AI-TW GUIDE TO EXPLORE THE MULTIFUNCTIONAL PROPERTIES OF TRANSPARENT WOOD

AI-TRANSPWOOD

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AI-TW Guide to explore the multifunctional properties of Transparent Wood

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Why this guide?

This guide is designed to provide a **clear and accessible** introduction to **Transparent Wood (TW)**, a groundbreaking material with remarkable properties. By simplifying complex scientific concepts, it aims to **make information about TW available to a wide audience**, not just experts in the field.

Here, readers will find an **easy-to-understand overview** of how Transparent Wood is **produced, its peculiarities and key applications, and the methods used to model its properties**. Whether you are a researcher, a student, a designer, or simply someone curious about **new sustainable materials**, this guide will help you discover the potential of TW and its role in future innovations.

Enjoy the reading!

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The importance of wood

Wood is one of the most widely used natural materials on Earth, valued for its **sustainability**, strength, **renewability**, and versatility. Since the earliest days of civilization, humans have relied on wood for shelter, tools, furniture, and other countless applications. What makes wood so special is its combination of useful properties: it is lightweight yet strong, visually appealing, pleasant to the touch, and, most importantly, renewable. Besides, as trees grow, they absorb carbon dioxide from the atmosphere, making wood an environmentally friendly material with a ***low carbon footprint***.

Because of these advantages, wood is used in many industries, including construction, furniture-making, automotive design, and even advanced product design. It is found in everything, from homes and buildings to artistic and hand crafted objects. However, despite all its remarkable features, traditional wood has one major drawback: **it is not transparent**.

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01 INTRODUCTION

Why isn’t wood transparent?

Unlike glass or plastics, wood does not allow light to pass through. This is because of the way its internal structure interacts with light. When light hits wood, it doesn’t simply pass straight through. Conversely, it gets **scattered** in many different directions due to the complex arrangement of the material’s structure. Additionally, some of the light is absorbed, making the wood appear solid and opaque.

For centuries, wood has been used primarily in applications where transparency was not required. However, in recent years, scientists and engineers have developed a way to modify wood to make it **see-through**, opening up exciting new possibilities for its use in construction, design, and even energy-efficient applications.

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From opaque wood to Transparent Wood

The journey toward **Transparent Wood** (Figure 1) began in 1992 when researcher Sigfried Fink successfully created a see-through version of pine veneer (1 mm thick). He achieved this by **removing lignin**, a key component responsible for wood's color and opacity, then **filling the empty wood channels** with methyl methacrylate (MMA), a transparent monomer, and finally polymerizing MMA. This process allows for the **transmission of light** through the wood, making it transparent. However, at the time, Fink viewed this as merely way to study wood's internal structure rather than a step toward the design of a revolutionary material. As a result, he did not pursue further research in this area.

The concept of **Transparent Wood resurfaced in 2015**, when two academic groups—one at the University of Maryland (USA) and another at KTH Royal Institute of Technology (Sweden)—independently **revisited** Fink's work. These teams systematically explored the potential of Transparent Wood, leading to exciting discoveries about its **possible real-world applications**. Since then, the interest in Transparent Wood has increased continuously. Researchers keep on developing and refining the material, unlocking new possibilities in various industries.

Today, Transparent Wood is being explored for **high-tech applications**, including:

- Optical and optoelectronic devices (such as advanced lighting systems)
- Furniture (for stylish and futuristic designs)
- Flexible electronics (for next-generation devices)
- Construction materials (smart screens and windows for energy efficient buildings)
- Automotive applications (for lightweight, strong, and transparent components/parts)
- Aesthetic and decorative materials (for unique design possibilities, see *aesthetic wood*)

