Progress in the Study of Dry Shrinkage Deformation and Drying Stress of Raw Bamboo

Jiayi Zhu,[a] and Lin Yang [a,b,*]

Bamboo is a sustainable material that supports carbon sequestration and helps address the imbalance of timber supply *vs.* demand. Drying is a crucial step in bamboo processing, in the course of which shrinkage and stress accumulation can lead to defects such as cracking and deformation. Understanding stress and strain development during drying is critical for improving bamboo processing. This review paper explores bamboo's gradient structure and moisture migration characteristics, focusing on the mechanisms behind shrinkage strain formation and the sources of stress. It reviews literature on bamboo drying and cellular structural changes, evaluating the evolution of stress and strain testing methods, from traditional sectioning techniques to advanced methods such as digital imaging and acoustic emission. The paper also summarizes progress in stress-strain research at both macroscopic and cellular scales. Current challenges include species-specific shrinkage variations, limitations in measurement techniques, and insufficient research on shrinkage above the fiber saturation point. To address these issues, the study recommends developing universal theoretical models, employing advanced detection technologies, comparing shrinkage patterns between bamboo culms and nodes, exploring drying stress composition, and adopting multi-scale research approaches. These strategies aim to enhance the quality of bamboo processing and promote higher-value applications within the industry.

DOI: 10.15376/biores.20.1.Zhu

Keywords: Bamboo drying; Raw bamboo; Shrinkage strain; Drying stress; Moisture content

Contact information: a: College of Furnishings and Industrial Design, Nanjing Forestry University, Nanjing 210037 China; b: Jiangsu Co-Innovation Center of Efficient Processing and Utilization of Forest Resources, Nanjing Forestry University, Nanjing 210037, China;
** Corresponding author: yanglin@nifu.edu.cn*

INTRODUCTION

Raw bamboo is a material that retains its original form, including full cross-sectional tubes and partial cross-sectional slices (Tian *et al.* 2018). Regardless of origin, species, age, and harvesting site, issues related to drying and shrinkage are topics of importance for raw bamboo. It is susceptible to moisture and can easily interact with environmental humidity, resulting in dry shrinkage or wet swelling (Hone *et al.* 2020). This moisture sensitivity results in poor dimensional stability (Li *et al.* 2022). Thus, this review article considers studies aimed at improving raw bamboo's drying and shrinking characteristics is crucial for its subsequent processing and utilization.

Drying is an essential step in bamboo processing, as proper drying treatments can improve its physical properties, mechanical properties, and dimensional stability (Li *et al.* 2003). Dry shrinkage is a critical indicator for assessing the performance and stability of bamboo. A greater degree of dry shrinkage increases the risk of cracking and warping after the bamboo is processed into panels (Cui *et al.* 2010). Studying bamboo shrinkage provides a scientific basis for optimizing drying parameters and improving processing and utilization methods. However, raw bamboo’s gradient structure and the uneven moisture content distribution during drying result in anisotropic drying strains, which generate drying stresses. These stresses vary in direction and can interact with one another, leading to defects such as cracking, warping, and crumpling upon accumulation, significantly affecting the efficiency of bamboo processing and utilization (Qi *et al.* 2023). Therefore, an in-depth study of the drying strain and drying stress of raw bamboo is of great theoretical and practical significance for optimizing the drying process (Wang *et al.* 2014; Dong *et al.* 2023).

Research on drying shrinkage strain and stress in raw bamboo is limited. While past studies have explored bamboo’s structure and its effect on drying strain, they have not fully addressed species differences, measurement limitations, or shrinkage beyond fiber saturation. These gaps hinder a complete understanding of bamboo drying and limit processing improvements.

This paper aims to fill these gaps by examining bamboo’s gradient structure, moisture migration’s effect on shrinkage, and the mechanisms behind drying stress. It will also review and compare the latest methods for measuring stress and strain. The goal is to provide insights and guidance to improve bamboo utilization and promote higher-quality, value-added products.

GRADIENT STRUCTURE AND WATER TRANSPORT MECHANISM OF THE ORIGINAL BAMBOO

Gradient Structure and Properties of Raw Bamboo

Bamboo material commonly used in the industry is primarily sourced from the culm sections. From a macro perspective, raw bamboo features staggered nodes and exhibits variable cross-sections that taper and curve. Each bamboo culm features a hollow interior surrounded by a three-layered bamboo wall structure. The outer layer, known as bamboo green due to its dense vascular bundles, contrasts with the inner layer, bamboo yellow, which is characterized by sparse vascular bundles (Zhou *et al.* 2024). Bamboo timber, positioned between bamboo green and bamboo yellow, serves as an intermediary layer (Chand *et al.* 2006; Zhiqian Li *et al.* 2014). As depicted in Fig. 1, studies have shown that bamboo nodes typically include sheath marks, nodal ridges, and diaphragms, which effectively prevent longitudinal splitting of the bamboo culm (Han *et al.* 2023; Jia *et al.* 2024).

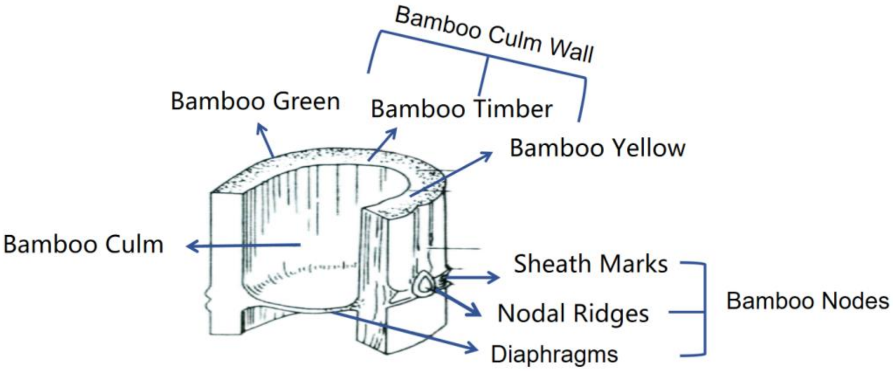

Fig. 1. Macrostructure of bamboo

Microstructural observations show that bamboo is mainly composed of longitudinal tissues, including essential tissues and vascular bundles. The primary tissue consists of thin-walled cells for storage, while vascular bundles contain bamboo fibers and transport tissues including ducts and sieve tubes (Xian *et al*. 1990). Bamboo fibers are thick-walled cells that significantly influence the mechanical strength of bamboo and the transport of nutrients such as water and inorganic salts (Ray *et al*. 2005; Xu *et al*. 2007). Thus, vascular bundle distribution impacts the drying and shrinkage of bamboo. The gradient structure of bamboo results from differences between bamboo fibers and thin-walled cells.

