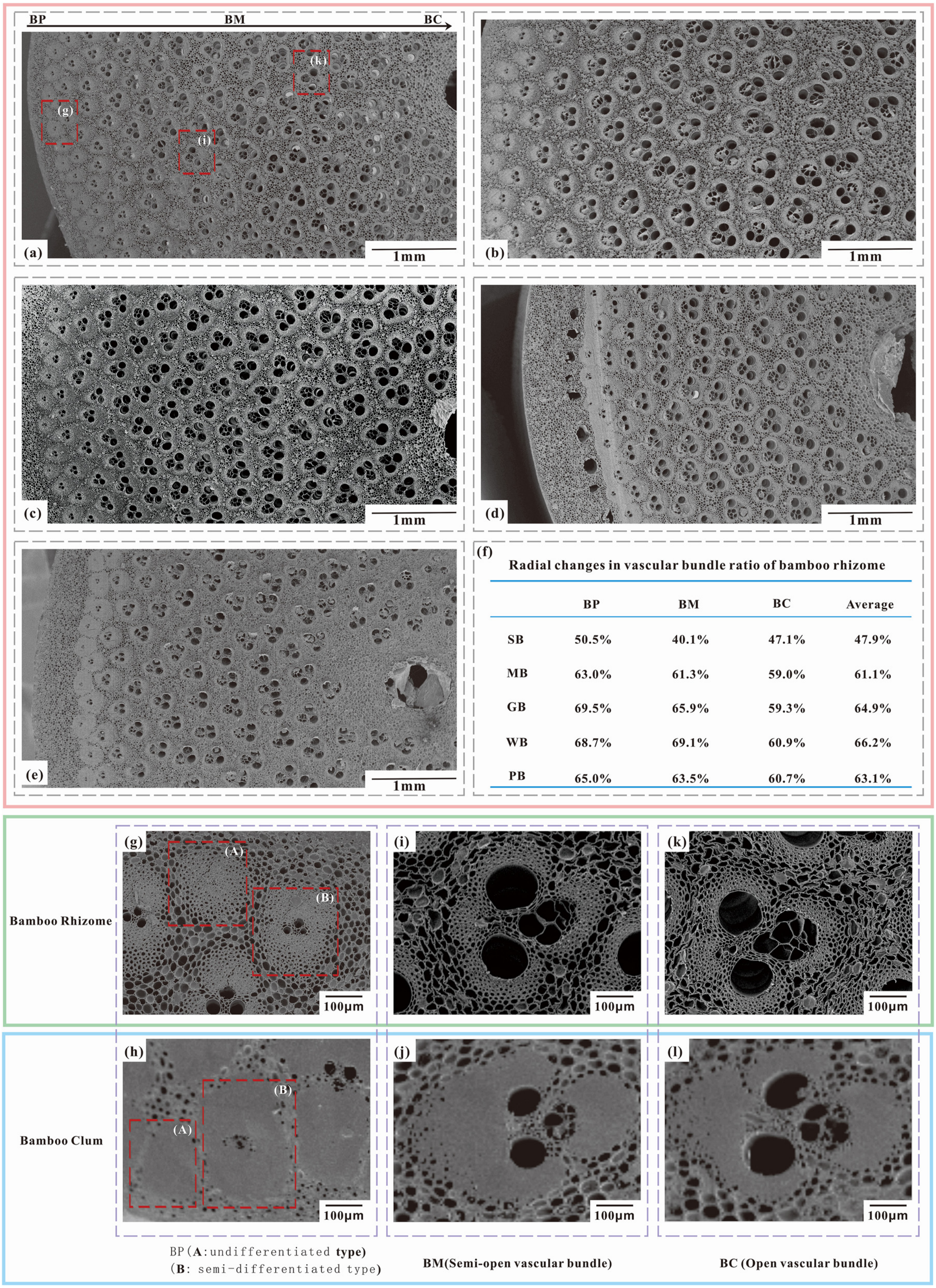

Figure 3: Vascular bundles in the rhizome of (a) BZ, (b) MZ, (c) GZ, (d) WZ, and (e) PZ. (f) Radial changesin vascular bundle ratio of bamboo rhizome; (g, h) undifferentiated and semi-differentiated vascular bundles; (i, j) semi-open vascular bundles; (k, l) open vascular bundles. SB: spotted bamboo, MB: moso bamboo, GB: golden bamboo, WB: water bamboo, PB: purple bamboo.

which contrasts with the distinct gradient distribution seen in bamboo culms. Li et al. (2024) found that the cross-sectional area of vascular bundles in bamboo culms decreases exponentially from the inner to the outer layers. Although the total number of vascular bundles is greater in the outer layers, the individual vascular bundles in the inner layers are larger. As shown in Figure 3a–g, i, and k, it can be observed that in the bamboo rhizomes, the vascular bundles are significantly smaller near the bamboo wall. The size difference between the middle and pith regions is much smaller (Figure 3i and k). The vascular bundles are primarily composed of fibers and vascular tissues, with a small number of parenchyma cells. According to the data in Figure 2, the fiber tissue proportion increases gradually from the inner to the outer side. In contrast, the vascular tissue show an almost opposite trend. For bamboo culms, the vessel content is relatively low, only 5 %–10 %. Therefore, the gradient of vascular bundles in bamboo culms is primarily determined by the proportion of fiber tissue (Latif and Mohd 1992). However, bamboo rhizomes have a higher proportion of vessel cells, ranging from 13 % to 20 % (Li et al. 2011). This means that the vascular bundles in bamboo rhizomes are influenced by both fiber and vessel tissue. In other words, bamboo rhizomes achieve a balanced state between conduction and mechanical support. This differs from bamboo culms, which mainly need to resist bending stress caused by wind load, where the pronounced gradient of vascular bundles aids in their growth (Wen and Chou 1984). Bamboo rhizomes, on the other hand, focus more on nutrient conduction and transfer (Ray et al. 2005).

