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İÇİNDEKİLER

DURABILITY OF WOOD MATERIALS AND PROTECTIVE METHODS

Orhan KELLECİ[1]

1. INTRODUCTION

The natural durability of wood, particularly its resistance to microbial decay, is influenced by both inherent properties and environmental conditions during use. Heartwood from various tree species exhibits enhanced decay resistance due to the presence of naturally occurring toxic compounds. These substances deter microbial activity and improve wood durability. Research has shown that antifungal heartwood extractives, such as pinosylvins in Scots pine, are critical for decay resistance(Belt et al., 2019). Similarly, high lignification in Kempas wood contributes to its structural resistance (Singh et al., 2018). The durability of Western red cedar highlights the role of extractives in resisting fungal attacks (Stirling et al., 2017). Furthermore, studies on various tree species confirm that extractive content is a key predictor of natural durability, while the relationship between wood density and durability may vary depending on the species (Perrot et al., 2020). The natural durability of wood is largely influenced by biotic and abiotic factors, as well as the anatomical structure and chemical composition of the tree species (Figure 1).

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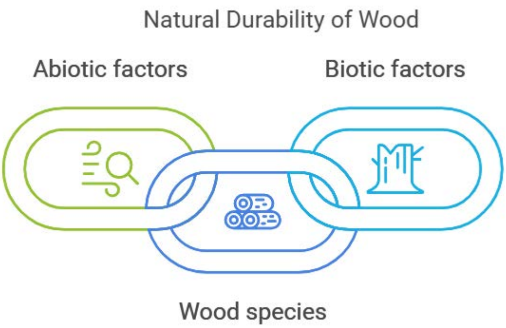

Figure 1. Some factors affecting the durability of wood

The preservation of wood has been a concern for millennia, inspiring various methods to enhance its durability. Early techniques included charring wood surfaces or applying tar to protect against decay and pests. While these traditional methods were effective, modern research highlights that some woods naturally resist decay due to toxic compounds in their heartwood, such as antifungal extractives and high lignin content (Belt et al., 2019; Singh et al., 2018). Modern wood protection techniques now include chemical treatments and natural oil coatings to enhance durability and resistance to decay (Perrot et al., 2020; Stanciu & Teacă, 2024).

Both traditional and modern wood preservation methods have their strengths and weaknesses (Figure 2). Traditional methods, such as charring or applying tar, are simple and accessible, making them ideal for small-scale woodworking and historic preservation projects (Singh et al., 2018). However, their effectiveness tends to decrease over extended periods In contrast, modern preservation techniques, such as chemical treatments and natural oil coatings, offer longer-lasting and more cost-effective solutions for large-scale applications (Perrot et al., 2020). For instance, treatments using extracts from durable woods, such as teak, have been shown to significantly enhance resistance to decay and termites (Hassan et al., 2019). Traditional techniques remain valuable for preserving cultural heritage, while modern methods excel in protecting wood used in harsh environmental conditions (Stirling et al., 2017).

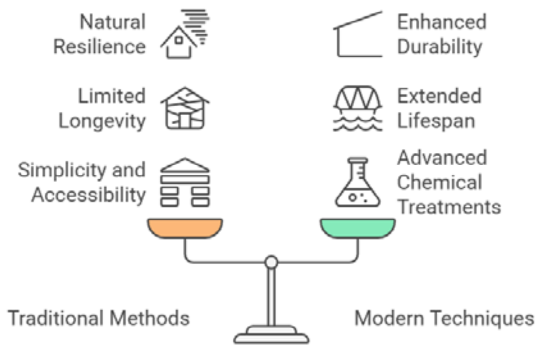

Figure 2. Comparison of traditional and modern wood preservation methods

1.1. Factors Affecting Wood Durability

Wood is a versatile material widely valued for its thermal insulation, acoustic absorption, ease of processing, and ability to create a warm and aesthetically pleasing environment (Figure 3). These properties, combined with its compatibility with protective treatments, make wood suitable for diverse applications. (Figure 3). These properties, combined with its compatibility with protective treatments, make wood suitable for diverse applications. Studies highlight wood's potential for acoustic optimization through natural materials and composites (Gokul et al., 2021) as well as its effectiveness as a thermal insulator (Berardi & Iannace, 2015). Innovations such as wood-based aerogels further enhance these characteristics, providing advanced structural and functional benefits (Nie et al., 2022). Despite its advantages, wood is susceptible to degradation from environmental and biological factors, including moisture, UV radiation, fungi, and insect attacks. To address these challenges, researchers have developed various preservation techniques, integrating wood with other materials to improve its performance in architectural and industrial applications (Tiuc et al., 2022). These advancements reinforce wood's enduring relevance, with over 5,000 documented applications across different industries.

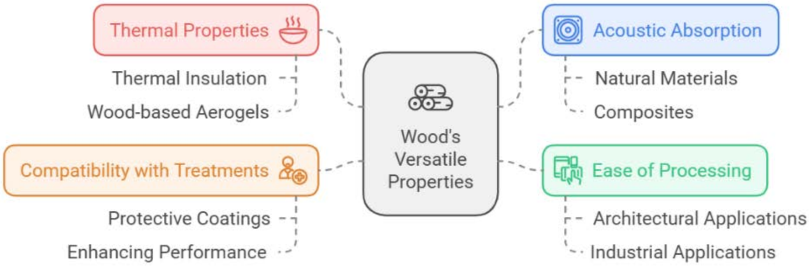

Figure 3. The versatile properties of wood

Maximizing efficiency in wood production across different tree species is critical, especially as the cost of replacing deteriorated materials continues to rise. Consequently, significant efforts have been made to optimize conditions that enhance wood durability. Many studies emphasize the development of reliable standards, the selection of appropriate materials, and the refinement of application techniques to achieve consistent and durable results (Belt et al., 2019). Research on wood treatments highlights the role of extractive content in prolonging service life (Perrot et al., 2020). Additionally, innovative composites that combine wood with synthetic materials have shown great potential for improving durability and extending usability (Tiuc et al., 2022). Advances in protective coatings further demonstrate how wood can be treated to withstand harsh environmental conditions (Stirling et al., 2017).

Wood is exposed to various factors that contribute to its degradation, including UV radiation, humidity fluctuations, wind, and microbial activity. These elements can cause discoloration, cracking, hydrolysis, erosion, and structural changes, depending on the wood's composition and environmental conditions. Studies indicate that UV radiation accelerates lignin degradation, leading to significant color and structural changes (Xing et al., 2015). Similarly, photodegradation from sunlight is a major cause of chemical alterations in wood, particularly on exposed surfaces (Ouadou et al., 2017). Additionally, moisture cycling and microbial colonization further weaken wood, contributing to erosion and loss of stiffness (Golkarieh, 2024). Understanding these degradation processes is essential for developing effective preservation strategies to enhance wood's durability and longevity.

Protecting wood from outdoor conditions requires measures to mitigate both biotic and abiotic threats. Environmental exposure can cause discoloration, degradation, and strength loss, with the extent of these changes depending on the resistance properties of specific wood species(Ajuong et al., 2018). Biotic and physical factors alter the organic composition of wood, highlighting the need to understand species-specific responses to these influences (Xing et al., 2015). Applying suitable protective agents through surface or deep treatments is essential for safeguarding wood against environmental damage (Kuka et al., 2023). Prolonged exposure to factors such as UV radiation and moisture can result in surface hardening, fiber separation, erosion, and chemical degradation over time (Ouadou et al., 2017). Implementing effective treatments significantly enhances the durability and performance of wood in demanding outdoor environments (Golkarieh, 2024).

Wood materials treated with latex or alkyd coatings exhibit enhanced durability against outdoor weathering, outperforming untreated panels (Jirouš-Rajković & Miklečić, 2021). These coatings help minimize surface cracking, fiber loss, and erosion caused by UV radiation, rain, and temperature fluctuations (Pánek & Reinprecht, 2019). Acrylic latex coatings also delay shear strength loss, making them particularly effective for prolonged environmental exposure (Oberhofnerová et al., 2019). The resistance of coated wood to weathering depends on both the type of treatment and the wood species (Darmawan et al., 2019). Implementing effective coating strategies not only extends wood’s lifespan but also preserves its aesthetic qualities, offering significant economic and environmental benefits (Dvořák et al., 2023).

Wood exposed to outdoor environments undergoes photodegradation and photooxidation due to UV light, resulting in significant surface changes. UV light penetrates up to 20 µm into the wood, breaking down lignin and forming chromophores, which cause discoloration and surface weakening (Zborowska et al., 2015). Natural weathering further accelerates degradation by generating free radicals that react with oxygen, forming compounds such as hydrogen peroxide (Zborowska et al., 2015). Studies indicate that UV exposure reduces the wood's contact angle, increasing wettability and contributing to surface erosion (Jirouš-Rajković & Miklečić, 2021). These effects highlight the need for protective treatments to improve wood’s resistance to photodegradation (Shi et al., 2023).

1.2. Wood Protective Chemicals and Wood Properties

Wood materials exposed to outdoor conditions are subject to repeated wetting and drying cycles, leading to stress, cracks, and surface degradation. Additionally, UV radiation accelerates erosion and weakens the wood's surface. Hydrophobic coatings, such as varnishes and specialized paints, play a crucial role in protecting wood from moisture and UV damage. Varnishes reduce water absorption but may crack under prolonged exposure (Rowell, 2017). Hydrophobic paints penetrate deeper into the wood, forming a waxy protective layer that enhances durability (Yuan et al., 2021). Advanced coatings incorporating UV stabilizers and nanoparticles effectively minimize surface discoloration, erosion, and fungal growth in cracks (Chang et al., 2024). These protective treatments are essential for extending the lifespan of wood in harsh environmental conditions (Teacă & Bodîrlău, 2016).

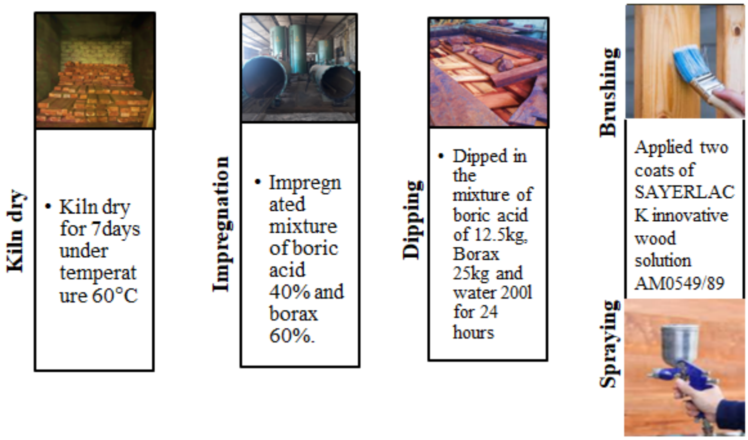

Figure 4. Some wood preserving methods (Sudeshika et al., 2020)

The durability of wood in outdoor conditions depends on multiple factors, including species, density, and surface treatments. UV radiation, moisture, and fungal growth are the primary causes of degradation, leading to discoloration, cracking, and loss of structural integrity (Kim, 2018). Protective coatings such as hydrophobic oils, paints, and varnishes help mitigate these effects (Figure 4). For example, acrylic coatings enhance UV resistance, though their effectiveness varies depending on application techniques and wood type (Dvořák et al., 2023). Additionally, heat-treated and chemically modified woods exhibit greater resistance to moisture and UV damage (Teacă & Bodîrlău, 2016). Implementing effective surface treatments and regular maintenance is essential for extending wood's outdoor service life (Tsapko et al., 2021).