The density of raw bamboo decreases from the bottom to the top, and its cellulose content varies with height, which contributes to differences in linear drying shrinkage at different heights (Guangrong Li *et al*. 2014). At the same height, the content of vascular bundles increases radially from the inside out, with fiber volume fraction following an exponential distribution (Ding *et al*. 2006). The variations in radial, tangential, and longitudinal shrinkage rates align with the distribution patterns of vascular bundles and thin-walled cells, as shown in Fig. 2. Li *et al*. (2021) noted the largest difference in shrinkage rates between radial and tangential directions in the bamboo yellow section, both in air-drying and full-drying conditions. This significant shrinkage difference makes the bamboo yellow prone to cracking and deformation, so controlling its shrinkage is a key focus. The functional gradient properties of raw bamboo arise from the anisotropic distribution of vascular bundles in longitudinal, radial, and tangential directions, leading to variations in mechanical properties.

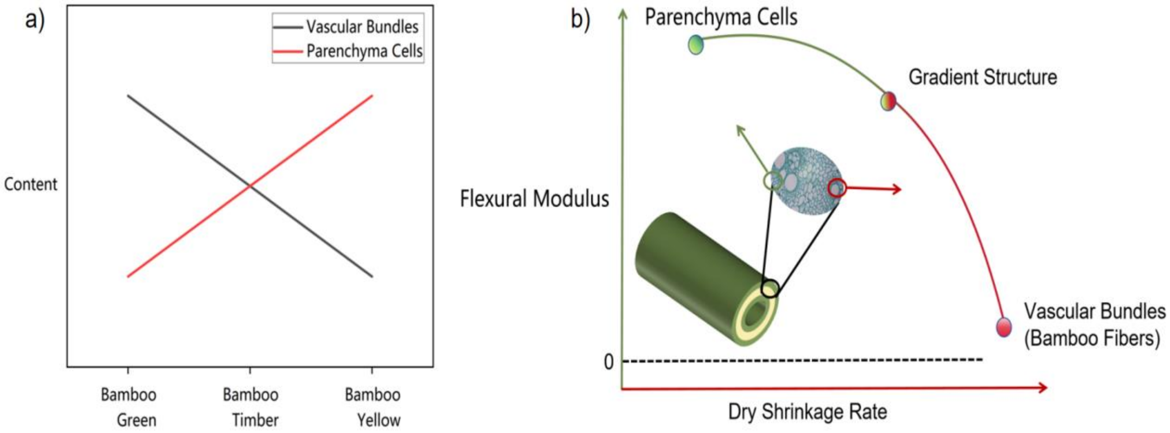

Fig. 2. a) Chemical composition of raw bamboo layers; b) Relationship between gradient structure and dry shrinkage of raw bamboo

The anisotropy of raw bamboo significantly affects drying shrinkage and stress variations across different parts, influencing product properties. Drying is crucial in bamboo processing, as it changes the material from brittle to rigid as moisture content decreases (Xu *et al*. 2014). A comprehensive understanding of drying deformation and stress can improve dimensional stability and support industry advancements toward higher quality and greater value.

Moisture Transport Mechanisms

The deformation of raw bamboo is significantly influenced by moisture, which affects its entire life cycle. During changes in moisture content, defects such as cracking and deformation may occur. Changes in the dimensions of sieve tubes and conduits in bamboo are most pronounced in the saturated and completely dry states, with moisture content (MC) serving as a critical indicator of bamboo's moisture characteristics. Inside the bamboo are numerous pores, including a sizeable capillary system and a microcapillary system, both of which serve as water storage spaces and channels for water movement.

Bamboo's moisture is categorized into two types: bound water and free water (Lv *et al.* 2021). The fiber saturation point (FSP), typically between 25% and 30% (Guan *et al.* 2003), indicates the water content when free water has completely evaporated while bound water remains in the cell walls.

When the MC exceeds the FSP, free water evaporates first from the bamboo's surface and moves through the large capillaries. This process is osmotic, driven by differences in capillary tension (Han *et al.* 2012). Since free water is not chemically bound to the cell walls, it evaporates mainly from the bamboo's outer surface, influenced by environmental humidity. This rapid evaporation causes significant moisture migration and fluctuations in MC, creating a drying gradient as moisture moves from the inside to the exterior, affecting drying behavior.

Once the MC falls below the FSP, bamboo's physical and mechanical properties change markedly; at this stage, accessible water is largely absent from the cell lumens, leaving only bound water in the cell walls. The internal moisture content remains higher than the external content, creating a gradient that drives water from high to low moisture areas. Bound water migrates through microcapillaries until equilibrium moisture content (EMC) is reached (Sun *et al.* 2006).

Raw bamboo's moisture migration follows a hierarchical gradient structure, leading to varying moisture transport efficiency along the longitudinal and radial directions (Zhan *et al.* 2020). Moisture diffuses faster in higher or outer radial regions. The higher porosity (38.9%) and larger pore size (15.0 nm) of the inner internode allow moisture to enter the bamboo cavity through the inner surface. Radial moisture distribution is asymmetric, with higher moisture at the center and lower at the sides. During drying, most moisture migrates outward along the gradient through the outer surface, while a smaller amount moves inward through the inner surface and slowly passes through the bamboo diaphragm, influenced by temperature (Cheng *et al.* 2024). Understanding this moisture migration is key to optimizing drying methods and improving bamboo material properties.

FORMATION MECHANISM OF DRYING SHRINKAGE STRAIN OF RAW BAMBOO AND THE ROLE OF DRYING STRESSES

Principle of the Formation of Dry Shrinkage and Deformation of Raw Bamboo

Raw bamboo is a porous material characterized by an anisotropic structure closely related to water movement. It can absorb or release water in response to ambient temperature or humidity changes. During drying, cells initially saturated with water generate surface capillary tension as free water in the cell lumen moves outward through the striated pore membranes (Zhang *et al.* 2020). This process induces drying stress (Hunter 2001; Kang *et al.* 2011). When the sum of these tensions exceeds the lateral limit compressive strength of the cells, irregular collapse and contraction occur (Wang *et al.* 2013), resulting in shrinkage.

When the moisture content (MC) exceeds the fiber saturation point (FSP), the collapse of thin-walled tissues, reduction in cell wall thickness, and decrease in cell diameter occur due to the evaporation of free and bound water within the cell walls (Patera *et al.* 2013). This gradual free water loss leads to crumpling (Han *et al.* 2012) and drying strain (Vetter *et al.* 2015). At this stage, the outer layer of bamboo shrinks more than the inner layer (Zhong *et al.* 2009), making the shrinkage similar to that of wood (Liu *et al.* 2024b). The evaporation of free water from the cell lumen causes capillary tension to gradually decrease or disappear (Yan *et al.* 2022).

When the MC falls below the FSP, water movement primarily involves bound water, driven by the water content gradient. In this state, the microcapillary system in the cell wall voids facilitates water movement through diffusion. The macroscopic manifestation of shrinkage in bamboo is a change in size, resulting from the interaction of water inside and outside the cell walls, which leads to cell deformation (Patera *et al.* 2013). The primary cause of desiccation in raw bamboo is water loss from the cell walls (Vetter *et al.* 2015). At the cellular level, the shrinkage of bamboo results from the collective actions of multiple cells, with varying degrees of shrinkage among different cell types. Bamboo fibers play a decisive role in this process, exhibiting a significantly higher degree of dry shrinkage than thin-walled cells (Lou *et al.* 2021).

