

Free Drying Shrinkage of Wood: A Review

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The free drying shrinkage of wood is critical for dimensional stability and industrial applications. This study reviews the influencing factors (drying parameters, environmental conditions, and anatomical structures) and summarizes evaluation indexes and measurement methods. However, current research exhibits significant limitations. Systematic comparisons of free drying shrinkage between softwoods and hardwoods have been lacking, and the mechanism by which internal moisture variations affect shrinkage have remained unclear. Furthermore, existing techniques have failed to simultaneously measure moisture content changes and shrinkage with high accuracy. To address these gaps, future studies should: 1) investigate species-specific free drying shrinkage conditions; 2) elucidate moisture-induced shrinkage mechanisms from macro- and micro-scale perspectives; and 3) develop high-resolution methods for synchronous measurements. Further industrial applications of these findings could optimize wood drying processes and advance wood science and processing technologies.

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INTRODUCTION

Wood is an environmentally friendly natural material. It is widely used in household and building products due to its ease of processing and wide range of applications. However, as a natural biomaterial, it is susceptible to microbial degradation by fungi and other microorganisms, as well as factors such as light and relative humidity in the environment. These factors can lead to dimensional changes in untreated wood, resulting in irregular deformation (Wang and Sun 2022). In precision woodworking, natural wood is very susceptible to drying temperature, humidity and other external influences caused by changes in moisture content and thus produce dry shrinkage and wet expansion. These dimensional changes can lead to deformation and cracking of the material, which can affect the subsequent use, making it necessary to employ drying treatment to improve the utilization of wood (Zhang *et al.* 2023). The anisotropy of the wood structure and the uneven distribution of moisture content in the drying process often leads to drying stress (Fu *et al.* 2021). One common approach to manage this stress is by using clamps, which physically restrain the wood to control its dimensional changes. For example, clamps can be strategically placed to prevent excessive shrinkage in specific directions, ensuring that the final product meets the required specifications. However, such constraints contrast with the concept of free drying shrinkage.

Before delving deeper, it is essential to clarify two key concepts. Free drying shrinkage refers to the shrinkage of wood that occurs under unconstrained conditions as it loses water. This phenomenon serves as a crucial foundation for the drying rheology of wood and holds significant importance in wood research. Studies have been carried out to reveal fundamental shrinkage characteristics of wood resulting from water loss without external restrictions (Listyanto *et al.* 2013; Liu *et al.* 2023; Zhang *et al.* 2025), providing a basis for understanding the complex viscoelastic and plastic changes during the drying process (Zhan *et al.* 2009b; Chai *et al.* 2024a,b). ‘Ideal free drying’ is a theoretical process, characterized by a sufficiently slow drying rate, whereby the moisture gradient within the wood approaches zero. Due to the influence of various factors in practical experiments, it is difficult to fully achieve this ideal process. As will be described in this article, experimental conditions can be set up in various ways to as to mimic ideal free drying. By comparing real-world drying scenarios—where clamps or other constraints are applied—to the concept of ideal free drying, researchers can better understand the impact of external forces on wood behavior. Through the study of free drying shrinkage, it is possible to optimize the drying process parameters, control the stress and strain of wood, prevent cracking and deformation, and improve the drying quality. Moreover, it can assist in predicting the properties of wood after drying, offering a reference for wood processing, facilitating the development of new treatment technologies, expanding the application fields of wood, and enhancing the added value and market competitiveness of wood (Lv *et al.* 2005).