Outdoor wood surfaces are commonly treated with oil-based, alkyd, latex, and solvent-based coatings to enhance durability and maintain aesthetic appeal. These treatments must ensure user safety, provide effective pest resistance, and offer long-lasting protection against environmental factors such as UV radiation and moisture (Terzi et al., 2019). While water-based coatings are more environmentally friendly, solvent-based systems often provide superior performance in demanding conditions (Drahl, 2018). Innovations in alkyd-acrylate hybrid coatings show promise in combining durability with eco-friendliness (Assanvo & Baruah, 2015).

Surface pre-treatments, such as epoxy or UV stabilizers (Figure 5), improve coating adherence and longevity, reducing color changes and surface erosion during outdoor exposure (Dvořák et al., 2023). However, environmental factors like rain and humidity require frequent maintenance to sustain protective performance (Chavenetidou et al., 2019). Multi-layered coatings generally provide superior results, with latex outperforming alkyd systems in moisture resistance and overall durability (Mihăilă et al., 2024). Effective application techniques and high-quality materials are essential for extending the lifespan of wood products in outdoor environments (Calovi et al., 2024).

Figure 5. Wood samples with and without UV stabilizer (Evans et al., 2015).

Protective chemicals for outdoor wood surfaces, such as varnishes and hydrophobic paints, are essential for enhancing durability and maintaining aesthetic appeal. Varnishes create a transparent film that shields wood from UV radiation and moisture absorption, making them one of the most effective protective materials in theory (Kim, 2018). However, prolonged outdoor exposure can cause varnishes to crack and degrade, reducing their effectiveness over time (Teacă & Bodîrlău, 2016).

Hydrophobic paints (Figure 6), which contain fungicides and UV-blocking pigments, form a waxy, water-repellent layer that penetrates up to 1 mm into the wood, providing superior protection against fungal growth and photodegradation (Teacă & Bodîrlău, 2016). Innovative formulations with nano-additives further enhance durability by reducing UV damage and abrasion while maintaining a smooth finish (Aksu et al., 2022).

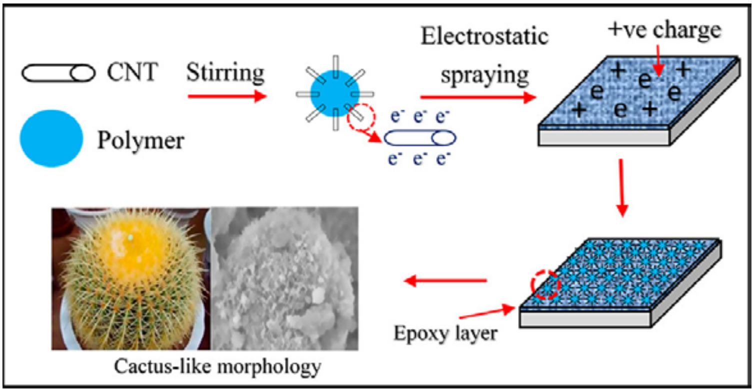

Figure 6. Superhydrophobic surfaces: Insights from theory and experiment (Parvate et al., 2020)

When working with sub-saturated fluids, differences in deposition must account for the interactions between wood biopolymers and biocides. These interactions play a crucial role in determining both the chemical composition of wood and the functional properties of biocides (Miyafuji, 2015; Patachia & Croitoru, 2016; Yang et al., 2020). A deeper understanding of these mechanisms can enhance biocide efficacy while reducing environmental impact (Figure 6).

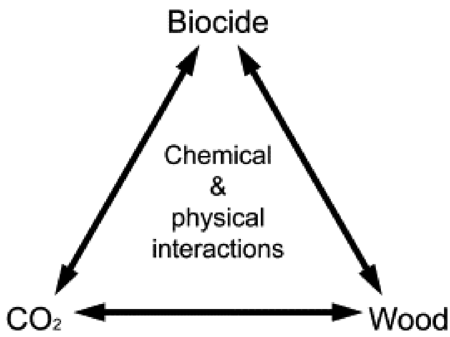

Figure 7. Biocide deposition in wood via supercritical impregnation depends on interactions among CO2, wood, and biocides, with co-solvents adding complexity (Kjellow & Henriksen, 2009)

Bio-based coatings have emerged as eco-friendly alternatives, providing effective protection against environmental stressors while promoting sustainability (Calovi et al., 2024). Regular maintenance, combined with advanced coating technologies, is essential for prolonging wood performance in outdoor environments (Bahchevandziev & Mihajlovski, 2022).

1.3. Effect of Outdoor Conditions on Wood Material

The use of natural wood in outdoor settings is popular for its aesthetic appeal but poses challenges in maintaining its appearance over time. Photodegradation, fungal decay, and weathering can significantly alter wood surfaces, leading to discoloration, cracking, and surface erosion (Figure 8) (Wang et al., 2022). Without protective treatments, wood is highly vulnerable to damage, particularly from UV radiation, moisture, and biological agents, resulting in both material deterioration and financial losses (Yuan et al., 2019).

Protective coatings, such as varnishes and paints, serve as essential barriers against environmental stressors. Hydrophobic paints provide resistance to water penetration and UV radiation, helping preserve wood's structural integrity (Tu et al., 2018).

Additionally, bio-based materials, including epoxidized vegetable oils and nanocomposites, offer innovative solutions for enhancing durability while promoting environmental sustainability (Varganici et al., 2021).

Figure 8. Surface degradation of wood (Babar & Kathryn, 2020).

The phenomenon of washing, caused by rain and UV exposure, affects only the surface layers of wood, highlighting the importance of effective surface treatments to slow degradation (Rosu et al., 2016). Surface changes, such as increased porosity and fiber loosening, further emphasize the need for regular maintenance and the application of protective coatings (Terzi et al., 2019).

Combining UV absorbers and hydrophobic elements in coatings provides long-lasting protection while preserving wood's aesthetic qualities, making it essential for both residential and commercial applications (Harandi et al., 2024).

1.3.1. Chemical Changes in The Structure of Wood Outside

Exposure to outdoor conditions causes significant changes in wood surfaces, primarily due to UV radiation and moisture. Lignin, a key component of wood, absorbs UV light, leading to its degradation. This process results in gray discoloration as lignin breakdown products are washed away by rain, leaving behind cellulose-rich fibers that are more resistant to UV damage (Živković et al., 2016). During initial exposure, wood undergoes rapid color changes, transitioning from yellow to brown due to lignin photodegradation and the oxidation of extractives (Wang et al., 2022).

Moisture alone has a minimal impact on wood surface chemistry but plays a significant role when combined with light. This interaction accelerates surface polymer degradation, leading to characteristic erosion and discoloration (Burud et al., 2015). Acetylation has been shown to reduce washing effects by up to 50% under decay-prone conditions, highlighting its protective potential (Varganici et al., 2021).

Wood-plastic composites (WPCs) (Figure 9), widely used in construction, are also susceptible to UV-induced degradation. Oxidative degradation of wood flour (WF) in high-density polyethylene (HDPE) composites exceeds that of pure HDPE, resulting in more pronounced damage and surface erosion (Stark & Matuana, 2004). In the initial stages of photodegradation, cross-linking in HDPE enhances its stability compared to WF/HDPE composites (Rosu et al., 2016).

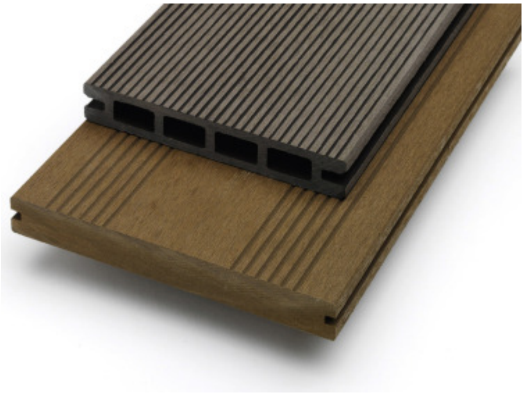

Figure 9. Wood plastic composite (WPC) (Kim & Pal, 2010).

Advanced coatings, such as UV-resistant varnishes and hydrophobic paints, play a crucial role in mitigating these effects. They slow lignin degradation, protect against moisture, and help preserve the aesthetic and structural integrity of wood (Yuan et al., 2019). Ongoing research on wood treatments and composites remains essential for extending wood's service life in outdoor environments (Terzi et al., 2019).

1.3.2. Physical Changes by Outdoor Condition

Wood surfaces exposed to outdoor conditions undergo significant chemical, mechanical, and color changes, along with physical degradation. The combined effects of light and water accelerate surface deterioration, leading to the formation of cracks and pores at both microscopic and macroscopic levels, which contribute to surface darkening (Rosu et al., 2016). Rainwater further erodes the surface, with coniferous woods deteriorating faster than hardwoods (Živković et al., 2016).

The rate of washing varies by wood species; denser woods generally exhibit lower erosion rates, while low-density species, such as oak, erode more rapidly (Varganici et al., 2021). In conifers, earlywood tends to experience less erosion than latewood (Anderson et al., 1991). The physical loss of wood material due to washing depends on various environmental factors, including wind, light, rain, exposure duration, wood species, density, and climate conditions (Stark & Matuana, 2003).

Washing creates a grooved or ribbed appearance on wood surfaces, with deciduous woods being less affected than coniferous species. Changes in moisture content also cause tension, swelling, and the formation of small cracks or pores, particularly in the distinct bands of earlywood and latewood (Teacă et al., 2019). Degradation from light, moisture, and microbial stains leads to color changes and contributes to both chemical and physical damage (Burud et al., 2015).

While chemical degradation involves complex free radical reactions, UV light penetrates only about 20 µm into wood surfaces, confining degradation to this superficial layer (Rosu et al., 2016). As a result, protective measures, such as UV-resistant paints and coatings, are essential for preserving the structural and aesthetic properties of wood (Terzi et al., 2019). Advanced coatings, including hydrophobic paints and bio-based varnishes, significantly improve wood durability under outdoor exposure (Samyn et al., 2022).

1.3.3. Wood Durability After Outdoor Exposure

The effects of washing and UV exposure on wood-plastic composites (WPCs) have a limited impact on modulus of elasticity, compression strength, and rupture modulus. However, surface roughness and wear resistance decrease significantly due to prolonged exposure (Jais et al., 2016). Surface erosion from rain and UV light primarily affects softer woods and wood components in WPCs (Kallakas et al., 2015).

Mechanical property loss in wood-plastic composites (WPCs) is more pronounced with certain production methods, as these influence surface characteristics and erosion susceptibility (Hirsch & Theumer, 2022). Modifying the production process could help mitigate mechanical property losses caused by washing (Durmaz, 2022). Additionally, higher wood content in the composite matrix exacerbates modulus of elasticity reduction following washing and UV exposure (Badji et al., 2017).

Wood-plastic composites (WPCs) made with modified or heat-treated wood particles exhibit reduced color fading and enhanced UV resistance compared to untreated composites (Kuka et al., 2020). However, despite these advancements, further refinements in surface treatment methods are necessary to minimize mechanical degradation and improve color retention in WPCs under prolonged outdoor exposure (Guo et al., 2019).