Cell displacement and deformation co-occur during the contraction process, with contraction stress primarily concentrated in the intercellular layer of the fibers (Yuan *et al.* 2023). Additionally, due to the gradient distribution of bamboo fibers in the vascular bundles, the tangential shrinkage stress on the green side of the culm wall is greater than that on the yellow side, increasing the likelihood of cracking in the bamboo material (Chen *et al.* 2019).

Measurement of drying shrinkage of raw bamboo

Strain is a physical quantity that reflects the degree of deformation, and studying the dry shrinkage strain of raw bamboo aims to understand its drying stress state. The stress-strain research methods for raw bamboo are analogous to those used for wood, although bamboo research has developed later. Due to the gradient structure of raw bamboo, measurement methods are less diverse compared to wood. The measurement techniques are primarily categorized into two main types: direct-contact and non-contact measurements. These include the slice, electrodiagnostic, digital scattering, and acoustic emission methods. The steps, advantages, and disadvantages of each measurement method are summarized in Table 1.

ANALYSIS OF DRY SHRINKAGE STRAIN PATTERN OF RAW BAMBOO

Relationship between drying strain and drying stress

The drying stress refers to the internal stress generated during the drying process due to the gradient differences in MC (Liu *et al.* 2023b; Zhang *et al.* 2024), which is the main factor causing drying defects such as cracking, internal fractures, and warping deformation. Given the challenges of directly measuring drying stress, it is typically analyzed and studied indirectly by measuring strain, which reflects the stress values. Throughout the drying process, the occurrence and development of stress are complex, with both the direction and magnitude undergoing dynamic changes. Additionally, different parts of the material experience significant variations in stress (Jiang *et al.* 2002).

Table 1. Measurement Methods for Stress and Strain in Raw Bamboo

Measurement Methods		**Steps**	**Advantages**	**Disadvantages**	**References**
Direct Contact Measurement	Slicing	There are two slicing methods: the first involves thin slices, measuring the length, and stabilized linear displacement after bending deformation. The second uses hollow rings, measuring changes in wall thickness and diameter.	It intuitively reflects the drying and shrinkage differences within raw bamboo, indirectly characterizes drying stress, and offers low cost, simple operation, and ease of use.	The process is cumbersome, and water loss during sampling is likely to lead to significant errors. Measurement accuracy is hard to control, and real-time measurement is not feasible.	(Yuan *et al.* 2021; Honghai Liu *et al.* 2024a; Liu & Yang 2024)
	Electrodynamics	Attaching a resistance strain gauge to the specimen surface and monitoring changes in resistance and current can provide information on local deformation.	The goal is to achieve high-sensitivity and high-accuracy synchronous continuous real-time acquisition of small deformations in multiple parts and directions.	The strain information for the entire area cannot be obtained solely from the measurement points, resulting in a somewhat biased measurement outcome.	(Yan *et al.* 2019; Yan *et al.* 2020)
Non-contact Measurement	Digital Scattering Method	By analyzing images of an object's surface before and after deformation, the probabilistic statistical correlation of random scattering points is utilized for computation.	The unique speckle pattern of vascular bundles in the bamboo cross-section eliminates artificial speckle preparation, enhancing measurement accuracy and efficiency while enabling real-time strain and stress monitoring through software.	Internal stress-strain cannot be measured and is susceptible to surface clarity.	(Yan *et al.* 2017; Zhu *et al.* 2024)
	Acoustic Emission Method	Determine strain, stress, and damage by monitoring the sound signals within the material.	Enables real-time monitoring of internal stress-strain conditions.	Drying stress and strain can only be inferred from the size and frequency of elastic waves generated during drying and cracking, making it impossible to predict defects in advance (Fu *et al.* 2021). The equipment is costly.	(Villalobos 2016)

From a structural mechanics perspective, raw bamboo is classified as a natural two-phase structural fiber-reinforced material, where the vascular bundles act as the reinforcing phase and the flexible thin-walled cells serve as the matrix (Tian *et al.* 2009). The multilevel weak interfaces present from tissues to cells contribute to bamboo's anisotropic composite structure (Tian *et al.* 2012). These weak interfaces can lead to uneven stress distribution, a condition that persists throughout the drying process.

Research shows that drying stresses in bamboo walls vary throughout the drying process due to moisture content changes and internal gradients (Liu *et al.* 2023a). Initially, bamboo green, with higher moisture content, experiences compressive stresses due to the moisture gradient between the inside and outside. As drying progresses, these compressive stresses shift to tensile stresses, which increase until drying is complete.

During this phase, tensile stresses are higher in the outer layers, as they lose moisture faster. In contrast, bamboo yellow (partially dried or aged bamboo) primarily experiences compressive stresses, which increase as moisture content decreases, due to differential shrinkage between the inner and outer sections. This leads to a significant difference between actual tangential drying strain and free drying strain. In bamboo yellow, the actual drying strain (from both moisture loss and material properties) is higher than the free drying strain (from moisture loss alone). In bamboo green and bamboo timber, the opposite occurs, with free drying strain higher due to faster shrinkage of outer layers (Yan 2021).

The gradient structure of raw bamboo creates significant anisotropy, with differential drying shrinkage being the primary cause of drying stress. Both drying stress and capillary tension contribute to cell shrinkage (Lv 2018), and moisture content gradients further generate drying stresses (Behr *et al.* 2014). Thus, drying stress arises from bamboo's two-phase structure and water content variations.

Research on drying strain in raw bamboo borrows from wood drying strain components, including free drying strain, elastic strain, viscoelastic strain, and mechanically adsorbed strain (Yin *et al.* 2021). Yan (2021) explored drying stress in raw bamboo, developing a framework with moisture content analysis, drying shrinkage strain composition, and drying stress analysis, along with a calculation model. However, most recent studies on drying shrinkage and stress focus on wood, with limited attention on bamboo, especially raw bamboo. Research has primarily focused on bamboo slices or strips, leaving questions about whether drying strain components are similar to those in wood and whether drying stress differs across raw bamboo parts. Further investigation and exploration are needed in these areas.

Manifestations of Drying Strain

Macro-level drying and shrinkage strains

The macroscopic structure of raw bamboo primarily consists of two major components: the culm and the node. Due to the spatial structure formed by alternating hollow internodes and nodes, the drying and shrinkage behaviors of the culm and node exhibit a cyclic pattern of alternating strengths and weaknesses (Yan 2021). Research has found that the volumetric shrinkage and tangential drying shrinkage of the internode are significantly greater than those of the node. Specifically, the volumetric shrinkage of the internode is 41.5%, much higher than the node's 12.5%, while the tangential shrinkage of the internode is 6.2%, compared to 8.1% for the node (Chen *et al.* 2023). This indicates that the anisotropy of the node is more pronounced than that of the internode, making the node section more prone to cracking. These differences in shrinkage behavior are attributed to variations in structure and chemical content (Wahab *et al.* 2013).

Structurally, bamboo nodes have distinct shapes and unique features such as diaphragms, sheath scars, and nodal ridges, and they also contain a certain number of transverse and curved vascular bundles (Peng *et al.* 2014; Palombini *et al.* 2020; Xiang *et al.* 2021). In contrast, bamboo culms are primarily composed of longitudinal cells, with vascular bundles that show a parallel distribution from top to bottom and a gradient distribution along the radial direction. The vascular bundles on the outer side of the bamboo are smaller, with a high distribution density and a greater change in water content, resulting in more significant shrinkage.