RESTRICTED DRYING OF WOOD

Wood drying shrinkage refers to the phenomenon of wet wood shrinking in size and volume due to drying, which only occurs when the Moisture Content (MC) of wood is below the Fiber Saturation Point (FSP). This is when the evaporation of free water from the surface of the wood ends, and the water adsorbed within the cell walls begins to evaporate. As a consequence, the wood shrinks, and the effect increases with the decrease of MC (Ozyhar *et al.* 2013). Various types of wood have different drying capacities, even in the same piece of wood, due to the presence of wood anisotropy and MC gradients. Thus, internal stresses develop during the course of the drying process. Generally, the outer layer will experience a pre-drying tensile stress, which later becomes a compressive stress. Meanwhile, the inner layer changes from a state of pre-pressure stress to tensile stress, triggering a large drying shrinkage differences in different directions between different layers (Zhan *et al.* 2005). Generally, longitudinal shrinkage (along the direction of the wood fibers) is the smallest, followed by the radial direction, then followed by tangential direction, which exhibits the largest shrinkage. The tangential direction shrinkage can be about two to three times higher than the radial direction (Zhang *et al.* 2020). Wood drying changes the wood size and volume. For small-size specimens without binding stress, the two changes should be reversible; for large-size specimens, due to the presence of drying stress, the wood experiences restricted drying, so it is not fully reversible. The effect of drying shrinkage on wood utilization is mainly the dimensional shrinkage of wood products, which can lead to gaps, warping deformation, and cracking (Jiang and Lv 2012).

When the moisture content of the wood surface layer drops below the FSP, the drying shrinkage phenomenon commences, and at this time the moisture content of the wood internal MC and the surface layer of the existence of a MC gradient, the internal MC

is still higher than the FSP. Therefore, the drying shrinkage is small or has not yet manifested itself as a drying shrinkage phenomenon on the surface. In this way, it can play a role in inhibiting the internal stresses within the wood (Almeida and Hernández 2006). This drying phenomenon is known as the limited drying shrinkage (Liu *et al.* 2015).

FREE DRYING OF WOOD

Free drying shrinkage is a special state in wood drying shrinkage (Shen *et al.* 2020), when thin and small wood is dried under no external constraints. In that circumstance, the dimensional reduction produced by MC lower than FSP can be regarded as a process happening in the absence of an internal MC gradient and the absence of internal stresses. Thus, the dimensional shrinkage is produced only because of the reduction of MC (Tu *et al.* 2004), and the free drying shrinkage strain is directly proportional to the change of MC. However, this condition is highly idealized. In practical experiments, researchers strive to minimize internal stresses. Therefore, experimental protocols typically employ thin section specimens subjected to controlled low temperature drying to approximate these idealized stress-free conditions (Tu *et al.* 2009; Zhu *et al.* 2021; Liu *et al.* 2024).

Free Drying Mechanism

The wood structure from macroscopic to microscopic order can be expressed as the trunk→ heart sapwood→ growth rings→ early and latewood→ cells→ cell wall→ cell wall layers→ chemical components (Yin *et al.* 2023). When MC is higher than FSP and the free water in the cell lumen decreases, the dimensions of the wood do not change; when MC is lower than FSP, less water is adsorbed in the cell wall through hydrogen bonding with hydroxyl groups present (Fig. 1), and the resulting forces cause deformation of the microfibrils (Thybring *et al.* 2022). Wood drying and shrinking is manifested microscopically as water expulsion and cellulose microfibrils approaching each other, and macroscopically as a change in wood dimensions. Free shrinkage refers to the dimensional reduction of wood occurring below the FSP when thin, isolated specimens dry under minimized stress conditions. This phenomenon is driven exclusively by moisture loss and subsequent cell wall relaxation (Sun *et al.* 2019).

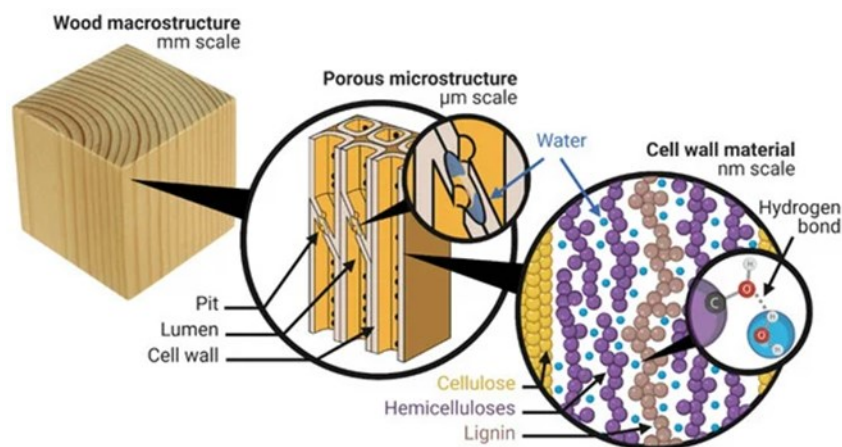


Fig. 1. The location of various types of water in wood (Reprinted from Thybring *et al.* (2022), *Forests*, 13(12), 2051, CC BY 4.0. <https://doi.org/10.3390/f13122051>)