Recycled wood-plastic composites (WPCs) show promising performance with proper surface treatment, exhibiting minimal impact on mechanical properties when recycled content remains below 20% (Luo & Cheng, 2021). These findings highlight the importance of further refining WPC production and protection technologies to ensure long-term performance and durability under environmental stresses.

1.3.4. Protection Against Washing

Wood used in outdoor environments can be preserved through paints and surface treatments, ensuring durability under harsh conditions. Several factors influence wood protection, including moisture content, density, resin and oil content, growth ring patterns, knots, and fungal susceptibility (Teacă & Bodîrlău, 2016). Protective measures help shield wood surfaces from natural washing processes and contribute to maintaining their appearance and longevity (Jirouš-Rajković & Miklečić, 2021).

Current technologies integrate recycled materials to produce natural fiber-reinforced thermoplastic composites, creating expanding markets for waste-based materials (Friedrich, 2019). Widely used in construction, these composites have experienced significant market growth, particularly in decking applications, where they now account for approximately 4% of the outdoor decking market within a decade (Godinho et al., 2021). However, concerns regarding durability and performance continue to limit broader adoption among homeowners (Falk et al., 1996).

Varnishing treated wood enhances its protective capabilities, helping to preserve both its aesthetic and structural integrity for interior and exterior applications (Kim et al., 2020). However, environmental factors such as temperature, humidity, light, and chemicals including organic solvents, acids, and ozone can lead to color fading and surface deterioration (Gupta et al., 2015).

In non-washing environments, untreated wood may be used, but protective coatings significantly extend its service life. The effectiveness of coatings depends on bonding agents such as synthetic resins, latexes, and drying oils, which vary in their resistance to environmental stressors (Herrera et al., 2018). Advances in nanosilica-reinforced coatings have further improved UV resistance and durability in wood-plastic composites (Liu et al., 2019).

2. CONCLUSION

Wood is a renewable and environmentally friendly material, offering significant sustainability benefits. With low carbon emissions during production and recycling potential, wood has a smaller environmental footprint than alternatives like glass, concrete, metal, and ceramics. Its natural aesthetic appeal and workability make it a preferred choice for both architectural and industrial applications. However, its suitability for specific uses depends largely on its natural durability characteristics.

The natural durability of wood is crucial for enhancing material quality and extending its service life. Durable wood species, particularly those resistant to insects and fungi, offer both economic and functional advantages. Applications using naturally durable wood require less maintenance and provide longer-lasting performance. In contrast, wood species with lower durability can be strengthened through various preservation methods.

However, wood durability challenges include flammability, susceptibility to biotic factors, and dimensional instability in humid environments. Overcoming these challenges requires careful wood species selection and the application of suitable preservation methods. Common preservation techniques include impregnation treatments, surface coatings, and the use of natural or synthetic protective materials. The choice of method depends on factors such as intended use, environmental conditions, and wood type.

Selecting appropriate preservation techniques maximizes wood's performance and longevity. For outdoor applications, protection against insects, fungi, and weathering is essential. In indoor settings, aesthetic preservation methods such as finishes and varnishes help maintain appearance and durability.

In conclusion, wood is a renewable, aesthetic, and eco-friendly material with great potential as a sustainable construction resource. Choosing naturally durable species reduces costs while enhancing quality. Meanwhile, preservation treatments improve the usability and longevity of less durable species. Maximizing wood's benefits requires careful species selection, effective preservation strategies, and consideration of environmental factors.

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STRUCTURAL, MECHANICAL, AND FUNCTIONAL PROPERTIES OF WOOD

Süheyla Esin KÖKSAL[1]

1. INTRODUCTION

Wood is one of the cornerstones of materials science and engineering disciplines, and studies in this field are essential for understanding and optimizing the properties of various materials. Each material has its own unique physical, chemical, mechanical, and thermal properties, and a thorough understanding of these properties ensures that the material is used in the most appropriate manner. In engineering applications, every stage from material selection to processing, from design to performance is carried out based on the knowledge provided by materials science (Güldal & Üllen, 2018; Hrčka & Babiak, 2017; Roy et al., 1989; Wei et al., 2018).

This becomes even more evident, particularly for wood, which is a naturally occurring biological material. Wood holds a unique position among engineering materials due to its wide variety of species, diverse texture, and complex internal structure. Assessing the characteristics of wood should not be limited to its mechanical performance and workability but should also take into account key factors such as environmental sustainability, biodegradation, and renewability (Kılınçarslan & Şimşek Türker, 2020; Tunçel, 2016).

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The structural complexity of wood makes it a more challenging subject of study compared to other engineering materials. Its cellular structure, xylem tissue, and the presence of components such as lignin and cellulose significantly influence its physical and mechanical properties. For example, cell wall density plays a crucial role in determining the hardness and durability of the material. Additionally, anatomical and chemical differences between wood species can significantly impact its performance in engineering applications (As et al., 2001; Bal & Bektaş, 2018; Çalışkan et al., 2019).

This structural complexity makes its characteristics more complex to assess compared to other engineering materials, such as metals, ceramics, and polymers. However, these challenges also highlight wood's potential for engineering applications. With the right analyses and tests, key properties of wood such as strength, flexibility, workability, and aesthetics can be effectively assessed. Additionally, wood is a bio-renewable material with a low carbon footprint, making it an ideal choice for sustainable engineering solutions (Nuñez Avila & Blanca-Giménez, 2022; Żmijewki & Wojtowicz-Jankowska, 2017).

Extensive research on the anatomical, physical, mechanical, and chemical properties of wood has been conducted both globally and in our country. The findings of these studies have been made available to researchers and professionals through various publications. However, compiling data on different tree species from multiple sources can sometimes be challenging. Given this, ensuring that industrially important tree species are easily accessible to researchers, industry experts, and practitioners in both digital and print formats has become essential (As et al., 2001).

1.1. Structural Features of Wood Material

The fundamental structural component of wood is a complex biological material composed of specialized cells. These cells develop, differentiate, and specialize as the tree grows, forming distinct tissues with specific functions. The structure and composition of these cells largely determine the biological and mechanical properties of wood. At the microscopic level, many wood cells, such as tracheids and vessel elements, have a hollow structure that facilitates water transport and mechanical support (Figure 1). This hollow structure contributes to the lightweight strength and flexibility of wood, while durability depends on the composition of the cell wall (Daniel, 2016; Salmén, 2018).

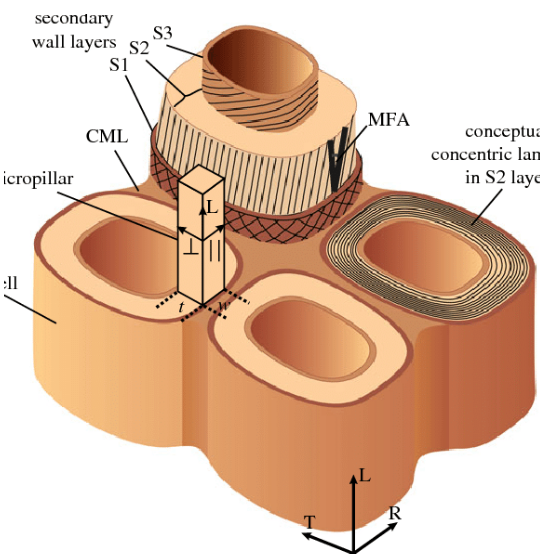

Figure 1. General structure of a wood cell (Rafsanjani et al., 2014).

1.1.1. Cell Wall Structure

One of the most distinctive features of wood is the complexity of its cell walls and hierarchical structure (Figure 2). Cell walls are structural components that surround individual cells, providing shape, rigidity, and mechanical support. The cell wall is primarily composed of biopolymers, including cellulose, hemicellulose, and lignin, which contribute to its structural and mechanical properties. Cellulose provides tensile strength to the cell wall, while hemicellulose acts as a matrix, influencing its mechanical behavior and bonding properties. Lignin enhances structural integrity by providing rigidity, hydrophobicity, and resistance to microbial degradation while also contributing to the adhesion between cell walls (Li & Zheng, 2020; Mellerowicz & Sundberg, 2008; Zhang et al., 2022).

The proportions of these three components vary depending on the wood species and growing conditions, influencing the mechanical properties of the wood. Wood species with a higher lignin content tend to be harder and more resistant to decay and environmental factors. In contrast, species with a higher cellulose content often exhibit greater flexibility, especially when combined with a lower density and specific microfibril angles (Huang et al., 2003).

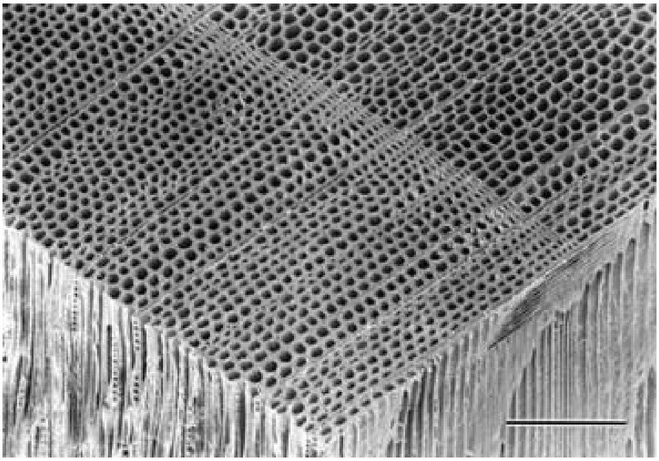

Figure 2. Wood cross-section (200 µm) Scanning Electron Microscope (SEM) image (Huang et al., 2003).

1.1.2. Characteristics of Cell Structure

The cellular structure of wood, along with its chemical composition and density, plays a crucial role in determining its mechanical and physical properties. The arrangement, density, and shape of wood cells influence its strength characteristics in both the fiber direction and perpendicular directions. Additionally, microfibril angle and cell wall composition significantly contribute to these properties. The tensile strength of wood is typically very high along the fiber direction, whereas in the perpendicular direction, it is significantly lower due to weak intercellular bonding. Studies show that the tensile strength along the fiber direction is significantly influenced by fiber morphology, microfibril angle (MFA), and cell wall thickness. When fibers are loaded in the perpendicular direction, wood may exhibit brittle failure, such as intercellular delamination and cleavage due to weak bonding between cells (Bingxin et al., 2024; Feng et al., 2021).

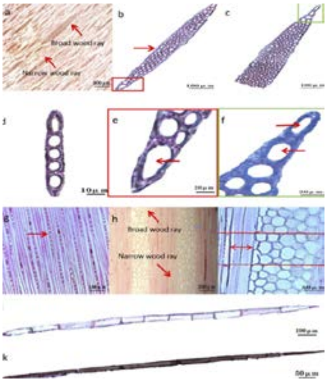

Figure 3. The microscopic structure of three wood species in tangential section. (a) Beech (Fagus spp.) with wide and narrow wood rays. (b) Beech multi-columnar wood rays containing a single square cell. (c) Beech multi-columnar wood rays containing one or more square cells. (d) Beech uniseriate ray (single-row wood ray). (e) A square cell. (f) One or more square cells (three in this case). (g) Poplar (Populus spp.). (h) Dillenia species with wide and narrow wood rays. (i) Comparison of wide and narrow wood rays in Dillenia species. (j) Dillenia uniseriate ray. (k) Dillenia uniseriate ray containing gum deposits (Bingxin et al., 2024).