On the other hand, the inner vascular bundles are larger, with a lower distribution density and less variation in water content (Zhang *et al.* 2024). The distribution of vascular bundles in bamboo affects its density, with the outer side being denser than the inner side. Since drying shrinkage is generally positively correlated with density, the outer side shrinks more. In bamboo timber, drying shrinkage increases by about 2%, while in the bamboo green section, it rises sharply. Specifically, the air-dry shrinkage rate of bamboo green increases by about 4%, and the full-dry rate increases by around 10% (Zhong 2011). During water loss, this gradient in water content between the inner and outer sides makes bamboo prone to cracking along the tangential direction (Yu 2003).

Yan (2021) found that while the tangential drying behavior of bamboo nodes and culms shares some similarities, the culms exhibited more shrinkage than the nodes. The complex joint structures of bamboo slowed down the tangential drying of the bamboo wall, and it was concluded that the difference in drying behavior between bamboo nodes and culms resulted from the combined effects of wall shrinkage and joint retardation.

The shrinkage in the thickness direction of the bamboo wall is mainly caused by radial shrinkage, and the decrease in diameter is a combined result of radial and tangential shrinkage (Han *et al.* 2012). Additionally, the microfibril angle and fiber length vary along different heights of bamboo, with less variation in the middle section (Jiang *et al.* 2000). This uniformity in the middle section leads to more synchronized drying and shrinkage behaviors (Yang *et al.* 2006). During water loss, water is primarily transported along the axial direction, and drying shrinkage decreases with height, with the bottom nodes experiencing significantly higher shrinkage strain than the middle and top nodes (Yan *et al.* 2020). At the same height, neighboring segments also show differences in shrinkage.

Bamboo’s dry shrinkage proportions vary significantly by direction, with tangential and radial shrinkage much higher than longitudinal shrinkage (Zhu *et al.* 2019). Tangential shrinkage ranges from 5.0% to 6.0%, slightly exceeding radial shrinkage, which falls between 4.4% and 5.1%. In comparison, longitudinal shrinkage is notably lower, measuring between 0.6% and 1.1% (Su *et al.* 2007). Since bamboo’s drying occurs primarily in the early stages, and because of the moisture content gradient within the bamboo, uneven tangential shrinkage between the inner and outer sides of the bamboo wall can result in cracking. Thus, bamboo cracking is closely related to tangential drying shrinkage.

Research on bamboo’s macro-scale drying behavior primarily examines differences between nodes and culms, axial variations at different heights, and tangential-radial variations at the same height. Most studies focus on specific bamboo sections (*e.g.*, bamboo green, bamboo yellow) and static drying behavior, with less emphasis on dynamic changes in shrinkage, stress accumulation, and release during drying. Investigating the dynamic process of bamboo shrinkage strain and stress will provide a more comprehensive understanding of its drying behavior.

Drying and shrinkage strains at the micro level

Bamboo's drying and shrinking behavior are interconnected at both macro and micro scales, with micro-scale studies essential for understanding the overall mechanism. Bamboo comprises essential tissues and vascular bundles; the basic tissues primarily consist of thin-walled cells, while the vascular bundles contain bamboo fibers (Jin *et al.* 2019). The basic tissue is primarily composed of thin-walled cells, and the vascular bundles also contain fibers and transport tissues such as ducts and sieve tubes (Xian *et al.* 1990; Abe and Yano 2010). These cells are bonded through the intercellular layer, sharing the load and stress.

Bamboo's cell walls are rich in hydrophilic hydroxyl groups, making them susceptible to water absorption and loss, which leads to expansion and contraction. Water loss causes dry shrinkage, and advanced techniques such as nano-infrared spectroscopic imaging now allow for detailed studies of cell wall composition and changes during drying.

While microscopic mechanisms of drying and shrinking are studied, the link between macro and micro scales still lacks definitive conclusions (Nakano 2018; Gao *et al.* 2021). Research shows that sieve tubes and conduits in bamboo change significantly under different water conditions, with varying saturation points for different cell types affecting water movement. Wei *et al.* (2017) applied nano-infrared technology to overcome the limitations of traditional infrared spectroscopy, offering higher spatial resolution to study cellulose molecular arrangements (Feng *et al.* 2020).

Chen *et al.* (2019) used laser confocal techniques to study the wetting and swelling of bamboo cell walls under different humidity conditions. They found that the wetting and swelling strain of the cell wall was closely related to the cell type. Bamboo fibers exhibited greater absolute wetting and swelling than thin-walled cells. As the moisture content (MC) increases by 1%, the absolute swelling rate of fiber cells is higher than that of parenchyma and vessel cells, in the following order: fiber cells > parenchyma cells > vessel cells. However, in terms of relative swelling rate, the swelling rate of fiber cells (0.53%/%) is lower than that of parenchyma and vessel cells (both 1.1%/%). Zhang *et al.* (2024) studied changes in vascular bundles at different water contents. They showed that drying in the inner bamboo wall was primarily due to the contraction of thin-walled cells and a few vascular bundles while drying in the outer wall was dominated by a large number of vascular bundles and a small portion of thin-walled cells. The anisotropy of bamboo drying shrinkage was mainly influenced by density and, on the cellular scale, by the number of bamboo fibers surrounding the vascular bundles (Vetter *et al.* 2015; Yuan *et al.* 2021). The distribution of bamboo fibers across the vascular bundles resulted in a gradient of dimensional changes in drying shrinkage from the outer surface to the center of the bamboo (Azadeh and Ghavami 2018).

Feng *et al.* (2020) revealed the spatial distribution of cellulose linked to lignin in thin-walled cells using confocal microscopy Raman spectroscopy imaging. Liu *et al.* (2024b) studied the dynamic contraction behavior of individual bamboo cells with time-lapse microscopy. They combined it with the long short-term memory (LSTM) model to predict the morphological changes in individual thin-walled cells during contraction. Their findings revealed that fiber cells contracted at a rate of 2.53% per minute, significantly faster than the 0.58% per minute contraction rate observed in thin-walled cells. Consequently, the diameter of fiber cells decreased by about 30%, while thin-walled cells showed a smaller reduction of approximately 7%. Zhang *et al.* (2023) found that when the moisture content (MC) decreases from 64% to 0%, the shrinkage rate of bamboo fibers is 15%, which is higher than that of other cell types.

As shown in Fig. 3, bamboo microstructure changes when comparing the material before and after drying, with noticeable shrinkage of vascular bundles. Figures 3b–d show minimal change in fiber shape, with the tangential dimension decreasing from 202 μm to 193 μm, while parenchyma cells deform and collapse significantly (Yan *et al*. 2020). Yuan *et al.* (2023) using confocal laser scanning microscopy, revealed significant differences in deformation and stress between bamboo fibers and parenchyma cells. The wall thickness of fibers and parenchyma cells decreased by 24.7% and 25.4%, respectively. Contraction stress in fibers caused parenchyma cell areas to increase by 24.2%. Finite element simulations showed that shrinkage stress concentrated in fiber cell walls and intercellular layers, indicating the role of fiber wall shrinkage and intercellular stress in the drying and cracking of raw bamboo.