Introduction

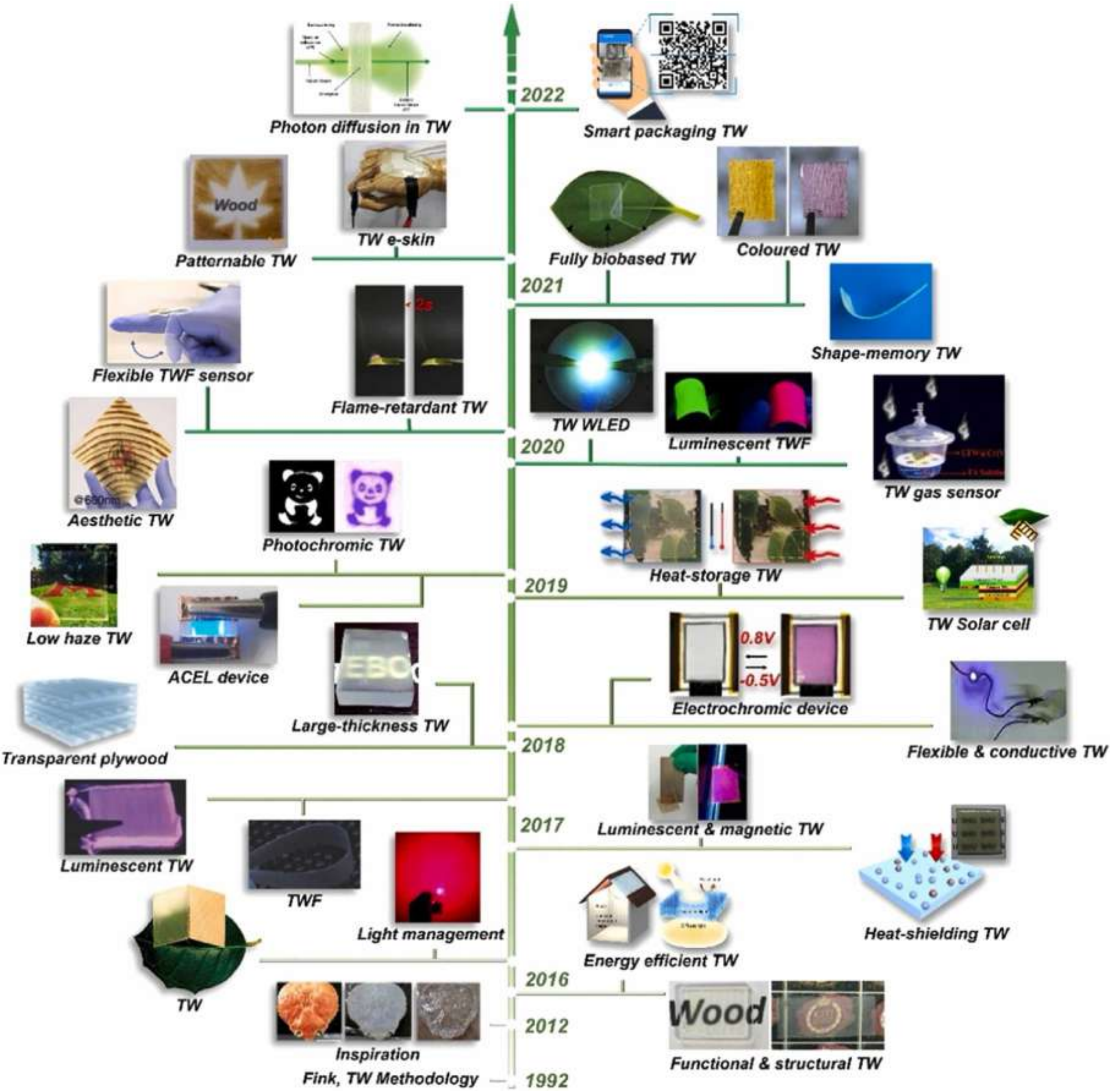


Figure 1: Summary of the inspiration and research progress of TW. Reproduced from Mariani & Malucelli, 2024 under CC-BY licence.

The Complex Structure of Natural Wood

Wood has a highly **complex and organized structure** (Figure 2), which gives it unique mechanical and physical properties. One of its key characteristics is **anisotropy**, meaning its properties vary depending on the direction in which they are measured.

At a microscopic level, wood is made up of **three main components**, namely:

- **Cellulose** – The primary structural component, forming strong fibres.