Several unique phenomena were observed in some bamboo rhizomes. The SB-rhizome has a very thick bamboo wall, with evenly distributed circular structures (orange circles in Figure 4a, a_2 and a_3). This observation is consistent with the findings of Li et al. (2019), who noted the presence of ventilation pores in the underground stems of *P. heteroclada*. Gong and Zhao (1990) also found the existence of lenticels in the bamboo culms of *P. heteroclada*. They believed the development of these gas channels was related to the growth of underground buds. Bamboo species growing in high-humidity conditions tend to have more prominent lenticels and higher densities (Gong and Zhao 1990). Additionally, the vascular bundles near the bamboo wall of the WB-rhizome are very tightly arranged, forming a fiber cell band (red box in Figure 4a).

The PB-rhizome shows distinct anatomical features. Its vascular bundles and parenchyma cells contain a large amount of starch granules (Figure 4b). Starch granules are the main storage form of substances and energy in plants. Their content and distribution closely relate to plant development (Hu et al. 2021). No similar phenomenon was observed in PB-culms, but Ito Ito et al. (2014) found starch granules in the MB-rhizome. Unlike PB-rhizome, which has starch granules in almost all fiber and parenchyma cells, the starch in MB-rhizome is only found in some vascular bundle sheath cells and the cells near the pith.

Additionally, the GB-rhizome has some unusual vascular bundles. These bundles consist of three vessels, two sieve tubes, one primary xylem vessel, fiber sheaths, and parenchyma cells (Figure 4c). While no similar phenomena were observed in other bamboo species, Ito et al. (2015) found some vascular bundles in the MB-rhizome containing two pairs of secondary xylem vessels.

3.3 Fiber parameters of bamboo rhizomes

The box plots in Figure 5 show the fiber parameters of five bamboo rhizomes, including length (Figure 5a), width (Figure 5a), lumen diameter (Figure 5a), double wall thickness (Figure 5a), aspect ratio (Figure 5c), and wall-to-lumen ratio (Figure 5c), as well as a scatter plot for length (Figure 5b). It is clear that the average fiber length of the five bamboo rhizomes is approximately between 600 and 900 μm, and the fiber width is around 15 μm, indicating that the fiber widths of the five bamboo rhizomes are similar. In contrast, the fiber length of bamboo rhizomes is much shorter than that of typical bamboo culms (usually 1,500–4,500 μm), but the fiber width is similar to that of bamboo culms (10–30 μm) (Liese and Köhl 2015).

Figure 5a shows that the double wall thickness of the fibers in the five bamboo rhizomes range from 7.7 μm to 9.3 μm, similar to that of typical bamboo culms. Additionally, the wall-to-lumen ratio in Figure 5c, which is the ratio of the fiber cell wall thickness to the lumen diameter, is a key indicator of bamboo hardness, density, and strength. The wall-to-lumen ratio of the five bamboo rhizomes is around 1.3–2.0 (Figure 5c), slightly higher than that of Moso bamboo (0.5–1.5) and Ci bamboo (0.5–1.2) (Kamthai and Vaivudh 2012). The aspect ratio of the fibers in the five bamboo rhizomes is approximately 43.2–64.0 (Figure 5c), much smaller than that of typical bamboo culms, which range from 100-300 (Moso bamboo: 150–250, Ci bamboo: 100–200) (Amada and Untao 2001).

In conclusion, compared to bamboo culms, the fibers in bamboo rhizomes exhibit distinctly different characteristics. Their length and aspect ratio are much smaller, but their width and wall thickness are similar, with a slightly larger wall-to-lumen ratio. It can be summarized that bamboo culm fibers are long and thin, while bamboo rhizome fibers are short and thick. This difference significantly reduces the adhesive force and load-bearing capacity between bamboo