The intercellular spaces and vascular tissues within the wood facilitate essential physiological processes, such as water and nutrient transport, while also influencing the density and mechanical properties of the material. These structural characteristics not only affect the physical properties of wood but also play a crucial role in its workability and potential applications (Feng et al., 2021; He et al., 2023).

1.2. Mechanical Properties of Wood Material

The mechanical properties of wood play a crucial role in its suitability for various engineering applications. These properties include tensile strength, compressive strength, bending strength, shear strength, and hardness. These properties are influenced by wood species, moisture content, density, and cellular structure (Winandy & Rowell, 2005)

1.2.1. Tensile and Compressive Strength

Tensile strength refers to the ability of a material to withstand stress without breaking or undergoing excessive elongation. Wood demonstrates superior tensile strength, particularly when the load is applied parallel to the grain. This is due to the alignment of fibers in the grain direction, which significantly increases resistance to tensile stress, primarily supported by cellulose microfibrils (Genet et al., 2005).

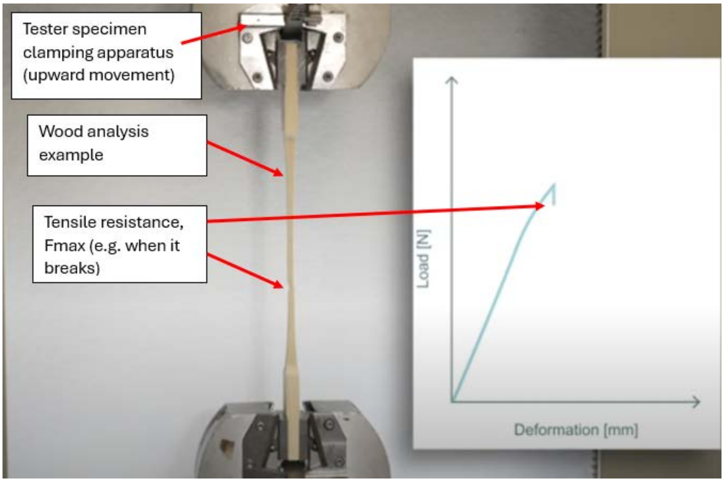

Figure 4. Tensile strength testing assembly (Aolto University, 2023).

Compressive strength refers to a material's ability to resist deformation under compressive stress. Wood has significantly lower compressive strength when loaded perpendicular to the grain. This is primarily due to the collapse and buckling of wood cells, causing permanent deformation in the cellular structure (Benabou, 2010).

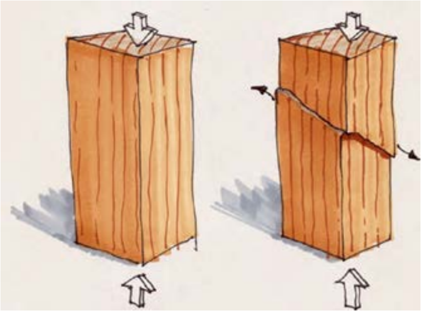

Figure 5. Direction of applied force in compressive strength testing (Kaltimber, 2019).

1.2.2. Flexural and Shear Strength

Flexural strength refers to the ability of wood to withstand bending stress without breaking or significant deformation.

Flexural strength is typically greater when the load is applied parallel to the grain. The parallel arrangement of fibers and the capacity of the cell structure to distribute and dissipate stress contribute to its high bending resistance (Burdon et al., 2001; Säll et al., 2007).

Shear strength, on the other hand, refers to the ability of a material to resist internal sliding failure when subjected to opposing forces. Wood exhibits low shear strength when loaded parallel to the grain. This is due to weak interfiber bonding and the low cohesive strength of the middle lamella (Longui et al., 2017; Riesco Muñoz, 2021).

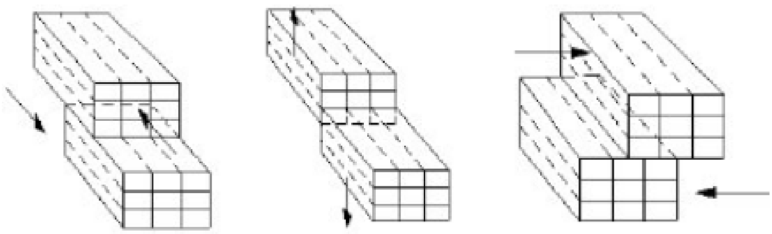

Figure 6. Shear strength of solid wood (Wang et al., 2014).

1.3. Physical Properties of Wood Material

The physical properties of wood influence its suitability for engineering applications, as well as its machinability and workability. These properties include density, moisture content, water absorption and retention capacity, and thermal characteristics.

1.3.1. Density

The density of wood is a key factor influencing its mechanical properties. Density is defined as mass per unit volume and varies depending on the wood species, growth conditions, and cellular structure. High-density wood species are generally harder and more resistant to mechanical stress (Ruiz-Aquino et al., 2018; Suhaya et al., 2023).

1.3.2. Moisture Content and Hygroscopic Behavior

Wood is hygroscopic, meaning it can absorb and release water vapor from its surrounding environment. The moisture content of wood directly affects its mechanical properties. As moisture content increases, the structural integrity, mechanical strength, and hardness of wood decrease. Additionally, the hygroscopic nature of wood causes swelling and shrinkage, resulting in dimensional instability and potential warping(Aquino et al., 2022; Withanage & Amarasekera, 2024).

1.3.3. Thermal Properties

Wood is a good thermal insulator. This is due to its cellular structure. The air-filled voids within the cellular structure and the low density of wood reduce heat transfer throughout the material. Therefore, wood offers effective thermal insulation when used in construction (Storodubtseva et al., 2018; Wang et al., 2019).

1.4. Applications of Wood

These unique properties of wood make it suitable for various engineering applications. It is widely used in fields such as construction, furniture manufacturing, paper and bioenergy production. Today, wood is utilized in thousands of products across various industries (Coles et al., 1978; Schultz et al., 2007; Tsapko et al., 2023).

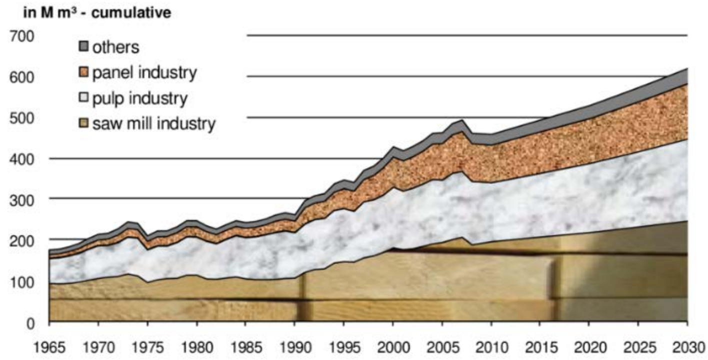

Figure 7. Trends in Wood Consumption in Europe by Sector (Mantau et al., 2010)

1.4.1. Wood as a Building Material

Wood has been used as a building material for centuries. Its low density, durability, and workability make it an ideal construction material. Wood is commonly used in timber-framed structures, bridges, and flooring. Additionally, the aesthetic value of wood plays a significant role in interior design (Schultz et al., 2007; Żmijewki & Wojtowicz-Jankowska, 2017).

1.4.2. Furniture & Decoration

Wood is widely used in furniture and interior decoration due to its versatility. The wood species preferred in furniture production are generally those with high density and durability, ensuring longevity and structural integrity. Wooden furniture is favored in both traditional and modern interior design styles for its aesthetic appeal, natural texture, and timeless elegance, making it a preferred choice for residential and commercial spaces.(Adiji et al., 2022; Jayalath et al., 2024).

1.4.3. Paper & Pulp Products

Wood is a fundamental raw material for the production of paper and other cellulose-based products. Cellulose, derived from wood, is the primary component used in paper manufacturing.

The fibrous structure of wood provides the necessary fibers for paper production, and the length and quality of these cellulose fibers directly influence the strength, texture, and overall quality of the final paper product (Dadzie et. al., 2015; Gayda, 2018).

1.4.4. Power Generation

Wood is also a significant source of biomass energy. Through photosynthesis, trees convert solar energy into chemical energy, which can be released through combustion. This stored energy is utilized in various applications, including power generation, heating, and cooking (Ratnasingam et al., 2015; Toklu, 2017).

2. CONCLUSION

Understanding the characteristics of wood is essential for optimizing its use in engineering applications. The cellular structure, composition of the cell walls, and mechanical and physical properties of wood determine its suitability for various applications and influence its overall performance. With its natural attributes and sustainable nature, wood will continue to play a crucial role in engineering and design, both today and in the future.

In this context, conducting comprehensive studies on wood and gaining a deeper understanding of its properties are critical for advancing both academic research and practical applications.

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STRUCTURAL ANALYSIS AND FUNCTIONS AT THE MICROSCOPIC LEVEL IN WOOD

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1. INTRODUCTION

Wood is a complex structure composed of a large number of small cells. For example, 1 cm^3 of spruce wood contains approximately 350,000 to 500,000 cells. The outer walls of these cells are connected through pits that facilitate the transport of water and nutrients. During secondary growth (or lateral growth), cells in different parts of the wood take on different roles (Figure 1). The inner cavity of the cell is called the lumen. The main functions of wood include conduction, mechanical support, and storage. Vessel elements (tracheae) and tracheids are responsible for both water conduction and mechanical support. However, vessel elements are primarily found in angiosperms, while tracheids are more common in gymnosperms. Wood rays (radial

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parenchyma), which are composed of parenchyma cells, play a critical role in the lateral transport of water and nutrients, connecting the vascular system of the tree. Parenchyma cells are responsible for long-term storage functions and also contribute to the repair and regeneration of wood, playing a vital role in the biological processes of wood (Donaldson et al., 2015; Słupianek et al., 2021).

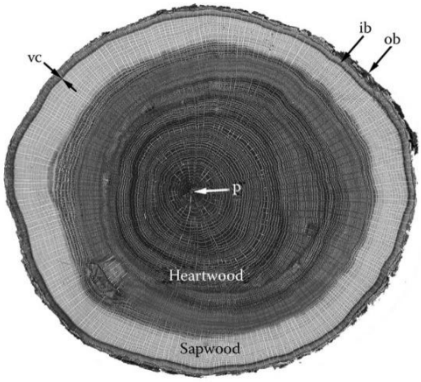

Figure 1. Macroscopic view of the cross-section of the trunk of Quercus alba. Starting from the outside of the tree, the outer bark (ob) appears first. Next comes the inner bark (ib), followed by the vascular cambium (vc), which is too narrow to be seen at this magnification (Wiedenhoeft, 2005).

On the inside of the vascular cambium is the sapwood, which can be easily distinguished from the heartwood. At the center of the trunk lies the barely visible pith (p) within the heartwood.

The anatomical structure of wood is directly related to the spatial arrangement of cells. This is particularly true for the Pinaceae family, where wood structure provides valuable insights into the systematic classification of species. For example, resin canals and ray tracheids are common anatomical features within this family. However, the absence of these traits in certain species also plays a role in interspecific differentiation, which aligns with molecular phylogenies (García Esteban et al., 2021).