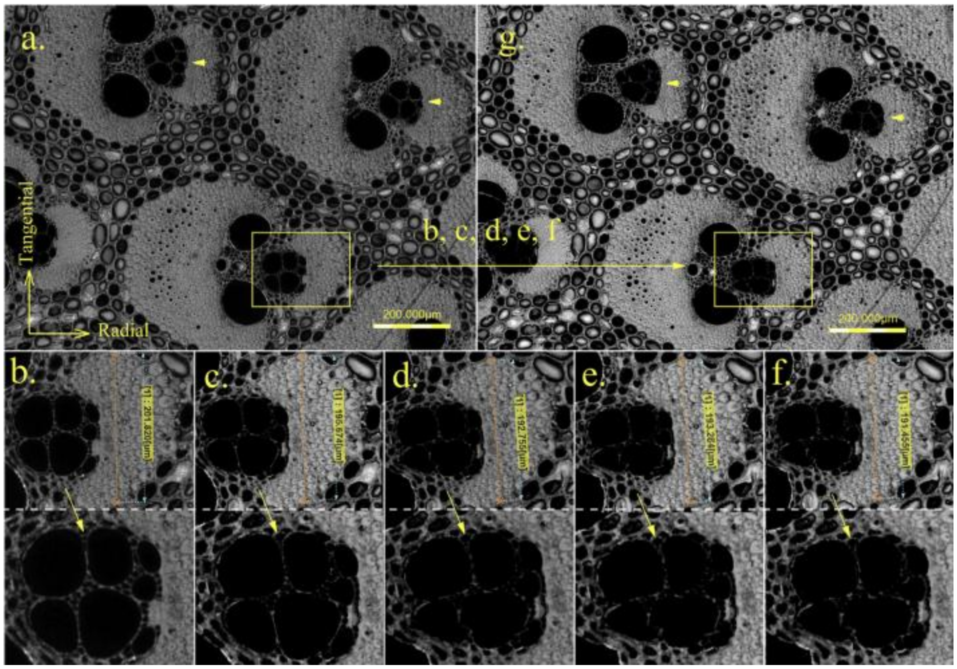

Fig. 3. Changes in the microstructure of raw bamboo before and after drying (Permission granted by Talor & Francis, Yan *et al.* 2020)

Bamboo fibers shrink more than thin-walled cells at the cellular scale. Although collapsed cells may recover some of their deformations (Liu *et al*. 2023c), strength loss is irreversible, and some deformations are complex to restore (Saifouni *et al.* 2016; Yang *et al.* 2018). Even in the late stages of drying, bamboo cell walls still contain bound water, exhibiting high plasticity and low energy storage modulus (Zhan *et al.* 2016). As the water content decreases, the thin-walled tissues continue to shrink and collapse, exacerbating the shrinkage of bamboo fibers, and these strains are hard to reverse (Yan *et al.* 2020). Future research should focus on the drying and shrinkage mechanisms of bamboo fibers and thin-walled cells in vascular bundles, further exploring the effects of intercellular layer stresses. Dynamic monitoring of the drying process and the establishment of quantitative models at both macro and cellular scales are needed to clarify their interactions and improve predictions and control of bamboo materials' drying and shrinking behaviors.

SUMMARY AND OUTLOOK

In summary, raw bamboo retains its unique structural advantages and excellent physical and mechanical properties. However, drying deformation and stress during drying significantly affect the outcome, highlighting the need to study the drying and shrinkage mechanisms and stress interactions to improve product quality. Current research has limitations, including variations in physical properties, drying behavior, and stresses across species, processing methods, and bamboo parts, which require further exploration. Most studies rely on traditional methods with limited accuracy, and the focus has largely been on shrinkage below the fiber saturation point, while the effects of wrinkling at higher moisture content remain underexplored.

On the basis of work cited in this paper, five future research directions can be proposed:

(1) *Establishment of a Universal Theoretical Model:* Research should focus on bamboo in its original state, further studying the drying and shrinkage strain behavior across different bamboo species. Establishing a universal theoretical model will aid in systematically understanding the drying and shrinkage behavior of various bamboo materials, offering a theoretical foundation for a standardized drying process.

(2) *Application of Advanced Detection Technology:* Advanced technologies such as digital scattering and acoustic emission methods could enable real-time monitoring and analysis of bamboo drying strain and stress. Combined with numerical simulations, these technologies can enhance measurement accuracy and provide comprehensive data for modeling drying strain and stress.

(3) *Comparative Study of Bamboo Culm and Node Drying and Shrinking:* Future studies should compare bamboo culms and nodes' drying and shrinking behaviors, as most current research focuses on internodal parts. A detailed analysis of nodes could reveal differences and commonalities in how each part responds to the drying process, guiding the creation of a more precise drying protocol.

(4) *Study on the Composition of Drying Stress:* In-depth research is needed to determine whether the shrinkage during bamboo drying, particularly above the fiber saturation point (FSP), is equivalent to wood wrinkling. Exploring the components of drying stress in raw bamboo will provide valuable data for optimizing the drying process and minimizing defects.

(5) *Multi-Scale Research:* Combining macro- and micro-scale studies is crucial for comprehensively understanding bamboo drying. Investigating the drying behavior at the cellular level, including the influence of intercellular stress, and constructing a multi-scale strain model could bridge the gap between cellular and macro-scale drying. This approach may offer new insights into bamboo drying and shrinkage mechanisms.

REFERENCES CITED

Abe, K., and Yano, H. (2010). "Comparison of the characteristics of cellulose microfibril aggregates isolated from fiber and parenchyma cells of moso bamboo (*Phyllostachys pubescens*)," *Cellulose* 17, 271-277. DOI: 10.1007/s10570-009-9334-9

Azadeh, A., and Ghavami, K. (2018). "The influence of heat on shrinkage and water absorption of Dendrocalamus giganteus bamboo as a functionally graded material," *Construction and Building Materials* 186, 145-154. DOI: 10.1016/j.conbuildmat.2018.07.011

Behr, V. C., Hill, S. J., Meder, R., Sandquist, D., Hindmarsh, J. P., Franich, R. A., and Newman, R. H. (2014). "Carbon-13 NMR chemical-shift imaging study of dewatering of green sapwood by cycling carbon dioxide between the supercritical fluid and gas phases," *The Journal of Supercritical Fluids* 95, 535-540. DOI: 10.1016/j.supflu.2014.08.026

Chand, N., Jain, D., and Nigrawal, A. (2006). "Investigation on gradient dielectric characteristics of bamboo (*Dendrocalamus strictus*)," *Journal of Applied Polymer Science* 102(4), 3489-3494. DOI: 10.1002/app.23979

Chen, Q., Fang, C., Wang, G., Ma, X., Chen, M., Zhang, S., Dai, C., and Fei, B. (2019). "Hygroscopic swelling of moso bamboo cells," *Cellulose* 27(2), 611-620. DOI: 10.1007/s10570-019-02833-y

Chen, Q., He, Y., Jiang, Y., Qi, J., Zhang, S., Huang, X., Chen, Y., Xiao, H., Jia, S., and Xie, J. (2023). "Effect of bamboo nodes on crack generation of round bamboo and bamboo-based composites during drying," *European Journal of Wood and Wood Products* 81(5), 1201-1210. DOI: 10.1007/s00107-023-01942-7

Cheng, A., Chen, F., Xu, K., Xiang, J., Wang, X., Hu, C., Zhou, Q., and Tu, D. (2024). "Moisture migration mechanism of round bamboo in the radial direction during drying," *Construction and Building Materials* 435, article 136819. DOI:10.1016/J.CONBUILDMAT.2024.136819.