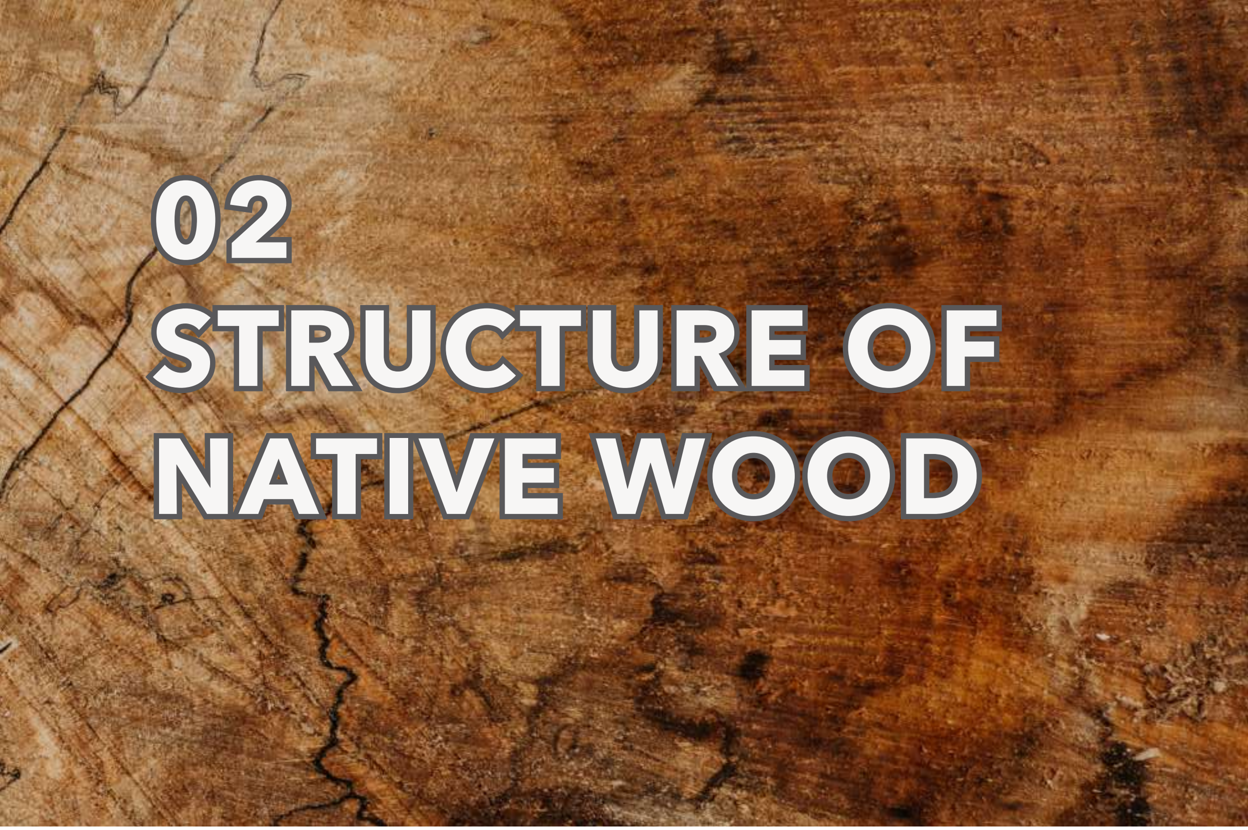
- **Hemicellulose** – A supporting material that binds fibres together.

- **Lignin** – A glue-like substance that fills the spaces between fibres, providing wood with its colour and additional strength.

A Hierarchical Network

These components are arranged in a **porous network** where cellulose macromolecules form tiny structures called elementary fibrils. These fibrils group together into **microfibrils**, which then bundle into **cellulose microfibers**—the main building blocks of wood cell walls.

Photo by Marina Reich on Unsplash.