Factors Affecting Free Drying Shrinkage

Effect of external factors on free drying shrinkage

The thickness of wood specimens significantly influences their free shrinkage characteristics, which holds critical implications for industrial wood processing. Studies demonstrate that while the total shrinkage of *Eucalyptus urophylla* × *E. grandis* specimens (1 to 3 mm thick) shows negligible variation upon complete drying, their FSP increases with thickness, with 1 mm specimens exhibiting collapse when MC exceeds FSP (Yang *et al.* 2018a; Zhang *et al.* 2025). Comparative analyses reveal that 0.5 mm thick specimens maintain structural integrity during drying, whereas 1-mm and 2-mm specimens display significant collapse (Redman *et al.* 2016). And 5-mm thick *Juglans mandshurica* specimens develop restrained shrinkage that precludes accurate free shrinkage measurement (Liu *et al.* 2024). These findings indicate that although the final shrinkage magnitude may be thickness-independent, the shrinkage process exhibits distinct thickness-dependent behaviors: specimens ≤ 0.5 mm thick are suitable for fundamental free shrinkage characterization, the 1 to 2 mm range represents a critical transition zone prone to collapse, while thicker specimens require FSP adapted drying protocols. Consequently, industrial applications should establish species-specific thickness thresholds and implement precise humidity and temperature control within critical thickness ranges, which is essential for defect minimization in dimensional lumber production and engineered wood manufacturing.

In addition to the influence of specimen thickness on the occurrence and measurement of free drying shrinkage in wood, drying conditions are also crucial determinants. In conventional drying experiments, as the temperature used in the experiment increases, the synergistic effect of the plastic deformation of the wood surface layer and the moisture content gradient occurs. The surface layer loses part of its elastic deformation ability, generates irreversible plastic deformation, and is fixed in a stretched state, thereby providing a buffer for the overall shrinkage of the wood (Bengtsson and Kliger 2003). When the moisture content of the internal wood drops below the fiber saturation point and shrinkage occurs, the plastic deformation of the surface layer restricts its further shrinkage, resulting in a significant reduction in the free shrinkage strain and the free shrinkage coefficient. Moreover, there is a significant correlation between the temperature and the free shrinkage strain (Zhan *et al.* 2011). When the temperature is relatively high (taking 100 °C as an example), the shrinkage anisotropy between different layers increases significantly (Chai *et al.* 2024b). Therefore, to ensure the smooth progress of free shrinkage (a process without defects such as cracking and warping that may interfere with the overall quality and predictability of the results), thin specimens should be dried slowly under low temperature and high humidity conditions (Liu *et al.* 2025).

In conclusion, specimen thickness and drying conditions have varying degrees of influence on the occurrence and measurement of free drying shrinkage. Understanding these differences is crucial for optimizing the practical processing and utilization of wood and for advancing the theoretical framework of wood rheology.

Effect of intrinsic factors on free drying shrinkage

A study of the microstructure of wood found that the arrangement of cells, microfibril angle (MFA), and early and late season timber all have an effect on wood dryness and shrinkage (Patera *et al.* 2017). In addition, there is an inhibitory effect of the wood rays, and the differences between the cell wall layers also have an effect on the dryness and shrinkage (Wiedenhoeft 2012). Changes of the tubular cells in the process of