Cui, M., Yin, Y., Jiang, X., Liu, B., and Zhang, S. (2010). "Variation analysis of physical characteristics in *Phyllostachys pubescens* stem at different growth ages," *J. Fujian Coll. For.* 30(4), 338-343. DOI: 10.13324/j.cnki.jfcf.2010.04.014

Ding, X., Li, G., and Zhang, Z. (2006). "A mechanics study on adaptiveness of biological morphologies and structure and its applications," *Advances in Mechanics* 36(1), 103-110. DOI: 10.3321/j.issn:1000-0992.2006.01.015

Dong, Y., Wang, N., Xue, Q., Kang, H., and Li, Y. (2023). "Research progress and prospects in anti-mildew performance of bamboo," *Journal of Forestry Engineering* 8(6), 24-32. DOI: 10.13360/j.issn.2096-1359.202302019

Feng, L., Sun, C.-J., Bi, W.-S., Ren, Z.-Z., Liu, X.-E., Jiang, Z.-H., and Ma, J.-F. (2020). "The distribution and orientation of cell wall components of moso bamboo parenchyma," *Spectroscopy and Spectral Analysis* 40(9), 2957-2961. DOI: 10.3964/J.ISSN.1000-0593(2020)09-2957-05

Fu, Z., Cai, Y., and Zhou, Y. (2021). "Current status and prospects of wood drying stress research," *Scientia Silvae Sinicae* 57(9), 160-167. DOI: 10.11707/j.1001-7488.20210916

Gao, Y., Zhou, Y., and Fu, Z. (2021). "Interdependence of shrinkage behavior between wood macroscopic and cellular level during moisture content loss," *Drying Technology* 40(15), 3241-3248. DOI: 10.1080/07373937.2021.2017300

Guan, M., Zhu, Y., and Zhang, Q. (2003). "Research on FSP of *Dendrocalamus membranaceus* according to its shrinkage," *Journal of Bamboo Research* (3), 40-43+54. DOI: 10.3969/j.issn.1000-6567.2003.03.009

Han, J., and Luo, D. (2012). "Changes of physical characteristics of bamboo in process of air-drying," *Journal of Central South University of Forestry & Technology* 32(7), 110-114. DOI: CNKI:SUN:ZNLB.0.2012-07-024

Han, S., Li, X., Ye, H., Ou, X., and Wang, G. (2023). "Three-dimensional visualization structural characteristics and performance of discontinuous coarse fiber bamboo nodes," *Journal of Materials Research and Technology* 26, 8181-8191. DOI: 10.1016/J.JMRT.2023.09.142

Hone, T., Cahill, L., Robinson, A., Korde, C., and Taylor, D. (2020). "The splitting of bamboo in response to changes in humidity and temperature," *Journal of the Mechanical Behavior of Biomedical Materials* 111, article 103990. DOI: 10.1016/j.jmbbm.2020.103990

Hunter, A. (2001). "The distribution of mechanical stresses in the cell wall of wood induced by capillary tension in the lumen water—An approximate analysis," *Wood Science and Technology* 35(4), 283-296. DOI: 10.1007/s002260100098

Jia, S. Y., Wang, Y., Wei, P. L., Ma, X. X., and Wu, Y. M. (2024). "Structure and mechanical properties of bamboo nodes: A review of current research," *World Bamboo and Rattan* 22(03), 90-99.

Jiang, Z. H., Fei, B. H., Wang, X. M., Zhao, R. J., and Liu, J. L. (2002). "Study on reduction of collapse of eucalyptus wood in drying," *Chinese Journal of Wood Science and Technology* (4), 3-6. DOI: 10.19455/j.mcgy.2002.04.001

Jiang, Z. H., Zhou, H. Y., Ruan, X. G., Wang, J., and Liu, Y. F. (2000). "A study on the ultrastructure of bamboo cell wall by x-ray," *Scientia Silvae Sinicae* (3), 122-125. DOI: 10.3321/j.issn:1001-7488.2000.03.020

Jin, K. X., Kong, L. Y., Liu, X. G., Jiang, Z. H., Tian, G. L., Yang, S. M., Feng, L., and Ma, J. F. (2019). "Understanding the xylan content for enhanced enzymatic hydrolysis of individual bamboo fiber and parenchyma cells," *ACS Sustainable Chemistry & Engineering* 7(22), 18603-18611. DOI: 10.1021/acssuschemeng.9b04934

Kang, H., Muszynski, L., and Milota, M. R. (2011). "Optical measurement of deformations in drying lumber," *Drying Technology* 29(2), 127-134. DOI: 10.1080/07373937.2010.482725

Li, G., Gu, Z., and Li, J. (2014). "Study on physical and mechanical performance of *Phyllostachy pubescens*," *Hubei Forestry Science and Technology* 43(5), 44-49. DOI: 10.3969/j.issn.1004-3020.2014.05.014

Li, R., He, C., Peng, B., and Wang, C. (2021). "Differences in fiber morphology and partial physical properties in different parts of *Phyllostachys edulis*," 38(4), 854-860. DOI: 10.11833/j.issn.2095-0756.20200649

Li, Y., Du, C., Liu, Z., Lin, Y., and Zhang, Y. (2003). "Production technology and development prospect of sliced bamboo fineline veneer," *China Forest Prod. Ind* 30(3), 36-38. DOI: 10.19531/j.issn1001-5299.2003.03.010

Li, Z., Jiang, Z., Fei, B., Cai, Z.-y., and Pan, X. (2014). "Comparison of bamboo green, timber and yellow in sulfite, sulfuric acid and sodium hydroxide pretreatments for enzymatic saccharification," *Bioresource Technology* 151, 91-99. DOI: 10.1016/j.biortech.2013.10.060

Li, Z., Luan, Y., Hu, J., Fang, C., Liu, L., Ma, Y., Liu, Y., and Fei, B. (2022). "Bamboo heat treatments and their effects on bamboo properties," *Construction and Building Materials* 331, article 127320. DOI: 10.1016/j.conbuildmat.2022.127320

Liu, H., Ke, M., Zhou, T., and Sun, X. (2023a). "Effect of samples length on the characteristics of moisture transfer and shrinkage of eucalyptus urophylla wood during conventional drying," *Forests* 14, article 1218. DOI:10.3390/f14061218

Liu, H., Xie, Y., Li, Z., and Zhang, X. (2024a). "Comparative study on supercritical carbon dioxide dewatering and conventional kiln drying of bamboo strips," *The Journal of Supercritical Fluids* 204, article 106121. DOI: 10.1016/J.SUPFLU.2023.106121