02 STRUCTURE OF NATIVE WOOD

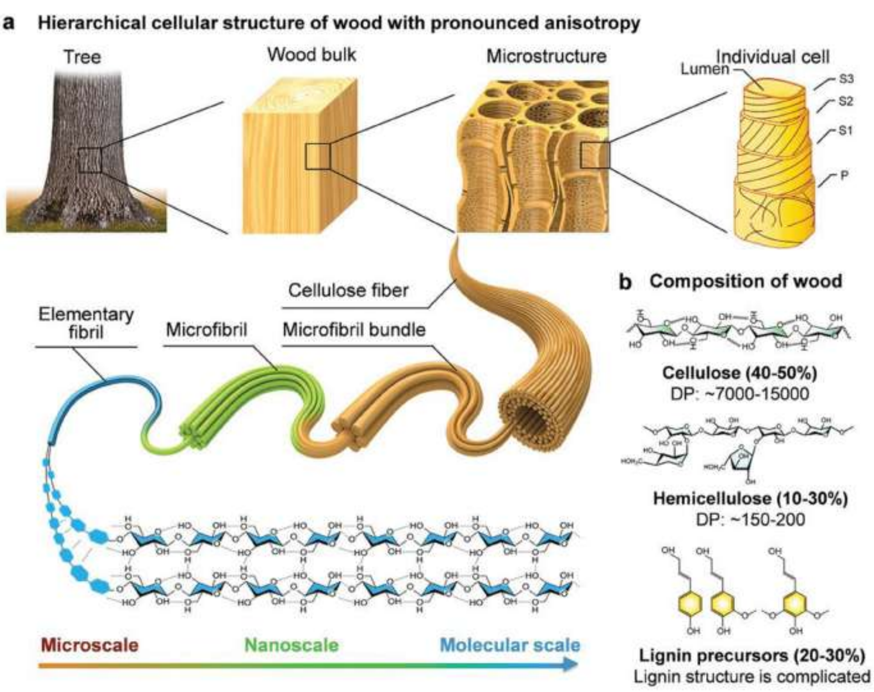


Figure 2: Hierarchical structure of wood. Reproduced from Chen & Hu, 2021 under CC-BY licence.

The wood channels, or vascular structures, are lined by these cellulose-based walls and filled with **lignin**. Lignin gives wood its natural colour and reinforces its strength and durability.

The Multi-Layered Structure of Wood Cells

Each individual wood cell is made up of multiple layers (Figure 2):

- **A primary layer** (P layer), the outermost part of the cell wall.

- **A secondary layer** (S layer), which is further divided into three sub-layers: S1, S2, and S3.

The overall anisotropic nature of wood comes from the alignment of its internal channels along the longitudinal axis, i.e., the direction in which the tree grows. This alignment is crucial for transporting water and nutrients within the tree and also influences the mechanical behaviour of wood when used in construction or other applications.

This intricate, multi-layered structure is what gives wood its unique strength, durability, and directional properties, making it a versatile material for various applications.

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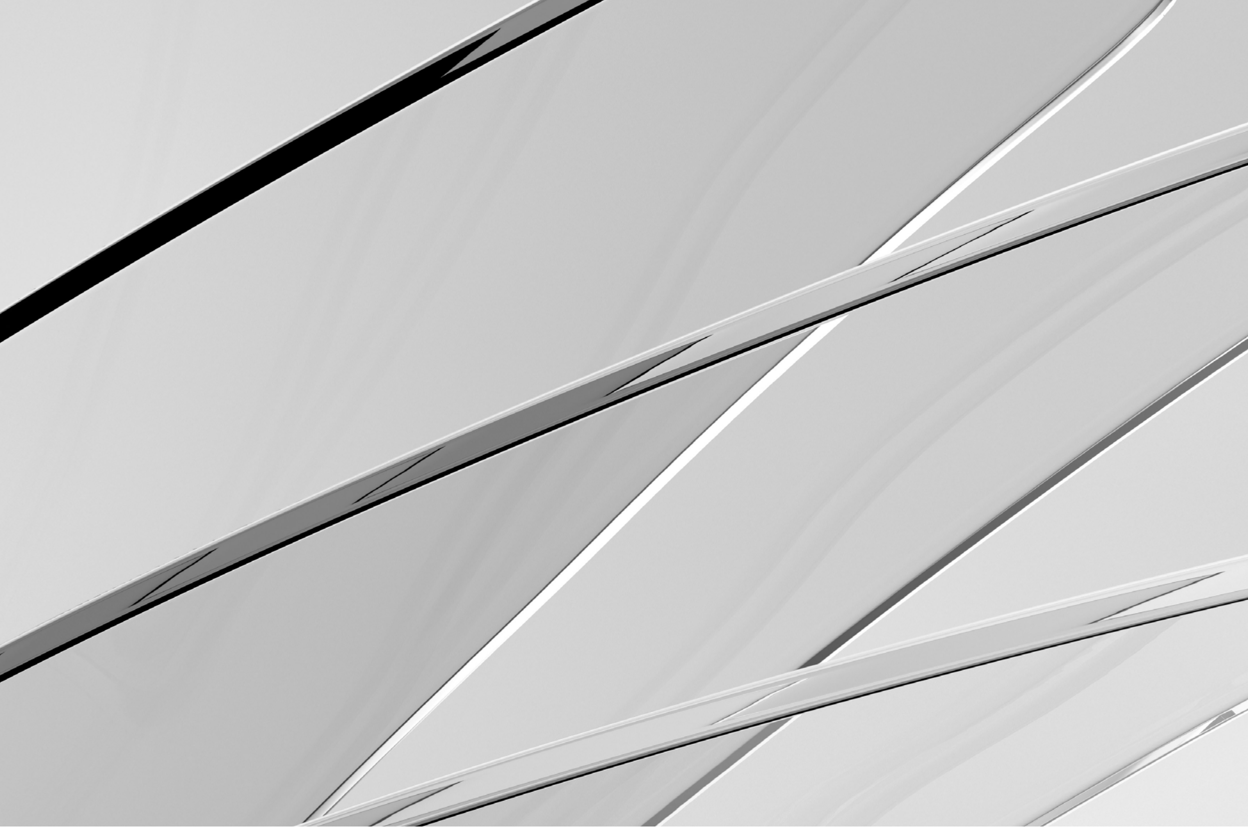