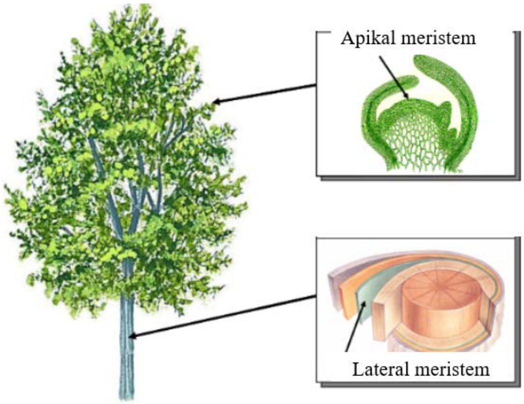

Figure 2. Apical and lateral meristem tissues (Michaletz & Johnson, 2007).

The stems of trees increase in volume due to both height and girth growth. Height growth originates from the apical meristem (Figure 2), while girth growth results from the lateral meristem, specifically the vascular cambium. The apical meristem gives rise to primary growth, while the lateral meristem is responsible for secondary growth. The vascular system of wood, in particular, is composed of tissues that develop between the xylem and phloem. These structures, which play key roles in conduction, mechanical support, and storage, are essential to the biological processes of wood (Barotto et al., 2016; Słupianek et al., 2021).

Mature (heartwood) wood cells are usually dead and lack both protoplasm and nuclei. A large portion of these cells is responsible for ensuring water conduction and providing mechanical support. In particular, vessel elements (tracheae) and tracheids, which are the main conductive elements of wood, facilitate the transport of water and minerals, while parenchyma cells play crucial roles in storage and defense-related functions (Secchi et al., 2017).

When thin sections of wood from the transverse, tangential, and radial surfaces are examined under a light microscope, it can be observed that the cell walls consist of different layers. The first layer of these walls is the primary cell wall, and the second layer is the secondary cell wall. The layer called the middle lamella, located between the primary and secondary walls, facilitates the bonding of cells with each other. The middle lamella is often visible under a light microscope, and its decomposition during wood processing can affect staining procedures (Kim et al., 2019).

1.1. Pits in wood cell walls

In the wood cells, structures called pits (Figure 3) are present in the areas where the secondary wall layer is interrupted. These pits allow the exchange of water and nutrients between adjacent cells. Pits, which typically appear on the radial and tangential surfaces, are categorized into different types based on the structure of the cells. Bordered pits are found on tracheid cells, while simple pits are present on fiber cells (Donaldson et al., 2018).

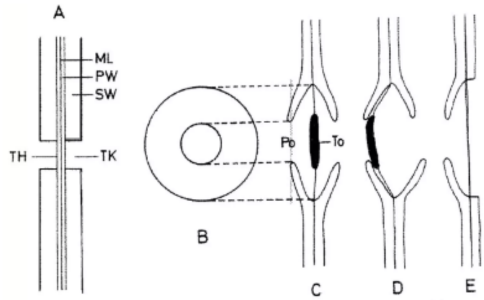

Figure 3. Pits in cell walls, A) simple pits, B) frontal view, C) bordered pits, D) closed-bordered pits, E) half-bordered pits (ML: middle lamella, PW: primary cell wall, SW: secondary cell wall, TH: pit membrane, TK: pit aperture).

Pits are crucial for water transport, and the structural changes that occur within these pits directly influence the movement of water. Structures known as pit pairs facilitate the exchange of fluids and gases between two adjacent cells. For example, in certain tree species, such as angiosperms, the pit membranes between cells play a vital role in regulating water transport under pressure. These membranes maintain water conduction by filtering both water and gas bubbles (Pereira et al., 2018).

Wood cell pits have two main components: the pit membrane and the pit aperture. These pits regulate the flow of water and nutrients between adjacent cells and exhibit structural diversity across different tree species. In bordered pits, particularly in coniferous trees, the central region of the pit membrane is thickened and is referred to as the torus. The torus plays a critical role in controlling the passage of water and gas bubbles between cells. The thin structure surrounding the torus is called the margo. The margo facilitates the transport of water while preventing the passage of torus gas embolisms (Dute, 2015).

These structures enhance the efficiency of wood tissue in water conduction while simultaneously providing resistance to cavitation. The development of the torus and margo structures in both angiosperms and gymnosperms represents important adaptations that optimize water conduction. Furthermore, the morphological characteristics of these pit structures can vary under different environmental conditions, directly influencing water transport and the hydraulic functions of the wood (Li et al., 2020; Sano, 2016).

1.2. Spiral thickening

Spiral thickening occurs in certain tree species through the spiral arrangement of microfibril bundles on the lumen side of the secondary cell wall. These structures are particularly common in broadleaf tree species, while they are less frequent in conifers. Spiral thickenings enhance the mechanical strength of the cell walls, thereby optimizing the plant's water-conducting and endurance capacity (Busse-Wicher et al., 2016).

Microfibrils play a crucial role in the secondary walls of wood cells and facilitate water transport. These spiral structures increase both water conduction and the mechanical strength of the wood. For this reason, spiral thickenings are regarded as a defining characteristic of broadleaf trees (Zhang et al., 2015).

1.3. Microscopic structure in conifers

The wood of coniferous trees is notable for its homogeneous structure and lightness. These trees are commonly preferred in construction and plywood production. In coniferous species, the xylem is relatively simple in structure, and water transport is carried out through tracheids. These trees are also significant for resin production, as they contain high amounts of resin. The simple and regular cell structures of coniferous trees set them apart from other species, and this structural simplicity contributes to the mechanical strength of the wood (Crang et al., 2018; García Esteban et al., 2021).

1.3.1. Longitudinal tracheids

Longitudinal tracheids in coniferous trees (Figure 5) are thin, elongated cells that constitute 90–95% of the wood's volume. These cells play a crucial role in the transmission of water and nutrients, typically aligning parallel to the axis of the tree. Tracheids can be up to 100 times their diameter in length, and their cross-section is typically rectangular. Water conduction occurs through the lumens of the tracheids, which ensures the hydraulic conductivity of the wood. The size and structure of tracheids influence their water-carrying capacity, which varies depending on environmental conditions (Lautner et al., 2017; Qu et al., 2022).

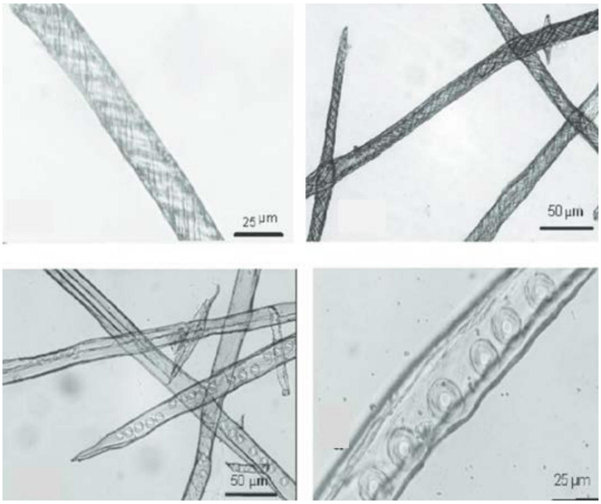

Figure 4: Tracheid cells in coniferous trees (Tarmian et al., 2011).

1.3.2. Strand tracheidler

Strand tracheids are found in certain coniferous trees and resemble parenchyma cells in tangential and radial sections. These cells are short and rectangular in shape, arranged perpendicular to the axis of the tree. Playing a crucial role in the transport of water and nutrients, they are typically located near resin channels or surrounding pathological tissues. They are particularly common in species such as Larix and Pseudotsuga and can be distinguished from other tracheids by their lumen, which is empty. These structures can also serve storage functions, as they share structural similarities with parenchyma cells (Donaldson et al., 2015).

1.3.3. Longitudinal parenchyma cells

Longitudinal parenchyma cells play a critical role in the storage of water and nutrients in certain coniferous tree species. These cells share a similar structure to tracheids and run parallel to the axis of the tree. While they are rare in species such as Pinus and Picea, they can be found in varying proportions in species like Abies and Pseudotsuga. Typically located between the tracheids, longitudinal parenchyma cells are crucial for the plant's storage functions. These cells contribute to the survival of the plant by enhancing its water storage capacity (Arakawa et al., 2018; von Arx et al., 2015).

1.3.4. Epithelial cells

Epithelial cells are specialized parenchyma cells that surround resin channels in coniferous trees. These cells enhance the plant's defense mechanism by increasing resin production in response to injury. Resin channels are particularly common in species such as Pinus, Picea, and Larix, where epithelial cells regulate resin secretion, thereby accelerating the healing process in injured areas. The activity of these cells plays a critical role in the formation of a resin barrier against pathogens (Turner et al., 2019).

1.3.5. Essence ray tracheids

Sap ray tracheids are particularly common in species of the Pinaceae family and play a crucial role in water conduction. These tracheids are similar to longitudinal tracheids but are shorter and facilitate nutrient transport in the radial direction. Their length typically ranges from 0.1 to 0.2 mm, while their diameter is smaller. Sap ray tracheids usually have edged passages and are distinguished by their toothed or flat walls, which are evident when they participate in water conduction. In some coniferous species, these structures are essential for the durability and hydraulic efficiency of the wood (Crang et al., 2018; García Esteban et al., 2021).

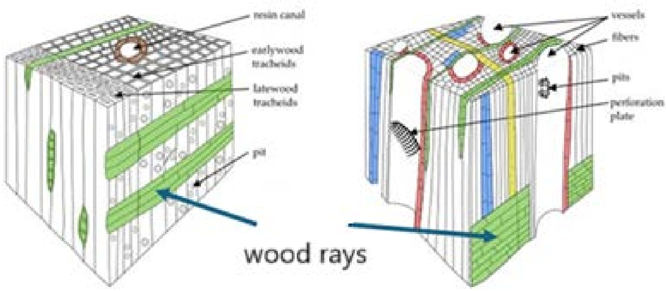

Figure 5. Sap rays in the structure of wood (Słupianek et al., 2021).

1.4. Microscopic structure in broad-leaved trees

The cell structure of broadleaf trees differs significantly from that of conifers. These trees contain a greater variety of cell types, and this diversity in cell structure greatly influences their morphological characteristics. Broadleaf trees are widely preferred for furniture and decorative purposes due to their more aesthetic texture and ease of processing. The microscopic structure of these species exhibits a complex arrangement in which longitudinal and transverse cells are organized into functional groups (Jud et al., 2017; Martínez-Cabrera et al., 2017).

1.4.1. Longitudinal cells of broadleaf trees

The longitudinal cells in broadleaf trees include vessel elements, which are specialized for water conduction. These cells originate from the vascular cambium and transport water and minerals essential for plant growth, forming vessel tubes. Vessel elements have perforation plates, which facilitate the efficient movement of water within the wood tissue. This structure enhances the overall water transport efficiency in the plant. In broadleaf trees, the structural characteristics of these vessels optimize water conduction and help the plant adapt to different growing conditions (Rejab et al., 2023).

The vessel arrangement in broadleaf trees is classified into three groups: ring-porous, diffuse-porous, and semi-ring-porous. Ring-porous vessels form large pores at the beginning of the growing season, with smaller pores developing toward the end. This pattern is common in species such as Quercus and Fraxinus. In contrast, diffuse-porous vessels produce evenly distributed pores throughout the growing season and are characteristic of species like Acer. Semi-ring-porous vessels exhibit an intermediate pattern between these two types and can be found in species such as Carya (Ravindran et al., 2022; Takahashi et al., 2015).