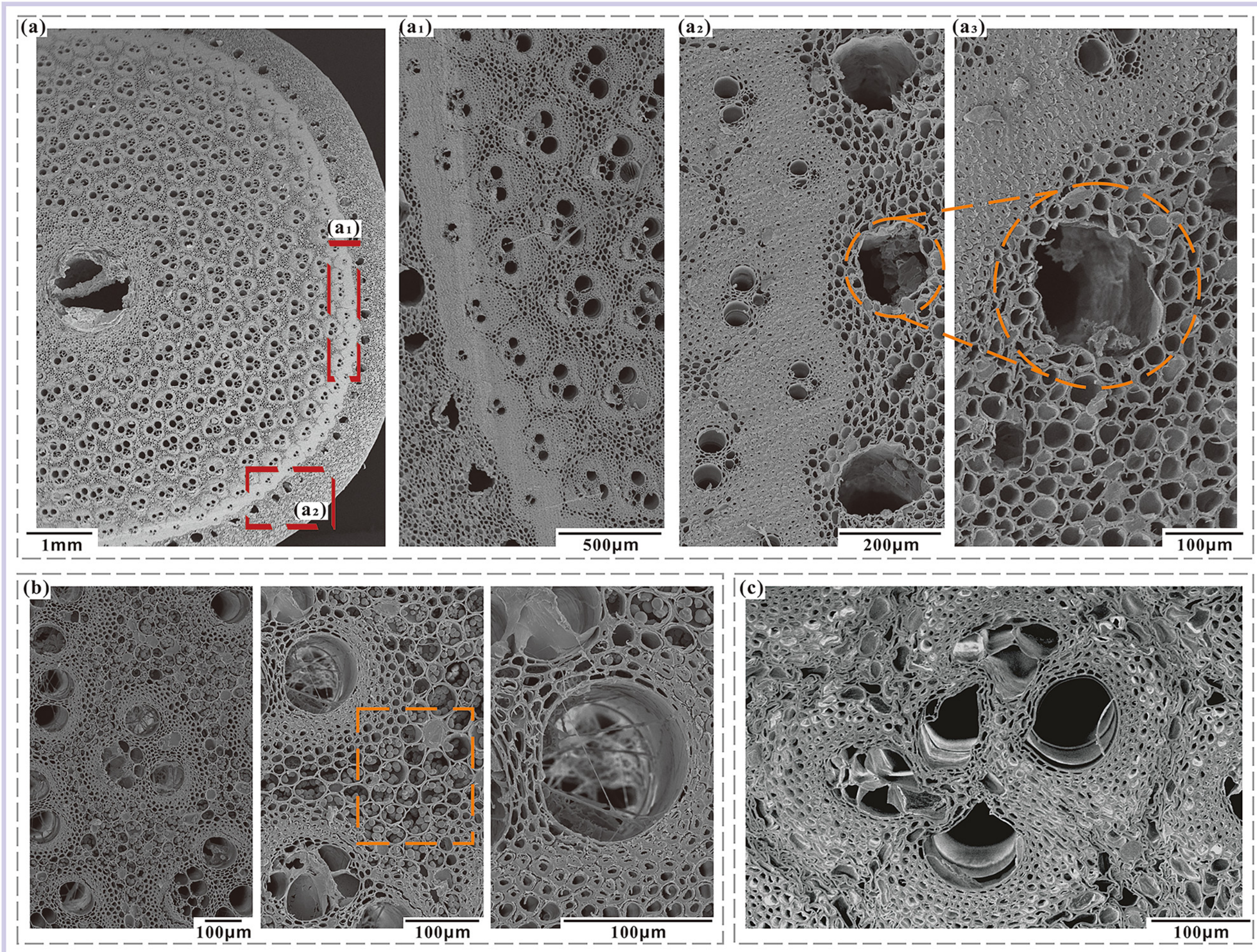

Figure 4: Special phenomena. (a) Culm wall of water bamboo rhizome; (b) starch granules in purple bamboo rhizome; (c) distinctive vascular bundles in golden bamboo rhizome.

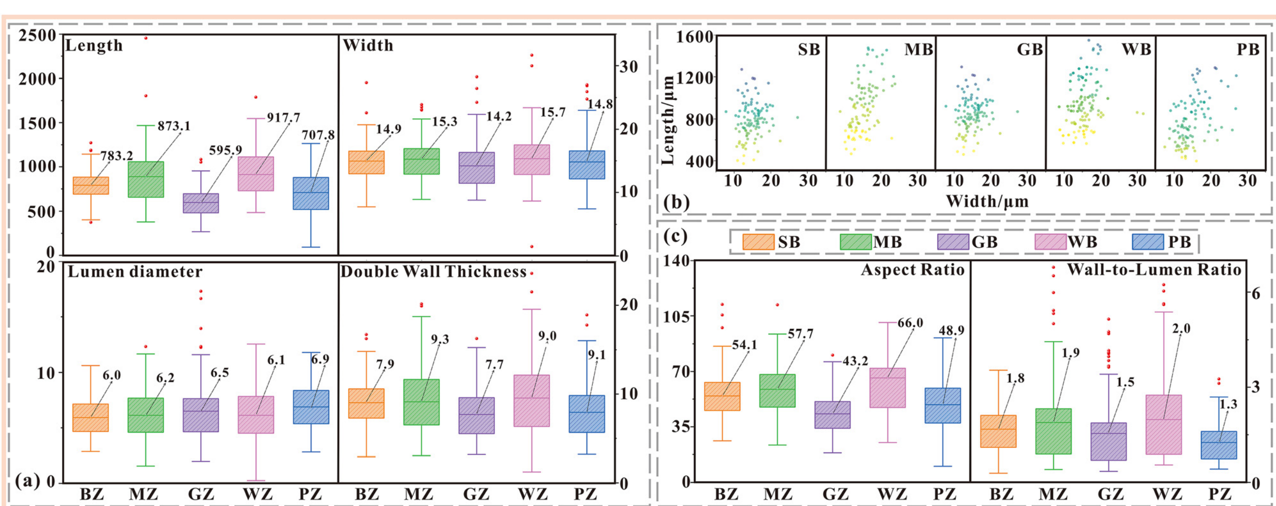

Figure 5: Fiber parameters. (a) The length, width, lumen diameter and double wall thickness; (b) scatter plot of fiber length and width; (c) the aspect ratio, and wall-to-lumen ratio parameters. SB: spotted bamboo, MB: moso bamboo, GB: golden bamboo, WB: water bamboo, PB: purple bamboo.

rhizome fibers, leading to lower overall strength and stiffness. Under bending or stretching forces, the fibers are more likely to detach. Moreover, the slightly larger wall-to-lumen ratio suggests that the fiber cell walls in bamboo rhizomes are relatively thicker, providing better structural support to withstand pressure.

Fiber length directly affects paper quality, such as fold endurance, burst strength, and tensile strength. Generally, the longer the fiber and the larger the fiber aspect ratio, the better the paper-making performance. Typically, fibers used for papermaking range from 0.4 to 5.0 mm in length (Zhu et al. 2018). Within this range, the longer the fiber, the greater the contact points, resulting in better paper quality after formation. Furthermore, Zhu et al. (2019) believed that a aspect ratio of fiber greater than 100 is necessary for high-quality papermaking materials, while a ratio less than 45 is unsuitable for papermaking. It is clear that the five bamboo rhizomes studied do not possess the advantages required for papermaking raw materials. However, shorter fibers contribute to better paper formation. In their study on aramid paper, Fan et al. (2020) found that when the short fibers content reached 20 %, not only did the paper achieve optimal tensile performance, but its tensile strength and Young's modulus also improved. Therefore, although the bamboo rhizomes studied are not ideal raw materials for papermaking, adding them in appropriate amounts to longer fibers could potentially result in paper with improved performance.