Liu, H., Li, Z., Xie, Y., and Xie, J. (2023b). "Dewatering fresh bamboo strips using supercritical carbon dioxide," *European Journal of Wood and Wood Products* 81(5), 1327-1335. DOI:10.1007/s00107-023-01951-6

Liu, X., Ma, W., Tu, X., Huang, H., and Varodi, A. M. (2023c). "Study on the wood characteristics of the Chinese ancient ship Luoyang I," *Materials* 16(3), article 1145. DOI:10.3390/ma16031145

Liu, L. M., Fang, Z. J., Zhang, Y. L., Wang, S. J., Zhang, L., Yuan, J., and Chen, Q. (2024b). "Decoding dynamic bamboo cell shrinkage with time-lapse microscopy and machine-learning," *Industrial Crops and Products* 218, article 118965. DOI: 10.1016/J.INDCROP.2024.118965

Liu, X., and Yang, L. (2024). "Research progress in drying of bamboo timber," *World Forestry Research* 37(4), 1-7. DOI: 10.13348/j.cnki.sjlyyj.2024.0056.y

Lou, Z., Yuan, T., Wang, Q., Wu, X., Hu, S., Hao, X., Liu, X., and Li, Y. (2021). "Fabrication of crack-free flattened bamboo and its macro-/micromorphological and mechanical properties," *Journal of Renewable Materials* 9(5), 959-977. DOI: 10.32604/jrm.2021.014285

Lv, H. F. (2018). *Research on Characteristics of Round Bamboo Microwave-Vacuum Drying*, Ph.D. Dissertation, Chinese Academy of Forestry, Bei Jing.

Lv, H., Chen, M., Lian, C., Li, H., Yang, S., Xu, B. and Fei, B. (2021). "Distribution and migration of moisture in round bamboo in response to microwave drying," *BioResources* 16(3), 5915-5925. DOI:10.15376/biores.16.3.5915-5925.

Nakano, T. (2018). "Dimensional changes of cell wall and cell lumens upon water sorption revisited. Literature review and mathematical considerations based on the cylindrical model," *Holzforschung* 72(5), 413-419. DOI: 10.1515/hf-2017-0162

Palombini, F. L., Nogueira, F. M., Kindlein, W., Paciornik, S., Mariath, J. E. D., and de Oliveira, B. F. (2020). "Biomimetic systems and design in the 3d characterization of the complex vascular system of bamboo node based on x-ray microtomography and finite element analysis," *Journal of Materials Research* 35(8), 842-854. DOI: 10.1557/jmr.2019.117

Patera, A., Derome, D., Griffa, M., and Carmeliet, J. (2013). "Hysteresis in swelling and in sorption of wood tissue," *Journal of Structural Biology* 182(3), 226-234. DOI: 10.1016/j.jsb.2013.03.003

Peng, G., Jiang, Z., Liu, X., Fei, B., Yang, S., Qin, D., Ren, H., Yu, Y., and Xie, H. (2014). "Detection of complex vascular system in bamboo node by x-ray micro-ct imaging technique," *Holzforschung* 68(2), 223-227. DOI: 10.1515/hf-2013-0080

Qi, Y., Sun, Y. U. E., Zhou, Z., Huang, Y. I., Li, J. and Liu, G. (2023). "Response surface optimization based on freeze-thaw cycle pretreatment of poplar wood dyeing effect," *Wood Research* 68, 293-305. DOI:10.37763/wr.1336-4561/68.2.293305

Ray, A. K., Mondal, S., Das, S. K., and Ramachandrarao, P. (2005). "Bamboo—A functionally graded composite-correlation between microstructure and mechanical strength," *Journal of Materials Science* 40(19), 5249-5253. DOI: 10.1007/s10853-005-4419-9

Saifouni, O., Destrebecq, J.-F., Froidevaux, J., and Navi, P. (2016). "Experimental study of the mechanosorptive behaviour of softwood in relaxation," *Wood Science and Technology* 50(4), 789-805. DOI: 10.1007/s00226-016-0816-2

Su, W., Gu, X., Zhu, R., Zhu, Y. and Lin, K. (2007). "Study on physical properties of *Bambusa wenchouensis* wood," *Journal of Nanjing Forestry University(Natural Sciences Edition)* (2), 42-46. DOI: 10.3969/j.issn.1000-2006.2007.02.010.

Sun, Z., Tian, Y., and Qing, Y. (2006). "A study of water movement during the process of hot-press drying of bamboo timber," *J. Cent. South For. Univ.* 26(4), 47-51. DOI: 10.1016/S0379-4172(06)60085-1

Tian, G., Jiang, Z., Yu, Y., Wang, H., and An, X. (2012). "Toughness mechanism of bamboo by in-situ tension," *Journal of Beijing Forestry University* 34(5), 144-147. DOI: 10.13332/j.1000-1522.2012.05.005

Tian, G. L., Jiang, Z. H., Yu, Y., Liu, X. E., and Sun, F. B. (2009). "Origin of bamboo toughness: Two-phase composite material and gradient weak interfaces mechanism," in: *Proceedings of the 3rd National Academic Seminar on Biomaterials Science and Technology*, pp. 81-84.

Tian, L. M., Jin, B. B., Hao, J. P., Kou, Y. F., and Sun, G. G. (2018). "Experimental study on mechanical properties of multi-function bamboo skeleton composite members sprayed with composite material," *Transactions of the Chinese Society of Agricultural Engineering* 35(13), 95-104. DOI: CNKI:SUN:NYGU.0.2018-13-012

Vetter, R. E., Ribeiro, R. A. S., Ribeiro, M. G. S., and Miranda, I. P. A. (2015). "Studies on drying of imperial bamboo," *European Journal of Wood and Wood Products* 73(3), 411-414. DOI: 10.1007/s00107-015-0900-6

Villalobos, G. (2016). "Acoustic emission signals resulting from the drying-induced fractures of *Phyllostachys pubescens* bamboo: Evidence of scale free phenomena," *Wood Science and Technology* 50(3), 489-501. DOI: 10.1007/s00226-016-0798-0

Wahab, R., Mustafa, M. T., Salam, M. A., Sudin, M., Samsi, H. W., and Rasat, M. S. M. (2013). "Chemical composition of four cultivated tropical bamboo in genus *Gigantochloa*," *Journal of Agricultural Science* 5(8), 66. DOI: 10.5539/jas.v5n8p66

Wang, X., He, Q., and Zhao, X. (2013). "Study on drying and collapse properties of eucalypts plantation," *Journal of Inner Mongolia Agricultural University (Natural Science Edition)* 34(1), 123-127. DOI: 10.16853/j.cnki.1009-3575.2013.01.025

Wang, Y., Sun, W., Yang, Z., Xu, L., Feng, Y., and Zhang, Z. (2014). "Research progress of wood drying technology," *Forestry Machinery & Woodworking Equipment* 42(10), 9-13. DOI: 10.13279/j.cnki.fmwe.2014.10.015

Wei, P., Huang, Y., Liu, R., An, X., and Fei, B. (2017). "Research on chemical constituents of bamboo fiber cell wall based on nano-IR technology," *Spectroscopy and Spectral Analysis* 37(1), 103-108. DOI: 10.3964/j.issn.1000-0593(2017)01-0103-06

Xian, X. J., and Xian, D. G. (1990). "The relationship of microstructure and mechanical properties of bamboo," *Journal of Bamboo Research* 9(3), 10-23.