water desorption are often probed at the microscopic scale, which is centered on the tubular cell cross-sectional area, tubular cell lumen cross-sectional area, tubular wall thickness, *etc.* Wood drying shrinkage is often attributed to changes in water molecules caused by hydroxyl changes in amorphous cellulose and hemicellulose in the cell wall. Gao *et al.* (2022) studied the shrinkage of Sargasso pine during drying at the macroscopic and cellular levels using the VIC-3D with a digital microscope system and found that at the macroscopic scale, tangential (T) and radial (R) shrinkage was larger, and the shrinkage of latewood tubular cells was significantly larger than the shrinkage of earlywood tubular cells in the timber. Shrinkage of earlywood tubular cells, and the shrinkage and anisotropy demonstrated at the cellular and macroscopic levels were significantly different, which may be a joint result of the interaction between early and latewood and under the inhibition of wood rays (Gao *et al.* 2022). Derome *et al.* (2011) studied the drying shrinkage of spruce cells by synchrotron radiation proportional X-ray tomography microscopy (srPCXTM). The latewood cells shrank more significantly but more slowly than the earlywood cells, and the anisotropy of earlywood cells was more remarkable. It was speculated that this might be influenced by the wood rays. Xue *et al.* (2018) further explored the influence of wood rays on the drying shrinkage property of wood. The work was done using low-temperature slicing and continuous drying of oak, black walnut, and teak. The results of the drying and shrinking of latewood were more severe than that of earlywood, and wood rays had a significant inhibitory effect on the shrinking of wood. MFA is an important factor affecting the dryness and shrinkage of wood, especially the S₂ layer of the tubular or fiber cell wall (Sun *et al.* 2019). Evaporation of water molecules inside the wood causes the water layer between the microfilaments of the cell wall to become thinner, and the microfilaments come closer together. The cell wall thus becomes smaller in size, and the wood undergoes drying and shrinkage (Zhan *et al.* 2019). The axial drying shrinkage of wood is positively correlated with the MFA of S₂ layer and is more constant when the MFA is less than 30°, but when it is more than 30°, the axial drying shrinkage of wood increases significantly and warping and deformation can easily occur (Leonardon *et al.* 2010).

Although there has been no detailed study on the influence of intrinsic factors on free drying shrinkage, from the relationship between free drying shrinkage and drying shrinkage it is not difficult to judge that the above intrinsic factors that influence of wood drying shrinkage should be attributable to free drying shrinkage. However, such results still need to be further explored.

Detection and Application of Free Drying Shrinkage

Free drying shrinkage measurement methods

Wood shrinkage measurement techniques span multiple dimensional scales. At the macroscopic level, conventional tools including vernier calipers, digital micrometers, and optical scanning systems provide essential data for characterizing free shrinkage behavior. The integration of precise dimensional measurements with moisture content gradient analysis ensures methodological reliability, as demonstrated by Redman *et al.* (2016) through combined balance and scanning laser micrometer measurements of directional shrinkage. Nopens *et al.* (2019) advanced this approach using CCD cameras to simultaneously monitor tangential and radial dimensional changes in *Fagus sylvatica* and *Pinus sylvestris*, establishing a high-throughput imaging methodology that minimizes thermal disturbances while improving temporal resolution.

At the microscopic scale, scanning electron microscopy (SEM) has been instrumental in visualizing cell wall dynamics, with Almeida *et al.* (2014) examining

earlywood/latewood differentiation and Gu *et al.* (2001) documenting cellulose protofibril organization in *Pinus sylvestris*. Laser scanning confocal microscopy (CLSM) enables real-time tracking of lignin autofluorescence during shrinkage, revealing moisture-dependent cell wall layer deformation at submicron resolution, as demonstrated by Murata *et al.* (2006) and Sakagami *et al.* (2007). Synchrotron radiation phase-contrast X-ray tomography (srPCXTM) coupled with 3D analysis (Patera *et al.* 2013) provides direct visualization of tissue-level shrinkage patterns, while optical microscopy (Perré *et al.* 2007; Rafsanjani *et al.* 2014) offers complementary insights into cell wall deformation. These multiscale approaches collectively establish quantitative structure-property relationships that enhance predictive control of free shrinkage in practical applications.