Additionally, a comparison of the fiber parameters of different bamboo rhizomes reveals that the WB-rhizome has the longest fibers (917.7 ± 264.7 µm) (Figure 5a), with the highest aspect ratio (66.0 ± 70.0) and wall-to-lumen ratio (2.0 ± 1.5) (Figure 5c). This indicates that its fibers are the longest and the cell walls are the thickest. Such a structure not only enhances the fibers' reinforcing role in composite systems but also improves their overall stiffness and load-bearing capacity, giving the WB-rhizome a significant advantage in mechanical properties. The MB-rhizome has fiber length (873.1 ± 278.7 µm) (Figure 5a), aspect ratio (57.7 ± 16.1) (Figure 5c), and wall-to-lumen ratio (1.9 ± 1.5) (Figure 5c) that are all relatively high, making its performance second only to that of the WB-rhizome, demonstrating excellent mechanical support and stability. In contrast, the SB-rhizome has medium fiber length (783.2 ± 189.8 µm) (Figure 5a), a moderate aspect ratio (54.1 ± 16.2) (Figure 5c), and a relatively high wall-to-lumen ratio (1.8 ± 1.0) (Figure 5c), indicating some advantages in stiffness, but due to the shorter fiber length, its reinforcing effect is limited. The PB-rhizome has lower fiber length (707.8 ± 247.3 µm) (Figure 5a), a lower aspect ratio (48.9 ± 15.9) (Figure 5c), and a lower wall-to-lumen ratio (1.3 ± 0.6) (Figure 5c), suggesting that its fiber walls are relatively thin, emphasizing flexibility over stiffness and strength. The GB-rhizome has the lowest fiber parameters overall (fiber length 595.9 ± 169.7 µm, aspect ratio 43.2 ± 12.5, wall-to-lumen ratio 1.5 ± 1.2) (Figure 5a–c), indicating that its fibers contribute the least to mechanical performance, showing weak overall load-bearing capacity.

3.4 Radial distribution of vessels of bamboo rhizome

Figure 6a–c show high-resolution cross-sectional images of bamboo rhizomes (12,800 dpi). Using a self-developed vessel detection model, these images were processed to extract detailed vessel characteristics, including the total number, density (number per unit area), average diameter, and area of single vessel. The different colored dots of the catheter are plotted out, as shown in Figure 6d. The color bar on the right side of Figure 6d further illustrates the size relationship: yellow dots for larger vessels and dark green dots for smaller ones. At the same time, the parameter of rhizomes vessels are summarized in Table 1. It reveals that the five bamboo rhizomes exhibit distinct differences in vessel number, density, and diameter. These structural features not only influence their material performance but also determine their potential suitability in different applications (Liese and Köhl 2015). First, regarding vessel diameter, the MB-rhizome and SB-rhizome exhibit the largest values, at 150.1 µm and 146.6 µm, respectively, significantly larger than those of the GB-rhizome (127.9 µm) and WB-rhizome (136.6 µm) (Table 1). According to the Hagen–Poiseuille law, the water transport capacity of a single vessel is proportional to the fourth power of its radius (Tyree and Zimmermann 2002). This indicates that MB-rhizome and SB-rhizome possess higher transport potential per vessel. However, an increase in vessel diameter is often associated with reduced mechanical strength, since larger vessels usually compromise tissue compactness (Hacke et al. 2006). Second, regarding vessel density, the WB-rhizome (16 vessels/mm^2) and GB-rhizome (15 vessels/mm^2) exhibit relatively high densities, whereas the MB-rhizome shows the lowest (10 vessels/mm^2) (Table 1). High-density vessel distribution contributes to conductive safety, as even if some vessels are blocked, redundant pathways can maintain transport function (Carlquist 2012). Furthermore, high-density, small-diameter vessels often indicate more compact microstructures, which enhance crack resistance and durability. Finally, in terms of vessel number, the MB-rhizome (1,410) and SB-rhizome (1,249) contain significantly more vessels compared with the PB-rhizome (931) and WB-rhizome (985) (Table 1). Although a greater number of vessels can increase overall permeability, insufficient density or excessively large diameters may diminish mechanical efficiency. Thus, the MB-rhizome, with large number and diameter but low density, is more suited for permeability-related functions rather than load-bearing applications. In contrast, the GB-rhizome, with fewer vessels and smaller diameter but high density, shows greater potential for structural durability applications.

Compared with the vessel characteristics of common bamboo culms, the vessels in bamboo rhizomes generally fall into a larger diameter range (127.9–150.1 μm) and exhibit medium-to-high densities (10.2–16.3 vessels/mm^2) (Table 1). Previous studies have shown that vessel diameters in bamboo culms typically range from 50 to 200 μm, with densities mostly between 5 and 20 vessels/mm^2 (Liese 1998; Grosser and Liese 1971). Therefore, the distribution of vessel number, density, and diameter in bamboo rhizomes is largely comparable to that of culms. This suggests that bamboo rhizomes may hold greater potential for modification and functional applications, such as adsorption, flame retardancy, or composite fabrication, while their performance in load-bearing applications may be less stable than that of bamboo culms (Sharma et al. 2015).

To further examine the radial variation in vessel shape and size within the cross-section of bamboo rhizomes, scanning electron microscopy (SEM) was employed. The results are presented in Figure 6b, where distinct differences in vessel dimensions and distribution along the radial direction can be clearly observed. Furthermore, based on prior work (Xu et al. 2024) that vessel distribution in bamboo culm cross-sections follows a radial exponential function, the radial distribution of vessel area in bamboo rhizomes was fitted accordingly, as described in Equation (1). The fitted curves are shown as red lines in Figure 6e, with the coefficient of determination (R^2) and the significance level (P-value) also provided. It can be observed that the vessel