How Wood Becomes Transparent

Although wood is naturally opaque, it can be made transparent through specific **chemical treatments** (Figure 3). These processes focus on either **removing lignin**—the component responsible for wood's colour and opacity—or **modifying lignin's chromophoric groups** (i.e., the parts that absorb light).

Lignin Removal: Making Space for Transparency

One of the most common methods to make Transparent Wood involves **removing lignin** from the pristine wood's structure. This can be done using:

- **Alkaline treatments** – Performed at high temperatures (140–170°C) using chemicals like ammonia or sodium hydroxide, sometimes combined with sulfides or sulfites.

- **Acidic treatments** – Carried out with strong mineral acids at temperatures between 100 and 200°C, often in the presence of organic solvents to aid the process.

Regardless of the method used, **it is crucial to preserve cellulose and hemicellulose**, as these components provide

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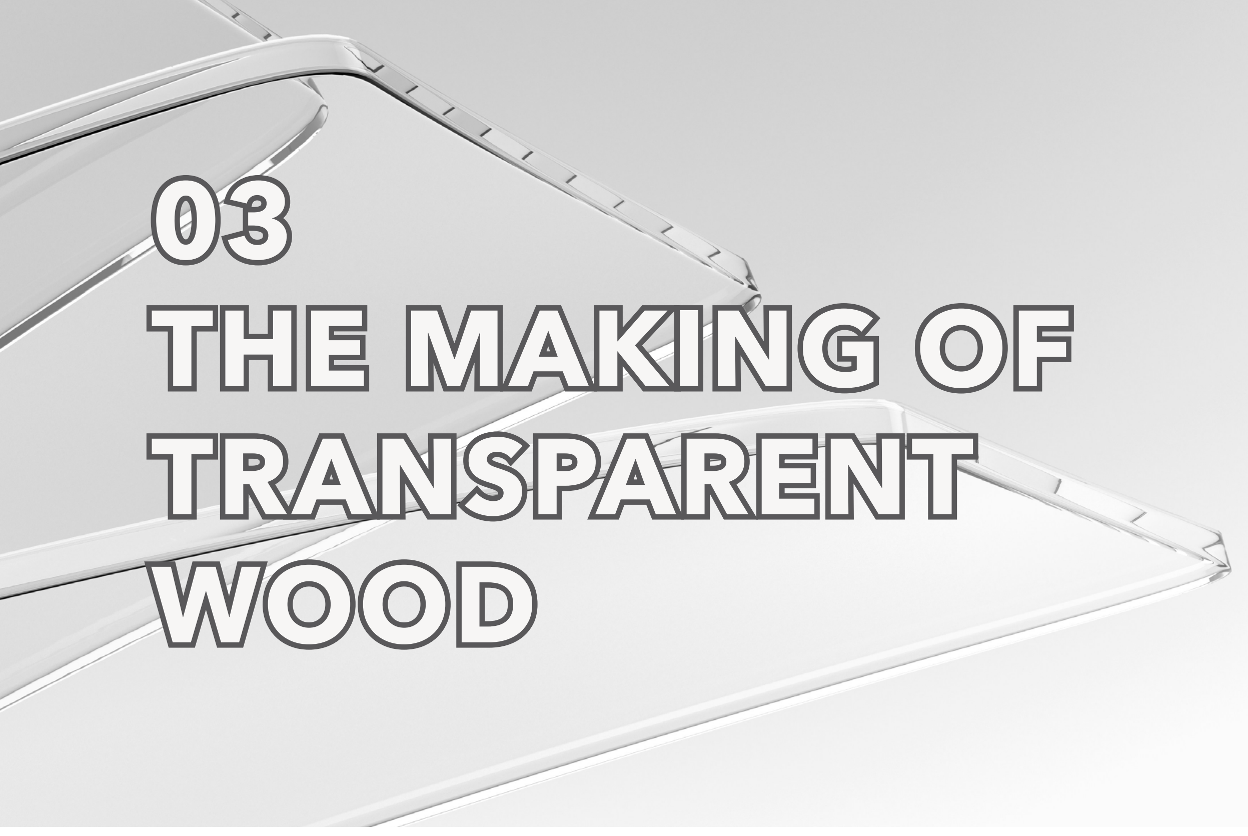