Perforation plates play a critical role in forming water conduction pathways by connecting vessel elements end-to-end. These structures are located at the ends of vessel elements and facilitate water flow. Perforation plates can have different shapes, such as simple, scalariform (ladder-like), and reticulate (multi-holed). For example, simple perforation plates are common in trees such as Quercus, whereas scalariform perforation plates are frequently observed in species like Fagus. These structural differences influence the water transport efficiency of the wood and its adaptation to environmental conditions (Gao et al., 2020; Medeiros et al., 2019).

The transmission of fluid between vessel elements occurs through numerous bordered pits located on their walls. These pits are smaller and more numerous than those found in the tracheids of coniferous trees. Typically measuring 5–12 μm in diameter, they play a critical role in inter-vessel water transport. The number and size of bordered pits influence the hydraulic conductivity of broadleaf trees. Additionally, the structure of these pits can create hydraulic resistance during water conduction, affecting the plant's efficiency in water transport (Lazzarin et al., 2016; Li et al., 2023).

Tylosis formation is common in vessels of broadleaf trees and occurs in non-functional vessels that can no longer conduct water during heartwood formation. These structures typically develop in response to stress factors such as fungal or bacterial infections, mechanical injury, or drought. The large diameter of vessels makes them prone to early loss of function, whereas parenchyma cells remain viable for a longer period and play a key role in heartwood formation. Tylosis development enhances the protective function of wood and significantly impacts its hydraulic conductivity (Pan & Tyree, 2019; Qu et al., 2022).

The term "fiber" refers to woody cells in broadleaf trees, primarily responsible for mechanical support. Fibers are categorized into fiber tracheids and libriform fibers. Libriform fibers are long, thick-walled cells that enhance the mechanical strength of wood. In contrast, fiber tracheids possess bordered pits on their walls, contributing to limited water transport. Additionally, the lignin content in these fibers increases cell rigidity and wood durability (Carvalho et al., 2023; Luostarinen & Hakkarainen, 2019).

Longitudinal parenchyma cells play a crucial role in water and nutrient storage within the wood structure of broadleaf trees. In tropical trees, these cells can make up to 50% of the wood volume. By increasing water storage capacity, longitudinal parenchyma helps plants adapt to environmental conditions. Additionally, these cells play a key role in protecting against embolism and influence the hydraulic capacity of the wood (Carlquist, 2015; Plavcová & Jansen, 2015).

Longitudinal epithelial cells play a crucial role in defense and healing by surrounding longitudinal resin or gum ducts in broadleaf trees. Particularly in tropical regions, these cells regulate the function of normal resin channels and facilitate resin secretion from epithelial cells in response to trauma. For instance, traumatic resin channels are commonly observed in species such as *Liquidambar orientalis*. These structures are especially important in plant defense mechanisms against fungal and bacterial infections (Cabrita, 2020; Turner et al., 2019).

1.4.2. Cells extending in the transverse direction

These cells form sap rays in broadleaf trees and perform vital functions, such as radial water conduction. They determine the width and structural arrangement of these sap rays. The structural diversity of sap rays plays a crucial role in transporting water and nutrients by enhancing the tree's hydraulic capacity. The radial transport process enables sap rays to move water between the xylem and phloem, which supports the tree’s adaptation to stress conditions like drought (Pfautsch et al., 2015; Słupianek et al., 2021).

In some broadleaf tree species, sap rays form distinct layers in the tangential direction. These layers play a crucial role in the hydraulic capacity of trees. Homogeneous essence rays typically start and end at the same height, while heterogeneous essence rays appear at varying heights. For instance, in species such as *Aesculus hippocastanum* and *Diospyros virginiana*, these rays can display different structures. Radial water transport may vary, particularly between homogeneous and heterogeneous sap rays (Rungwattana & Hietz, 2018; Singh et al., 2015).

1.5. Differences between coniferous and broadleaf tree cells

There are distinct differences in the cellular structures of coniferous and broadleaf trees. In coniferous trees, tracheids are homogeneous, whereas broadleaf trees exhibit more complex and heterogeneous structures. This difference is particularly evident in water transport and support cells. In conifers, tracheid cells are responsible for both water conduction and mechanical support, while in broadleaf trees, tracheae and fibers perform these functions. Additionally, the pith rays in broadleaf trees are wider, and their cell arrangement is more complex, leading to differences in radial water transport. Tracheid sizes can also vary with environmental conditions, influencing the trees' ability to adapt (Donaldson et al., 2018; Rungwattana & Hietz, 2018; Zheng et al., 2022).

2. RESULTS

This study discusses the microscopic properties of wood in detail. Wood is a material whose complex cellular structure is closely linked to functions such as water conduction, mechanical durability, and storage. In particular, the anatomical differences between coniferous and broadleaf trees are crucial to the functionality of the wood. The role of tracheid cells in water transport in conifers, along with the water conduction and mechanical support provided by tracheae and fiber cells in broadleaf trees, are critical elements in the biological processes of trees.

The more homogeneous structure of conifers makes them more durable as a construction material, while the cellular diversity of broadleaf trees makes them particularly preferred for furniture and decorative products. Additionally, the horizontal water transport facilitated by the sap rays of broadleaf trees contributes to their greater resistance to environmental stresses such as drought.

Passages in wood cells are structures that enhance the efficiency of water transmission by regulating the exchange of water and nutrients between adjacent cells. It has been stated that the role of edged passages in water transport is crucial, and that this structure also serves a protective function by facilitating the formation of tulle in some tree species.

As a result, the findings on the microscopic properties of wood provide valuable insights, both in materials science and for the wood industry. These cellular structures are crucial for understanding the biological processes of trees and evaluating the properties of wood materials, such as durability and water-carrying capacity. Future studies could expand the use of wood products and contribute to the development of more efficient processing techniques through deeper research into the microscopic structures of different wood species.

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MACROSCOPIC STRUCTURE AND PROPERTIES OF WOOD

Yasemin ÖZTURK[1]

1. INTRODUCTION

The macroscopic properties of wood (Figure 1) play a critical role in its description and classification. These characteristics vary depending on how the tree is cut and provide important information about its physical structure. In macroscopic examinations, distinct characteristics are observed in the transverse, radial, and tangential cross-sections of the wood. For example, in the transverse section, the annual rings form a circular structure, while in the radial section, they appear as straight lines. In the tangential section, the rings exhibit a wavy pattern. These cross-sectional properties are influenced not only by the direction of the cut but also by the physical properties of the wood, such as density, moisture content, and grain pattern (Żmijewki & Wojtowicz-Jankowska, 2017).

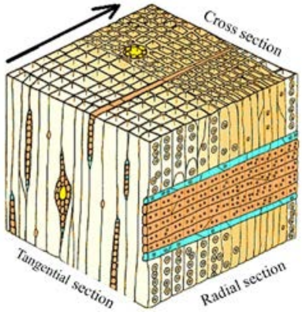

Figure 1. Macroscopic view of coniferous wood (Şenel et al., 2024).

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In the cross-section, structures such as annual rings and medullary rays are observed, while in the radial and tangential sections, different grain patterns and vascular arrangements emerge. The study of these macroscopic properties is an important step in the classification of wood, the determination of its areas of use, and quality control processes (Qing & Mishnaevsky, 2010). Understanding the macroscopic properties of wood greatly facilitates material selection, especially in areas such as furniture making, construction, and interior design. The structural characteristics of wood provide durability, aesthetic appeal, and functional properties suitable for various applications. In furniture making, selecting the right type of wood enhances the durability and aesthetic value of the products, while in construction and interior design, the texture and color of wood contribute positively to the overall ambiance of a space (Zeng & Jiang, 2018).

The macroscopic properties of wood, such as grain structure (Figure 2), texture, color, density, and porosity, directly influence material selection in areas such as furniture making, construction, and interior design. These properties determine not only the aesthetic appearance of wood but also its durability, strength, and workability. For example, hardwoods such as oak and walnut are popular choices for furniture and decorative applications due to their high density and distinctive grain patterns. The grain structures of these species are highly valued for their natural wood appearance and three-dimensional effect (McKenna et al., 2015). Additionally, the reproduction of wood patterns through printing techniques can create a three-dimensional and aesthetic effect while maintaining the appearance of natural wood (Iždinský et al., 2020). In contrast, softwoods such as pine are commonly used in construction projects where weight and cost efficiency are key factors, as they are lighter and easier to process (Ruffinatto et al., 2023). The texture and porosity of wood play a crucial role in painting, varnishing, and other surface treatments, as these characteristics determine how well the wood absorbs coatings (Kang et al., 2023). Furthermore, grain orientation significantly influences how wood responds to mechanical forces; straight-grain woods provide high strength and dimensional stability, which is particularly important in structural applications.

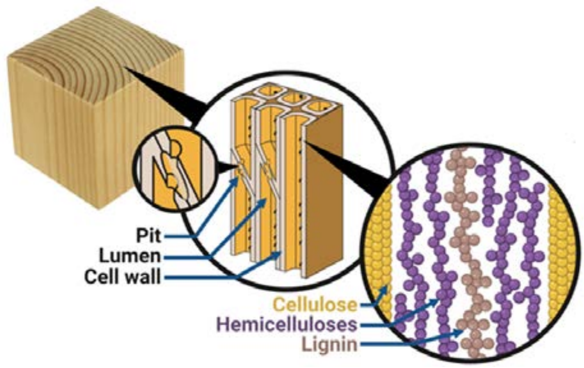

Figure 2. Overview of wood structure: from macroscopic to microscopic scale (Thybring & Fredriksson, 2021).

Therefore, understanding the macroscopic properties of wood helps professionals select materials that not only meet aesthetic expectations but also fulfill mechanical and practical requirements. For example, laminated wood materials can exhibit different strength properties depending on the orientation of the wood fibers (Alamsyah et al., 2023). These variations in mechanical properties have made laminated wood an essential material in the construction industry, influencing both its applications and overall performance.

In addition to macroscopic and physical properties, the use of recycled wood materials is gaining attention for its role in environmental sustainability. For example, cross-laminated timber (CLT) stands out as a structurally durable material that can be manufactured using both new and recycled wood (Munandar et al., 2019).

1.1. Some macroscopic properties of wood seen in cross-section

Certain macroscopic features visible in the cross-section of wood reflect the tree’s growth process and structural characteristics. For example, the prominence of growth rings, wood density, and chemical composition provide insights into the tree's long-term growth and physiological processes (Ortega Rodriguez et al., 2022). Additionally, factors such as vessel diameter, tracheid structure, and the anatomical characteristics of growth rings play a crucial role in the taxonomic classification of tree species (Ghimire et al., 2020). These properties are particularly important in industrial applications, as they determine key material qualities such as durability and workability.

1.1.1. Pith

The pith is a small, typically dark-colored structure located at the center of the tree stem. It develops during the early growth phase of the tree and is primarily composed of soft, thin-walled parenchyma cells. Over time, its growth ceases, and it no longer plays a significant structural role in the tree (Shunn & Gee, 2023).