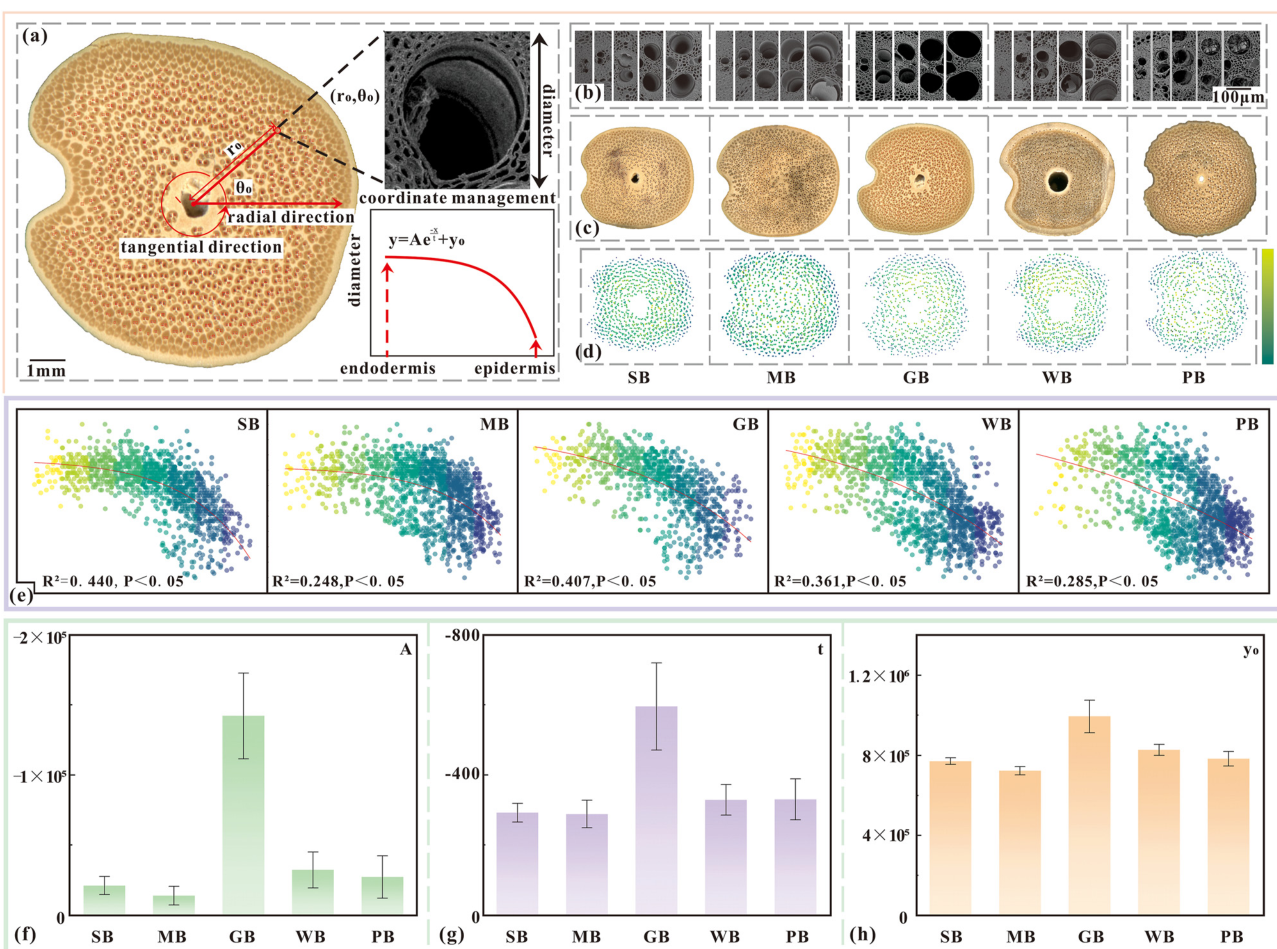

Figure 6: Vessel morphology and distribution. (a) Extraction of vascular features; (b) vessel size variation; (c) vessel radial changes; (d) vessel scatter plot; (e) curve fitting of blood vessel area; (f) change in parameter A; (g) change in parameter t; (h) change in parameter y_0. SB: spotted bamboo, MB: moso bamboo, GB: golden bamboo, WB: water bamboo, PB: purple bamboo.

Table 1: Parameters of vessels of five bamboo rhizomes.

	Number (pcs)	Density (pcs/mm^2)		Diameter (μm)	Area (μm^2)	A	t	y_0
SB	1,249	14	Average	146.6	21,478.1	−21,104.8	−292.0	771,247.1
			SD	18.5	4,954.8	6,331.5	26.7	16,613.6
MB	1,410	10	Average	150.1	22,522.5	−13,947.1	−288.3	723,405.0
			SD	25.2	6,956.0	6,656.9	39.5	20,636.2
GB	932	15	Average	127.9	16,366.7	−142,124.0	−595.3	994,190.7
			SD	21.1	4,906.7	30,561.8	124.3	80,665.8
WB	985	16	Average	136.6	18,662.8	−32,177.0	−328.6	827,758.2
			SD	22.0	5,463.3	12,742.5	43.7	27,467.8
PB	931	13	Average	138.1	19,060.5	−27,173.4	−330.2	783,510.4
			SD	24.9	6,398.1	15,091.1	58.6	36,609.0

SB: spotted bamboo, MB: moso bamboo, GB: golden bamboo, WB: water bamboo, PB: purple bamboo.

areas in bamboo rhizomes exhibit a radial distribution trend, gradually decreasing from the pith outward. The fitted model reveals a significant negative correlation, consistent with the distribution patterns reported for bamboo culms (Grosser and Liese 1971; Liese 1998). The parameter A portion reflects the average vessel diameter for each sample, while the magnitude of t indicates the rate of change. Among the studied rhizomes, GB-rhizome shows the fastest decline in vessel diameter, followed by PB-rhizome and WB-rhizome, while SB-rhizome and MB-rhizome display the slowest trends (Figure 6g). However, the explanatory power of the model remains limited ($R^2 < 0.5$), suggesting that, in addition to radial position, other factors such as developmental stage or local structural variations may also influence vessel dimensions (Zhang et al. 2017). In previous studies, the correlation models between vessel areas and radial position in bamboo culms showed R^2 values greater than 0.9, indicating strong explanatory power. The difference between the bamboo rhizomes and culms may be attributed to the incomplete evolutionary development of vascular bundles in bamboo rhizomes, where their distribution and size randomness are much higher than in bamboo culms (Xu et al. 2024). Nevertheless, to adapt to the underground environment, bamboo rhizomes retain the feature of larger inner vessels and smaller outer ones. The radial extent of the region containing large vessels is influenced by external factors such as temperature, humidity, and precipitation, and this distribution, ensures safe and efficient water transport.

$$y = Ae^{\frac{-x}{t}} + y_0 \tag{1}$$

where, y represents the vessel area, and x denotes the distance between the vessel and the geometric center of the rhizome. A is the constant term of the function, and a larger A generally indicates a greater average vessel diameter for the sample. e is the base of the natural logarithm. t is the constant in the exponent of x, which directly affects the curvature of the function and essentially determines the rate of change in vessel diameter. y_0 can be regarded as a correction factor. All the parameters of the 5 types of bamboo rhizomes have been calculated and are presented in Figure 6f.