Application of free drying shrinkage in wood rheology

(1) Calculate the actual drying value

Wood under drying stress develops four strain components: elastic strain, viscoelastic creep strain, mechanically adsorbed creep strain, and free drying shrinkage strain, which sum to the total drying strain or actual drying shrinkage strain (Zhu *et al.* 2025). Zhan *et al.* (2007a) found that the difference between wood drying and shrinkage increases with the increase of free drying shrinkage, resulting in an increase in drying stress. At the same time, the mechanically adsorbed creep strain is directly proportional to the amount of free drying shrinkage, so the mechanically adsorbed creep will also increase. At the beginning of wood drying when the surface layer MC drops to the FSP to produce free drying shrinkage, due to fact that the internal MC is higher than FSP, the actual shrinkage of the surface layer is less than the free drying shrinkage value. There are tensile stresses in the surface layer, and there are compressive stresses in the core layer. As drying continues, the surface layer moisture continues to decrease, the free drying shrinkage value increases, and the drying shrinkage is suppressed by the effect of the thickness. Thus, the surface layer tensile stress shows an increasing trend. If the core layer MC is still not reduced to the FSP, then the core layer of the compressive stress will also increase, and surface layer cracking may occur. In the late stage of drying, the MC of the core layer decreases so that the free drying shrinkage increases, but the surface layer under tensile stress exhibits a large mechanical adsorption creep deformation, and the compressive stresses at the late stage can make the tensile surface deformation fully recovered. Therefore, the surface layer cannot reach its free dry shrinkage value, *i.e.*, the value of free dry shrinkage is greater than the actual dry shrinkage. Fu (2014) in the course of drying of tree disks found that the MC of the disks dropped below the FSP, and the loss of bound water led to its drying shrinkage. The difference tangential strain of each ring layer caused by drying shrinkage anisotropy is proportional to the difference between the tangential and radial free drying shrinkage.

(2) Modeling wood drying stresses

Tu *et al.* (2009) used the slicing method to investigate and analyze the free drying and shrinkage characteristics of wood in the drying process. Assumptions about the drying stress in the conventional drying experiments were made in conjunction with the laws of free drying and shrinkage, which expanded the scope of the study of drying stress and provided a good direction. Zhan *et al.* (2007b, 2009a, 2017) focus on the stress-strain changes in the conventional drying process of wood, combined with specific experiments to establish a mathematical model of stress-strain in the drying process. This work further reveals the rule of law of the wood in the drying process, focusing on the investigation of

the free-drying shrinkage of larch in this experiment. The study focuses on the free-drying shrinkage of the test material chord radial law under different temperature conditions, elastic strain, and viscoelastic strain under different temperature conditions, which provides a theoretical basis for the setting of drying conditions and further investigation of the mechanical creep mechanism. Redman *et al.* (2016) used 0.5 mm thick specimens to do free drying shrinkage experiments, and the desorption isotherm of the wood was established to get the relationship between moisture content and drying shrinkage. Han *et al.* (2017) established the free shrinkage model by using the free shrinkage with elasticity, viscoelastic and viscous strain viscoelastic and derived the viscoelastic coefficient and viscosity coefficient. The respective elastic coefficients and modulus were obtained to predict the drying stress and deformation of red pine wood at a specific time during the drying process. Salinas *et al.* (2022) determined mechanical adsorption coefficients by using the stress-strain modeling after determination of elastic, free shrinkage and mechanically adsorbed strains of eucalyptus wood. Zhao *et al.* (2015) considered the establishment of a coupled thermal mass-stress-strain mathematical model that takes into account the phenomena of free drying shrinkage and mechanically adsorbed strain of wood in a more practical manner. These studies from various researchers adopt different methods and focus on diverse aspects, such as model establishment, coefficient determination, and relationship exploration, to investigate wood's free drying, shrinkage, and stress-strain characteristics. Collectively, they have advanced the theoretical understanding of wood drying and provided practical guidance for optimizing drying processes and predicting wood behavior.