Xiang, E. L., Yang, S. M., Cao, C. J., Liu, X. G., Peng, G. Y., Shang, L. L., Tian, G. L., Ma, Q. L., and Ma, J. F. (2021). "Visualizing complex anatomical structure in bamboo nodes based on x-ray microtomography," *Journal of Renewable Materials* 9(9), 1531-1540. DOI: 10.32604/jrm.2021.015346

Xu, M., Ren, H., Guo, W., and Li, X. (2007). "Advance of research on bamboo fiber and its cell ultrastructure," *Nonwood Forest Research* 25(4), 82-89. DOI: 10.3969/j.issn.1003-8981.2007.04.020

Xu, Q., Harries, K., Li, X., Liu, Q., and Gottron, J. (2014). "Mechanical properties of structural bamboo following immersion in water," *Engineering Structures* 81, 230-239. DOI: 10.1016/j.engstruct.2014.09.044

Yan, W., Zhang, B., Fu, W., and Zhou, J. (2017). "Strain characterization and mechanical study an annular shrinkage of bamboo culm (*Phyllostachys pubescens*)," *China Forest Products Industry* 44(10), 16-20. DOI: 10.19531/j.issn1001-5299.201710004

Yan, W., Zhang, B., Fu, W. S., and Zhou, J. B. (2019). "Hygrothermal strain response of bamboo culm," *Scientia Silvae Sinicae* 55(7), 137-145. DOI: CNKI:SUN:LYKE.0.2019-07-015

Yan, Y., Fei, B. H. and Liu, S. Q. (2020). "The relationship between moisture content and shrinkage strain in the process of bamboo air seasoning and cracking," *Drying Technology*, 1-10. DOI: 10.1080/07373937.2020.1819307

Yan, Y. (2021). *Study on Air Drying Characteristics and Cracking Mechanism of Moso Bamboo Culms Based on Wall-layer Gradient Structure*, Ph.D. Dissertation, Anhui Agricultural University, Hei Fei.

Yan, Y., Fei, B., and Liu, S. (2022). "The relationship between moisture content and shrinkage strain in the process of bamboo air seasoning and cracking," *Drying Technology* 40(3), 571-580. DOI: 10.1080/07373937.2020.1819307

Yang, L., and Liu, H. (2018). "A review of eucalyptus wood collapse and its control during drying," *BioResources* 13(1), 2171-2181. DOI: 10.15376/biores.13.1.yang

Yang, S., Jiang, Z., and Ren, H. (2006). "Present status and advances in anatomical characteristics of bamboo," *World Bamboo and Rattan* (3), 1-6+12. DOI: 10.3969/j.issn.1672-0431.2006.03.001

Yin, Q., and Liu, H.-H. (2021). "Drying stress and strain of wood: A review," *Applied Sciences* 11(11). DOI: 10.3390/app11115023

Yu, H. (2003). "Study on property of bamboo culms," *World Bamboo and Rattan* (04), 5-9. DOI: 10.3969/j.issn.1672-0431.2003.04.002

Yuan, J., Chen, L., Mi, B., Lei, Y., Yan, L., and Fei, B. (2023). "Synergistic effects of bamboo cells during shrinkage process," *Industrial Crops and Products* 193(33), 116232. DOI: 10.1016/J.INDCROP.2022.116232

Yuan, J., Fang, C., Chen, Q., and Fei, B. (2021). "Observing bamboo dimensional change caused by humidity," *Construction and Building Materials* 309, 124988. DOI: 10.1016/J.CONBUILDMAT.2021.124988

Zhan, T., Jiang, J., Peng, H., and Lu, J. (2016). "Evidence of mechano-sorptive effect during moisture adsorption process under hygrothermal conditions: Characterized by static and dynamic loadings," *Thermochimica Acta* 633, 91-97. DOI: 10.1016/j.tca.2016.02.003

Zhan, T., Sun, F., Lyu, C., He, Q., Xu, K., Zhang, Y., Cai, L., Huang, Z. and Lyu, J. (2020). "Moisture diffusion properties of graded hierarchical structure of bamboo: Longitudinal and radial variations," *Construction and Building Materials* 259. DOI: 10.1016/j.conbuildmat.2020.119641.

Zhang, J., Liu, H., Yang, H., and Yang, L. (2020). "Drying characteristics of *Eucalyptus urophylla* × *E. grandis* with supercritical CO_2," *Materials* 13(18), article 3989. DOI: 10.3390/ma13183989

Zhang, Y., Xu, H., Li, J., Zhong, T., and Wang, H. (2023). "Dry shrinkage of moso bamboo in relation to vascular bundle structure," *Holzforschung* 77(1), 63-71. DOI: 10.1515/hf-2022-0132.

Zhang, Y., Xu, H., Li, J., and Wang, H. (2024). "Unraveling the inhibition of bamboo node on dry shrinkage: Insights from the specific vascular structure of bamboo node," *Industrial Crops and Products* 211, article 118193. DOI: 10.1016/J.INDCROP.2024.118193.

Zhang, X., Wang, X., Zhao, M., and Liu, H. (2024). "Study on free shrinkage and rheological characteristics of *Eucalyptus urophylla ×E. grandis* during conventional drying," *Wood Material Science & Engineering* 19(6), 1173-1179. DOI: 10.1080/17480272.2024.2311827

Zhong, S. (2011). *Preliminary Study on the Principle and Protection of Moso Bamboo Tubes Splitting*, Master's Thesis, Beijing Forestry University, Bei Jing.

Zhong, S., Qin, D., Zhang, S., and Luo, Z. (2009). "Splitting-proof technology of *Phyllostachys pubescens* tubes," *Journal of Beijing Forestry University* 31(S1), 189-

192. DOI: CNKI:SUN:BJLY.0.2009-S1-044

Zhou, Y.-H., Chen, H.-L., Hou, J.-F., and Yu, Y.-M. (2024). “Preparation and properties of round bamboo phenolic resin composite pipes,” *Journal of Forestry Engineering* 9(1), 67-74. DOI: 10.13360/j.issn.2096-1359.202306003

Zhu, J., Tan, Y., Chen, K., Peng, H., Li, Z., Jiang, J., Lyu, J., and Zhan, T. (2024). "Evaluation of transverse shrinking and swelling of bamboo using digital image correlation technique," *Industrial Crops and Products* 211, article 118274. DOI: 10.1016/J.INDCROP.2024.118274

Zhu, J., Wang, H., and Wang, C. (2019). “Study on the swelling characteristics of bamboo based on its graded hierarchical structure,” *Wood Fiber Sci* 51(3), 332-342. DOI: 10.22382/WFS-2019-031

Article submitted: October 20, 2024; Peer review completed: November 14, 2024; Revised version received and accepted: November 22, 2024; Published: December 10, 2024.
DOI: 10.15376/biores.20.1.Zhu