3.5 The main chemical composition of bamboo rhizomes

Table 2 presents the main chemical composition of the five bamboo rhizomes, including cellulose, hemicellulose, and lignin, which are the same as those of bamboo culms. These three macromolecules jointly constitute the fundamental framework of the cell wall. Cellulose, the primary structural polysaccharide, exists in the form of microfibrils and provides the essential strength and stiffness of bamboo (Li et al. 2018). Hemicellulose fills the space between cellulose and lignin. Its strong hydrophilicity imparts flexibility and plasticity to the material, but also increases hygroscopicity. Lignin, a three-dimensional cross-linked aromatic polymer, enhances hardness and compressive resistance while improving durability against decay and biological degradation (He et al. 2016; Huang et al. 2019). Variations in the relative proportions of these three components directly determine the mechanical performance, durability, and environmental adaptability of different bamboo species.

From the perspective of cellulose content, PB-rhizome exhibits the highest proportion (39.4 %), suggesting strong load-bearing potential and structural rigidity. By contrast, SB-rhizome shows the lowest cellulose content (29.7 %), implying lower mechanical strength and stiffness. However, this weakness is partly compensated by its higher lignin content, which contributes to hardness and resistance. MB-rhizome and GB-rhizome show similar cellulose levels (35.7 % and 35.3 %, respectively), both in the medium-to-high

Table 2: The main chemical compositions of five bamboo rhizomes.

	Cellulose (%)	Hemicellulose (%)	Acid-insoluble lignin (%)	Acid-soluble lignin (%)	Lignin (%)	The three major substances (%)
SB	29.7	26.6	29.7	1.9	31.6	87.9
MB	35.7	26.2	28.3	1.7	30.0	91.9
GB	35.3	23.6	28.5	1.7	30.2	89.1
WB	33.1	25.8	29.4	1.6	31.0	89.9
PB	39.4	20.1	25.0	1.4	26.4	85.9

SB: spotted bamboo, MB: moso bamboo, GB: golden bamboo, WB: water bamboo, PB: purple bamboo.

range, indicating generally favorable mechanical performance.

Besides, the variation in hemicellulose content also carries significant implications. The SB-rhizome exhibits the highest hemicellulose proportion (26.6 %), suggesting greater sensitivity to moisture changes and stronger hygroscopicity, which provides certain flexibility but may compromise dimensional stability and durability (Hill and Callum 2006; Rowell 2012). In contrast, the PB-rhizome shows the lowest hemicellulose content (20.1 %), resulting in better dimensional stability and resistance to humid environments, albeit with reduced flexibility. The other rhizomes (MB-rhizome, WB-rhizome, and GB-rhizome) fall within an intermediate range, reflecting a relatively balanced performance.

Furthermore, in terms of lignin, both SB-rhizome and WB-rhizome demonstrate higher proportions (31.6 % and 31.0 %, respectively) (Table 2), which provide superior hardness and resistance to microbial degradation. This characteristic enhances their ability to adapt to underground environments that are moist and rich in microorganisms (Boerjan et al. 2003). In contrast, PB-rhizome shows the lowest lignin content (26.4 %) (Table 2), which may favor toughness and mechanical performance but limits its durability and environmental adaptability. MB-rhizome and GB-rhizome remain at intermediate levels (30.0 % and 30.2 %) (Table 2), thereby balancing mechanical strength and long-term stability.

Overall, the compositional characteristics of the three major constituents clearly reveal the functional differences among the bamboo rhizomes. The PB-rhizome, with its high cellulose content, demonstrates favorable mechanical performance; however, its relatively low lignin and hemicellulose proportions limit its durability. The MB-rhizome shows the highest total content of the three components (91.9 %) (Table 2), indicating the most balanced composition and thus providing stable and comprehensive performance. Similarly, the GB-rhizome, with compositional ratios close to those of MB-rhizome, also exhibits advantageous overall performance. The WB-rhizome, due to its higher lignin content, possesses enhanced durability and resistance to biodegradation. In contrast, the SB-rhizome, characterized by the highest proportions of both lignin and hemicellulose, presents superior hardness and corrosion resistance, but its limited cellulose content constrains its mechanical performance.

In addition, noteworthy differences are observed between the chemical composition of bamboo rhizomes and that of common bamboo culms. Bamboo culms typically contain a higher proportion of cellulose (40–55 %), which provides excellent strength and elasticity (Hossain et al. 2022). In contrast, the cellulose content of bamboo rhizomes is considerably lower (29.7–39.4 %) (Table 2), indicating their relatively weaker mechanical strength. Conversely, the lignin content of bamboo rhizomes is generally higher (26.4–31.6 %) (Table 2), endowing them with greater hardness, durability, and resistance to microbial degradation, which facilitates adaptation to underground environments that are moist and microorganism-rich. Hemicellulose contents show smaller differences between rhizomes and culms. Overall, the chemical composition of bamboo rhizomes suggests that they are more oriented toward durability and resistance to degradation.

4 Conclusions

This study conducted a systematic and in-depth analysis of the anatomical structures and chemical compositions of five common bamboo rhizomes, with conventional bamboo culms serving as a reference. Furthermore, a comparative evaluation among the five rhizome types was carried out, through which their common characteristics and distinctive differences were summarized. Overall, bamboo rhizomes and culms shared a similar macroscopic framework, both consisting of parenchyma tissues and vascular bundles, with cellulose, hemicellulose, and lignin as their primary chemical constituents. However, rhizomes exhibited a higher proportion of vascular tissues, with vessel diameters falling within the upper range of those in bamboo culms and with higher vessel density, highlighting their stronger roles in water conduction and storage. In terms of fiber characteristics, rhizome fibers were generally short and thick. Although this morphology provided a certain degree of stiffness, their strength and toughness were inferior to those of fibers of culms. Moreover, vascular bundles in rhizomes did not display the distinct radial gradient commonly observed in culm cross-sections. Chemically, rhizomes contained less cellulose but a higher proportion of lignin. This composition partly compromised their mechanical strength but enhanced durability and resistance. Differences also existed among species: WB-rhizome and MB-rhizome possessed longer fibers with thicker walls, combined with relatively high fiber proportions and cellulose contents, resulting in superior mechanical performance. In contrast, SB-rhizome showed a higher proportion of vessels, which favors conduction but provided weaker support. PB-rhizome and GB-rhizome had shorter fibers with lower wall-to-lumen ratios, offering limited reinforcement and weaker overall mechanical potential.