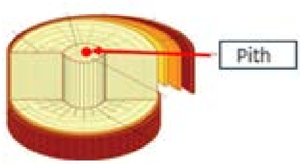

Figure 3. The central pith of the wood (Usta, 2024).

1.1.2. Annual Growth Rings

Annual rings represent the yearly growth cycles of a tree and consist of cells with varying densities formed during spring and summer. Earlywood is typically lighter in color and composed of larger, thinner-walled cells, while latewood is darker and consists of smaller, denser cells. These rings are also used to determine the age of a tree through dendrochronology (Blagitz et al., 2019).

1.1.3. Heartwood and Sapwood

Heartwood consists of darker, non-living tissues typically found in the inner part of the tree. Although it no longer conducts water and nutrients, it provides structural support and increases the tree's resistance to decay due to the accumulation of extractives such as tannins and resins (Kafuti et al., 2024). In contrast, sapwood is composed of living parenchyma cells in the outer layers of the tree and is responsible for conducting water and nutrients from the roots to the leaves. Sapwood is generally lighter in color, while heartwood darkens over time as extractives accumulate and undergo chemical changes (Pappas et al., 2022).

1.1.4. Medullary rays

Medullary rays are thin, linear structures that extend radially through the tree tissue, facilitating the lateral transport of nutrients and water (Figure 4). In some tree species, these rays are visible macroscopically and contribute to the structural integrity, durability, and water resistance of the wood (Słupianek et al., 2021).

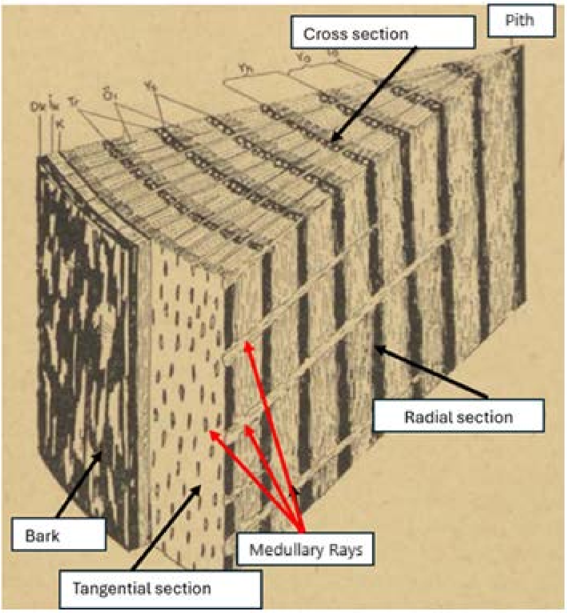

Figure 4. Medullary rays in wood (Bozkurt, 1971).

1.1.5. Resin Canals

Resin canals, found in certain coniferous tree species, play a crucial role in the tree's defense and healing mechanisms. These structures produce and transport resin, a sticky substance that is secreted in response to injury, helping to seal wounds and protect the tree from pathogens and insect attacks. In cross-section, resin canals appear as small, circular openings within the wood tissue (Klutsch et al., 2020).

1.1.6. Bark

The outermost layer, the bark, serves as a protective covering that shields the tree from external factors. It consists of two parts: the inner bark (phloem) and the outer bark (periderm). The inner bark (phloem) is responsible for transporting photosynthates, while the outer bark (periderm) protects the tree tissues from mechanical damage, harmful organisms, water loss, and extreme temperature changes (Milanez et al., 2021).

These properties allow wood to be evaluated based on its biological structure and intended use. For example, when selecting wood as a construction material, factors such as the durability of heartwood and the density of annual rings are crucial. Additionally, differences in color and texture play an important role in the selection of wood for decorative purposes (Mastouri Mansourabad et al., 2020).

1.2. Some macroscopic properties of wood in radial and tangential cross-section

The anatomical, physical, and mechanical properties of wood vary depending on the radial and tangential directions within the cross-section. Structural features of trees are analyzed through radial and tangential sections, where elements such as annual rings and sapwood are observed. These sections provide valuable insight into the wood’s longitudinal structural elements, which influence its functional properties and applications in wood processing.

Radial sections extend from the center of the tree to the outer bark and are oriented parallel to the wood’s rays. In these sections, annual rings are clearly visible, showing distinct layers of spring and summer wood. The arrangement of resin channels (Figure 5) and tracheids in longitudinal rows within radial sections varies depending on the tree species. For example, in beech and oak trees, wood rays appear as broad bands, whereas in maple trees, they are finer and more evenly distributed (Leggate et al., 2020). The distribution and size of resin channels, especially in radial sections, may differ depending on environmental conditions and species characteristics (Crang et al., 2018).

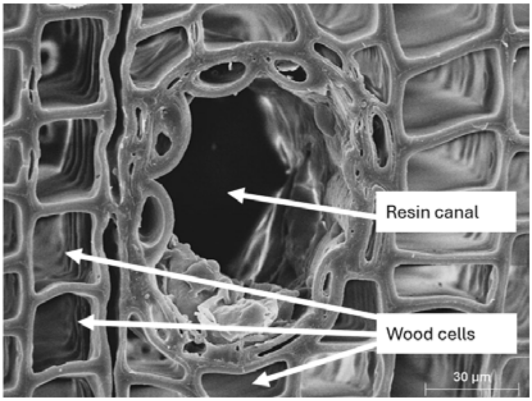

Figure 5. Stereo Electron Microscope (SEM) image of resin channel in cross section.

Tangential sections are longitudinal sections taken perpendicular to the radial plane, where annual rings appear as wavy or irregular bands rather than continuous rings. In these sections, features such as the arrangement of wood rays, the structure of fibers, and the wavy or irregular pattern of growth rings are especially prominent (Barański et al., 2017). In trees exposed to harsh climatic conditions, the formation and development of xylem cells (Figure 6) play a crucial role in determining the anatomical properties of wood (Balzano et al., 2021).

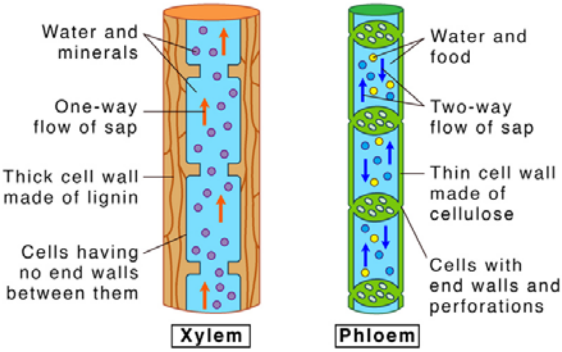

Figure 6. General structure of xylem and phloem cells.

Radial and tangential sections are essential for analyzing annual growth rings and the structural characteristics of wood. These sections provide valuable insights into key wood components, such as wood rays, resin channels, annual rings, and bark, which are crucial for both scientific research and industrial applications (Park et al., 2023).

1.3. Some distinctive features of wood material

The physical properties of wood are crucial for its applications across various industries. These properties significantly influence factors such as strength, durability, and usability, playing a critical role in determining how wood behaves in different environments.

1.3.1. Colour

One of the most important physical properties of wood is its color. Extensive research has been conducted on methods to preserve and modify the color of wood. Color variations in trees are primarily influenced by the presence of extractive compounds in the wood tissue and the oxidation of these substances. Extractives enhance the decorative appeal of wood, particularly by creating distinctions between heartwood and sapwood. For example, a study on *Cunninghamia lanceolata* found that the extractive content in heartwood was three times higher than in sapwood, significantly affecting the wood’s chemical composition and color (Li et al., 2019).

Similarly, a study on *Dalbergia oliveri* found that the color of its heartwood is influenced by variations in flavonoid pigment concentrations. Higher levels of coloring compounds, such as pelargonidin and vitexin, contribute to the darker appearance of the heartwood (Wei et al., 2022).

In the heartwood of *Tectona grandis* (teak tree), compounds such as 2-methylanthraquinone have been identified, contributing to both the wood’s biological durability and its coloration (de Castro et al., 2022). These color variations, along with wood density and light reflection properties, enhance the decorative appeal of the material.

A study on *Quercus faginea* found that the extractive content in heartwood was twice as high as in sapwood. These extractives enhanced both the wood’s color and its antioxidant properties (Miranda et al., 2017).

These studies confirm that the extractive compounds influencing wood color vary depending on both tree species and environmental factors, significantly impacting its decorative quality.

Fiber direction in trees is determined by whether the long axis of the cells aligns with the trunk axis, a property that plays a crucial role in the mechanical performance of wood. A well-aligned fiber structure enhances workability, durability, and aesthetic appeal, whereas deviations can negatively affect shape stability. For instance, spiral grain reduces wood’s strength and dimensional stability, leading to higher material loss during processing (Vilkovský et al., 2024).

The spiral arrangement of fibers, particularly in species like Pinus radiata, reduces the tensile strength of wood and negatively impacts production quality. Research indicates that the formation of compression wood can inhibit the development of spiral grain (Thomas et al., 2022). Therefore, preventing spiral grain formation can enhance wood quality.

Variations in fiber direction among tree species are also a crucial factor. In composite materials such as Laminated Veneer Lumber (LVL) (Figure 7), modifying fiber orientation can significantly influence the physical and mechanical properties of the wood (Alamsyah et al., 2023).

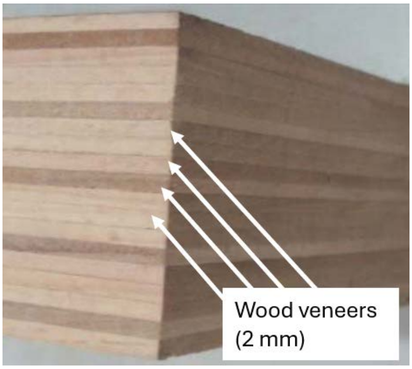

Figure 7. Laminated Veneer Lumber (LVL) lumber

1.3.2. Fiber Curl

Fiber curl (spiral grain) occurs when the cells in a tree trunk do not align parallel to the axis but instead grow in a helical pattern. This significantly impacts the mechanical properties of wood, reducing elasticity and making it more difficult to work with (Vilkovský et al., 2024). Additionally, fiber curl increases longitudinal shrinkage and enhances the wood's tendency to crack (Thomas et al., 2022). However, these irregularities can also create unique visual patterns, making them desirable for decorative wood products.

1.3.3. Irregular Fiber Structure

Irregular fiber structure occurs when wood fibers deviate from a parallel alignment with the trunk axis, shifting unpredictably in different directions. This variation alters the mechanical properties of wood, increasing its resistance to cracking while making it more difficult to process (Bossu et al., 2018). Additionally, these irregular fibers influence light reflection, creating distinctive visual patterns. This aesthetic effect is particularly valued in veneer boards, enhancing their decorative appeal and commercial value (Coelho et al., 2020).

1.3.4. Appearance Properties

During wood processing, patterns formed by the arrangement of annual rings, tracheids, and wood rays enhance its aesthetic appeal. Variations in fiber orientation and color influence the optical properties of wood, creating unique visual effects (Coelho et al., 2020). These irregularities, combined with fiber twisting and light reflection, make wood highly desirable for decorative applications (Bossu et al., 2018). In veneer boards, these characteristics play a key role in increasing the commercial value of wood.