ANALYSIS AND DISCUSSION

The research on the measurement and application of the free shrinkage of wood is of great significance for precisely controlling the wood drying process and improving the quality of wood processing. In terms of optimizing the measurement methods, the precise regulation of experimental conditions is the core to ensure the accuracy of measurement. Fu (2017) successfully eliminated the moisture content gradient during the wood drying process by setting the experimental conditions of constant temperature and gradually decreasing humidity in stages, thereby providing an effective solution for achieving stable measurement of free shrinkage. Zhang *et al.* (2018) found that reducing the thickness of the specimen can significantly enhance the shrinkage response. However, it is necessary to balance the potential changes in mechanical properties caused by an overly thin thickness. In addition, special drying processes such as supercritical CO₂ drying (Chang *et al.* 2011; Zhang *et al.* 2019; Mu *et al.* 2020) and freeze-drying (Yang *et al.* 2018b) exhibit unique advantages. These technologies open up new paths for high-precision measurement by eliminating interfacial tension and avoiding moisture content gradients.

From the perspective of application, special drying processes have remarkable value in the wood industry. Based on the characteristics of wood freeze-drying technology, which can effectively avoid shrinkage and reduce the moisture content gradient (Jin *et al.* 2021). Supercritical CO₂ drying technology shows great potential in the large-scale wood pretreatment process (Zhang *et al.* 2021; Liu *et al.* 2022). Its rapid and uniform drying characteristics can not only shorten the processing cycle but also provide support for precisely controlling the free shrinkage, facilitating the research, development, and production of customized wood products.

However, there are still urgent problems to be solved in the current research. There is a lack of a unified standard for the measurement of free shrinkage, making it difficult to conduct effective comparisons among different research results. The quantitative relationship between the changes in the microscopic structure of wood and its macroscopic shrinkage properties has not been fully clarified, which restricts the precise optimization of the drying process. Future research can make use of advanced simulation and monitoring technologies to deeply explore the dynamic change mechanism of free shrinkage. At the same time, actively explore new types of green, environmentally friendly, and low-cost drying technologies to accelerate the transformation of research results into practical production applications, thus promoting the high-quality development of the wood processing industry.

OUTLOOK

Despite significant progress in understanding wood free drying shrinkage, several critical gaps remain, necessitating further research to bridge fundamental knowledge with industrial applications:

1) The lack of standardized measurement protocols poses a major challenge. Existing methods vary widely in specimen preparation, experimental conditions, and data analysis, hindering direct comparisons across studies. Future efforts should prioritize developing unified guidelines for free shrinkage measurement, integrating multiscale techniques (from macroscopic dimensional analysis to microscopic cell wall imaging) to ensure consistency and accuracy.

2) Elucidating the quantitative relationship between wood microstructure and its free shrinkage behavior is critically important for advancing wood science. Although previous studies have identified influential factors including microfibril angle, cell wall lamellae organization, and ray parenchyma cells, the underlying mechanisms remain unresolved. Developing a multimodal characterization platform that integrates high spatiotemporal resolution with simultaneous monitoring of moisture content dynamics and free shrinkage would enable real-time observation of how nanoscale moisture variations manifest as macroscopic dimensional changes. This fundamental understanding will facilitate the establishment of predictive models to optimize drying processes for species-specific and application-tailored wood products.

3) Developing sustainable and cost-effective drying technologies is crucial for industrial applications. Although supercritical CO₂ drying and freeze-drying enable the control of free shrinkage, their high energy consumption and equipment costs limit industrial scalability. Future research should actively explore innovative methods to reduce operational costs. Furthermore, exploring the application of modifiers may provide new strategies for sustainable wood processing.

In summary, research on wood free drying shrinkage has achieved phased progress. Further development is required in both theoretical and practical aspects. Ideal free drying serves as a crucial theoretical benchmark for elucidating dimensional change mechanisms during wood drying. By systematically analyzing influencing factors, detection techniques, and application status in actual free drying processes, this study identifies the key parameters governing deviations from the ideal state. These findings provide not only theoretical guidance for experimental optimization but also a solid foundation for bridging the theory-practice gap and addressing research deficiencies.

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