These findings indicated that the performance of bamboo rhizomes was not solely determined by chemical composition but also regulated by the interplay of fiber morphology and tissue proportions. In summary, the anatomical and chemical features of rhizomes defined a functional specialization distinct from culms, which in turn shaped their performance characteristics and potential applications. This study provided systematic data to elucidate rhizome structural traits and laid a foundation for their further exploration in high-value utilization and functional development.

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References

Ai, L., Dai, Y., Chen, F., Yang, H., Ma, J.M., Bai, K.D., and Yang, Z.Q. (2024). Dynamic changes of soil metabolite profiles during moso bamboo (*Phyllostachys edulis* (Carrière) J. Houz.) expansion into adjacent planted forests in a typical karst river basin, South China. *Appl. Soil Ecol.* 203: 10567.

Amada, S. and Untao, S. (2001). Fracture properties of bamboo. *Compos. Part B: Eng.* 32: 451–459.

Boerjan, W., Ralph, J., and Baucher, M. (2003). Lignin biosynthesis. *Annu. Rev. Plant Biol.* 54: 519–546.

Carlquist, S. (2012). How adaptation to arid climates shapes wood structure. *Bot. Rev.* 78: 305–333.

Chaowana, P., Barbu, M.C., and Fruhwald, A. (2015). Bamboo—a functionally graded composite material. *For. Prod. J.* 65: S48–S55.

Fan, X., Zhang, S., and Yang, T. (2020). The effect of short fiber content on the mechanical properties of aramid paper. *J. Mater. Sci.* 55: 1342–1350.

Gong, Z. and Zhao, H. (1990). Comparative anatomical observation and preliminary taxonomy of underground stems of domestic bamboo species. *J. Nanjing Norm. Univ. (Nat. Sci. Ed.)*: 62–69, [in Chinese].

Grosser, D. and Liese, W. (1971). On the anatomy of Asian bamboos, with special reference to their vascular bundles. *Wood Sci. Technol.* 5: 290–312.

Guo, L., Plunkert, M., Luo, X., and Liu, Z. (2020). Developmental regulation of stolon and rhizome. *Curr. Opin. Plant Biol.* 59: 101970.

Hacke, U.G., Sperry, J.S., Wheeler, J.K., and Castro, L. (2006). Scaling of angiosperm xylem structure with safety and efficiency. *Tree Physiol.* 26: 689–701.

He, M., Wang, H., and Chen, J. (2016). Structural features and chemical composition of bamboo cell walls. *Wood Sci. Technol.* 50: 953–965.

Hill, C.A.S. and Callum, A.S. (2006). *Wood modification: chemical, thermal and other processes*. Wiley, Chichester.

Hossain, M.J., Ghosh, R.K., Das, A.K., Maryana, R., Nath, S.C., Islam, M.R., and Sarker, S.C. (2022). Effect of age and height on the chemical properties of Muli Bamboo (Melocanna baccifera). *ACS Omega* 7: 36568–36575.

Hu, T., Xu, T., Wei, Q., Yang, G.Y., and Yu, F. (2021). Changes in starch granules during growth of bamboo culms. *Nw. Plant Sci. J.* 41: 1843–1852, [in Chinese].

Hu, Y., Zhao, J., and Wang, Q. (2024). Structural adaptation of bamboo rhizomes in nutrient and water distribution. *Bamboo Sci. J.* 48: 98–106.

Huang, X., Jiang, Z., and Fei, B. (2019). Chemical composition and natural durability of bamboo materials. *J. Renew. Mater.* 7: 713–724.

Ito, R., Miyafuji, H., and Kasuya, N. (2014). Characterization of the rhizome of moso bamboo. *J. Soc. Mater. Sci., Japan* 63: 865–870.

Ito, R., Miyafuji, H., and Kasuya, N. (2015). Rhizome and root anatomy of moso bamboo (*Phyllostachys pubescens*) observed with scanning electron microscopy. *J. Wood Sci.* 61: 431–437.

Ji, S. (2024). *Mechanical properties and structural superiority verification of original Moso bamboo material*, PhD dissertation. Central South University of Forestry and Technology, Changsha, China [in Chinese].

Kamthai, S. and Vaivudh, S. (2012). Comparative study on chemical composition and mechanical properties of five bamboo species. *BioResources* 7: 5700–5711.

Kotangale, P., Agashe, A., Sawarkar, R., Dewangan, C., Tijare, G., and Singh, L. (2025). Unlocking the hidden power of bamboo rhizomes: a comprehensive review of their role in nutrient storage, water retention, and plant growth. *Adv. Bamboo Sci.* 10: 100122.

Latif, M. and Mohd, T.M. (1992). Variation in anatomical properties of three Malaysian bamboos from natural stands. *J. Trop. For. Sci.* 5: 90–96.

Li, D., Yang, S., Liu, Z., Wang, Z., Ji, N., and Liu, J. (2023). Effects of heat treatment under different pressures on the properties of bamboo. *Polymers (Basel)* 15: 143074.

Li, H., Zhu, Q., Lu, P., Chen, X., and Xian, Y. (2024). The gradient variation of location distribution, cross-section area, and mechanical properties of Moso Bamboo vascular bundles along the radial direction. *Forests* 15(6): 1023.