1.3.4.1. Uniform Texture

Uniformity in wood is achieved when fibers are consistently aligned, and color, gloss, and texture are evenly distributed. These characteristics improve the aesthetic, mechanical, and commercial value of wood. In particular, the balance between wood luster and consistent coloration enhances its visual harmony (Nakagawa et al., 2021). This uniformity is particularly valued in veneer boards and high-quality furniture production.

1.3.4.2. Pyramidal Grain Pattern

The pyramidal grain pattern is a distinctive texture resulting from the arrangement of annual ring boundaries, parenchyma bands, and resin channels in the tangential section. This structure influences both the anatomical and aesthetic properties of wood, contributing to its visual appeal (Fabijańska & Cahalan, 2023). Because of its distinctive geometric pattern, this structure is especially valued in decorative woodworking and veneer applications.

1.3.4.3. Striped Grain Pattern

The striped grain pattern in wood appears in three distinct forms, depending on fiber structure and the distribution of extractives and pigments. These include (1) stripes following the orientation of annual rings in the radial section, (2) alternating bands of light and dark coloration, and (3) continuous longitudinal striping along the grain direction. These banded patterns, visible in both radial and tangential sections, are particularly prominent in certain broadleaf and tropical hardwood species such as mahogany and zebrawood (Ortega Rodriguez et al., 2022).

1.3.4.4. Mirrored view

The mirrored view appears on the radial surfaces of wood as shiny, reflective flecks formed by medullary rays extending perpendicular to the fiber direction. This effect is particularly prominent in species such as Quercus and Fagus, enhancing the wood’s decorative appeal (Weng et al., 2021). Due to its distinctive visual effect, the mirrored view is highly valued in furniture, veneering, and decorative wood applications.

1.3.4.5. Marbled Grain Pattern

The variegated (marbled) grain pattern is a distinctive texture observed on radial surfaces, resulting from irregular grain patterns and light reflections caused by undulating fiber orientation. This unique grain effect is particularly prominent in *Khaya* and *Entandrophragma* species, increasing their appeal for decorative veneer and fine woodworking applications (Krawczyszyn, 2015).

1.3.4.6. Transverse Striped Pattern

The transverse striped pattern occurs when subtly undulating fibers on radial and tangential surfaces are intersected at a perpendicular angle to the trunk axis. This structure creates a distinctive visual effect that becomes more pronounced under varying light conditions (Collins & Fink, 2022). This effect is particularly noticeable in species such as *Acer* and *Fraxinus* excelsior and is highly valued for high-end furniture, veneering, and decorative woodwork.

1.3.4.7. Pommele Figure

The pommele figure is a distinctive scalloped or rippled pattern that appears on tangential surfaces, resulting from wavy and irregular fiber arrangements parallel to the trunk axis. This effect enhances the aesthetic value of wood by creating a dynamic interplay of light reflections and is particularly favored for decorative veneer and fine woodworking applications (Yuan & Yi, 2015).

1.3.4.8. Wavy Grain Pattern

The wavy grain pattern occurs when subtly undulating or irregularly oriented fibers are exposed in the tangential section. This structure is accentuated by light interactions, producing a visually striking pattern (Lewandrowski et al., 2024). This effect is particularly noticeable in species such as *Aningeria* and *Guibourtia*, making it highly valued in fine woodworking, furniture, and veneer applications.

1.3.4.9. Diagonal Striped Pattern

The diagonal striped pattern is a naturally occurring effect resulting from interlocked and wavy grain structures exposed in the tangential section. This structure is accentuated by varying light interactions and is particularly prominent in *Entandrophragma* and *Khaya* species (Wan et al., 2021). This aesthetic feature increases the value of wood for high-end decorative applications such as fine furniture and veneering.

1.3.4.10. Flame Figure

The flame figure is a distinct flame-shaped pattern that results from undulating grain structures exposed in tangential and radial sections parallel to the trunk axis. This effect is accentuated by light interactions, further enhancing the wood's aesthetic appeal. This pattern is particularly noticeable in *Betula* and *Pyrus* species (Collins & Fink, 2022).

1.3.4.11. Clustered Grain Pattern

The clustered grain pattern forms when burl formations and irregular grain clusters develop on the tree stem, creating a highly textured and unique grain structure. This distinctive grain pattern is commonly found in *Sequoia sempervirens* and *Acer* species (Michels & Russell, 2016). Wood with this characteristic is highly valued for its aesthetic and commercial appeal, particularly in fine woodworking and decorative veneer applications.

1.3.4.12. Birdseye Figure

The birdseye figure is a distinctive grain pattern characterized by small, dark circular indentations on the tangential surface of the wood, resembling tiny eyes. This unique texture is most commonly found in *Acer* species (maple trees) and significantly enhances the commercial and decorative value of the wood (Bal et al., 2020). Due to its aesthetic appeal and rarity, bird's eye figured wood is widely used in high-end furniture, musical instruments, and decorative veneers.

1.3.5. Moisture Content

The physical properties of wood are greatly affected by moisture levels, which directly affects the dimensional stability of wood and its susceptibility to rotting (Niemz et al., 2023). Variability in moisture content can also lead to differences in strength and durability (Schulz et al., 2020).

1.3.6. Dimensional Stability

Wood exhibits anisotropic behavior, meaning it expands and contracts at different rates along different axes. This property is crucial for applications requiring precise dimensions(Bajpai, 2018; Loiola et al., 2021).

1.3.7. Heat and Electrical Properties

The thermal insulation capacity and electrical resistance of wood are particularly important in construction and electrical applications (Niemz et al., 2023).

While these properties often provide advantages, the natural variability of wood can lead to inconsistent performance under different conditions. Understanding these factors is essential for optimizing wood use across various applications. The physical properties of wood include texture, gloss, odor, weight, and hardness. Texture is influenced by the size of tree cells, the width of wood rays, and irregularities in annual rings. Finely or coarsely textured woods vary in their ease of processing and decorative suitability (Herawati et al., 2021). Gloss refers to the wood's ability to reflect light, determining whether its surface appears glossy or matte. Advances in nano-coating technologies can enhance wood's brightness, a desirable feature in furniture and decorative finishes (Yan et al., 2017).

Wood's scent is primarily caused by essential oils and resins in the heartwood. Species such as sandalwood and cedar are well known for their distinctive aromas, making them valuable in the perfume and pharmaceutical industries(Bal et al., 2020). Weight and hardness are directly related to wood density and the amount of cell wall material. Light wood species tend to grow quickly, whereas denser hardwood species are more durable and long-lasting (Feng et al., 2019).

2. CONCLUSION

The macroscopic properties of wood are particularly important in construction, furniture, and decorative applications. These properties include texture, gloss, odor, hardness, and weight.

Texture results from the contrast between tree cell size, wood ray width, and annual ring patterns. Finely or coarsely textured woods vary in their ease of processing and suitability for decorative applications. Gloss, on the other hand, determines whether the wood surface appears shiny or matte, depending on its light-reflecting capacity. Nano-coating technologies can enhance gloss, making it a desirable feature in furniture and decorative finishes.

Wood’s scent is primarily caused by essential oils and resins within the tree. Species such as sandalwood and cedar are well known for their distinct aromas, making them valuable in the perfume and pharmaceutical industries. Hardness and weight are also critical physical properties that influence durability. These characteristics are directly related to cell wall density and vary by tree species. Light woods tend to grow faster, whereas heavier hardwoods are more durable and long-lasting. In construction, using dense, hard wood ensures long-term structural stability.

The physical properties of wood may also change depending on its processing and intended application. In decorative wood materials, aesthetic factors such as color variations and texture patterns become particularly significant.

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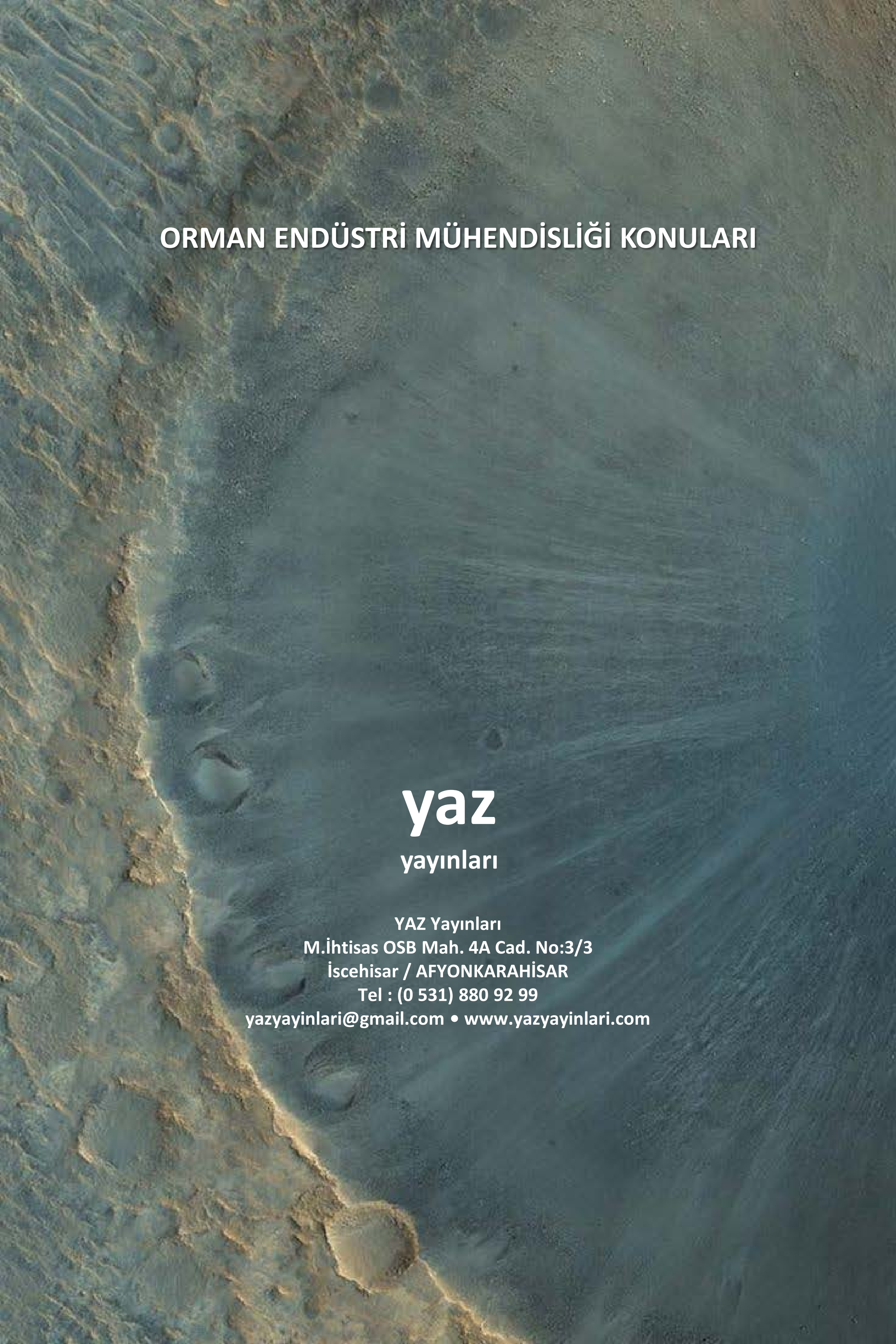

ORMAN ENDÜSTRİ MÜHENDİSLİĞİ KONULARI

yaz

yayınları

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