Li, X., Feng, J., and Xu, Y. (2018). Influence of cellulose and lignin contents on the mechanical properties of bamboo fibers. *Ind. Crops Prod.* 112: 378–383.

Li, X., Shen, S., and Fu, F. (2013). Chemical composition and mechanical properties of bamboo. *Wood Sci. Technol.* 47: 627–638.

Li, Y.G., Xue, L., Fan, L.L., Ye, L.T., Chen, L.Y., He, T.Y., and Zheng, Y.S. (2019). Research progress on germplasm resources and application value of *Phyllostachys* plants. *J. Sichuan For. Sci. Technol.* 40: 117–122, [in Chinese].

Lian, C.P., Chen, H., Zhang, S., Liu, R., Wu, Z., and Fei, B. (2022). Characterization of ground parenchyma cells in moso bamboo (*Phyllostachys edulis* – Poaceae). *IAWA J.* 43: 421–432.

Lian, C.P., Yang, J., Luo, J.J., Zhang, S.Q., Liu, R., Chen, H., Wang, X.H., Cao, M.X., Wu, Z., and Fei, B. (2022a). Microfibril orientation of the secondary cell wall in parenchyma cells of *Phyllostachys edulis* culms. *Cellulose* 29: 3153–3161.

Lian, C.P., Wang, X.H., Chen, H., Fei, B.H., Pang, X.R., Lian, J.C., and Wu, Z.H. (2022b). Using statistical methods to comparatively analyze the visual characteristics of flattened bamboo boards in different bamboo culms. *Polymers (Basel)* 14: 4327.

Liese, W. (1998). The anatomy of Bamboo culms. INBAR Technical Report No. 18. International Network for Bamboo & Rattan.

Liese, W. and Köhl, M. (2015). *Bamboo: the plant and its uses*. Springer, Cham, Switzerland.

Liu, S. (2015). *Preliminary study on high-value utilization of Moso bamboo rhizomes*, Master's thesis. Anhui Agricultural University, [in Chinese].

Luo, X., Zhang, L., and Li, H. (2020). Study on the nutrient transport mechanisms in bamboo rhizomes. *J. Bamboo Res.* 45: 123–132, [in Chinese].

Ming, C., Lin, G., Xiao, Z., Mingyun, J., Ru, W., Yulong, D., Gao, Z., and Wei, Q. (2018). Comparison of cell morphology of Moso bamboo fibers from fifteen main producing regions in China. *J. Nanjing For. Univ. (Nat. Sci. Ed.)* 42: 7–12.

Niu, S., Wang, N., Cui, B., Wang, C.G., Wu, H., and Zhang, S.Y. (2023). Effects of different ages and positions on fiber morphology and crystallinity of Phyllostachys edulis. *J. Zhejiang A F Univ*. 40: 446–452.

Pan, X., Li, S., and Chen, Y. (2025). Functional roles of bamboo rhizomes in water and nutrient absorption. *Bamboo Studies* 52: 65–75.

Ray, A.K., Mondal, S., Das, S.K., and Ramachandrarao, P. (2005). Bamboo—a functionally graded composite: correlation between microstructure and mechanical strength. *J. Mater. Sci.* 40: 5249–5253.

Rowell, R.M. (2012). *Handbook of wood chemistry and wood composites*. CRC Press, Boca Raton.

Sharma, B., Gatóo, A., Bock, M., and Ramage, M.H. (2015). Engineered bamboo for structural applications. *Constr. Build. Mater.* 81: 66–73.

Sluter, A., Hames, B.R., Ruiz, R., Scarlata, C.J., and Sluiter, J. (2012). *Determination of structural carbohydrates and lignin in biomass (NREL/TP-510-42618, Rev. 08-03-2012)*. National Renewable Energy Laboratory, https://www.nrel.gov/docs/gen/fy13/42618.

Sun, H., Li, X., Li, H., Hui, D., Gaff, M., and Lorenzo, R. (2022). Nanotechnology application on bamboo materials: a review. *Nanotechnol. Rev.* 11: 1670–1695.

Tyree, M.T. and Zimmermann, M.H. (2002). *Xylem structure and the ascent of sap*. Springer.

Wang, X. (2024). Topicalities in the research and application of bamboo and wood. *Forests* 15: 11917.

Wang, X. and Cheng, K.J. (2020). Effect of glow-discharge plasma treatment on contact angle and micromorphology of bamboo green surface. *Forests* 11: 1293.

Wen, T.H. and Chou, W.W. (1984). A report on the anatomy of the vascular bundle of bamboos from China (I). *J. Bamboo Res.* 3: 1–21.

Wu, Y., Wu, X.Y., Shi, T.L., Chen, H., Wang, H.K., Sun, M., and Zhang, J.L. (2019). The microstructure and mechanical properties of poplar catkin fibers evaluated by atomic force microscope (AFM) and nanoindentation. *Forests* 10: 938.

Wu, J., Zhong, T., Zhang, W., Shi, J., Fei, B., and Chen, H. (2021). Comparison of colors, microstructure, chemical composition and thermal properties of bamboo fibers and parenchyma cells with heat treatment. *J. Wood Sci.* 67: 56.

Xiang, E.L., Liu, X.E., Tian, G.L., Ma, J.F., Yang, S.M., and Wang, Y.G. (2019). Comparative study of anatomical characteristics of four clumping bamboo species in Guangxi. *China Paper* 34: 1–6.

Xu, H., Tian, F., She, Y., Wang, S., Su, N., and Xu, X. (2024). The robust hydraulic system in moso bamboo: unveiling the spatial distribution of metaxylem vessels. *Ind. Crops Prod.* 216: 118772.

Zhang, Y., Liu, M., and Li, J. (2017). The impact of fiber morphology on the mechanical properties of bamboo composites. *Compos. Sci. Technol.* 150: 84–92.

Zhu, H., Li, X., and Wang, J. (2018). Influence of fiber length on the papermaking properties of bamboo fibers. *J. Pulp Pap. Sci.* 44: 220–227.

Zhu, H., Li, Z., and Zhang, W. (2019). The effect of fiber length-to-width ratio on paper quality. *Appita J.* 72: 245–251.