03 THE MAKING OF TRANSPARENT WOOD

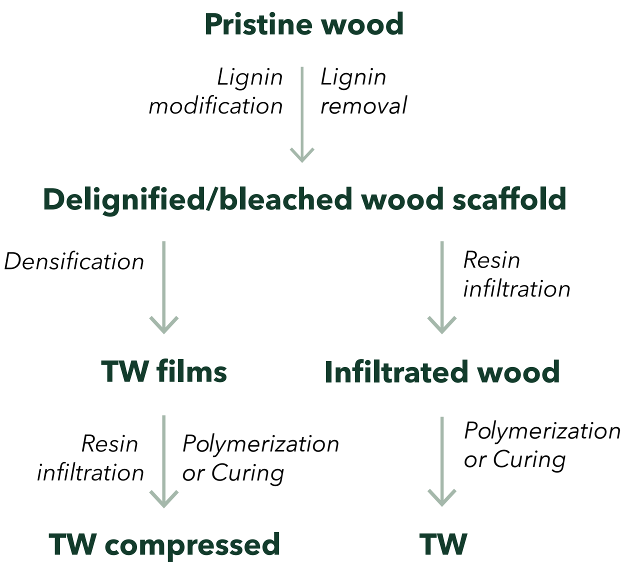

Figure 3: Scheme of the preparation of TW. Adapted by Mariani & Malucelli, 2024 under CC-BY licence

The thickness of the wood sample plays a key role in the process: thinner samples allow for more efficient lignin removal.

structural integrity to the wood. If damaged, unwanted byproducts may form, potentially leading to toxic or hazardous substances. Additionally, removing lignin and replacing it with a resin-like material may affect the final **mechanical properties** of transparent wood.

A widely used alternative method involves **prolonged bleaching** with **sodium chlorite ($NaClO_2$) or hydrogen peroxide (H_2O_2)** (Mi et al., 2020; Li et al., 2019). However, the **thickness of the wood sample** plays a key role in the process—**thinner samples allow for more efficient lignin removal**.

Figure 4 illustrates this transformation by comparing native balsa wood (a), delignified balsa wood (b), and transparent balsa wood infiltrated with poly(hydroxymethylacrylate) (c).

Lignin Modification: An Alternative Approach

Interestingly, some studies (Li et al., 2017) have shown that Transparent Wood can be created **without fully removing lignin**. Indeed, by selectively **modifying**

Figure 4: Main steps: balsa wood (a), delignified balsa wood (b), and transparent balsa wood. Reproduced from Kivikytö-Reponen et al., 2024 under CC-BY licence.

lignin's chromophoric groups, light absorption is reduced, making the wood **partially transparent** while preserving its original mechanical strength.

Aesthetic Wood: A Middle Ground

Beyond fully transparent wood, researchers have developed a material known as "**aesthetic wood**", where **lignin is selectively removed**. This allows the wood to maintain its **natural grain pattern** while gaining some transparency, offering a unique balance between traditional wood aesthetics and modern innovation (Figure 5). Another key advantage of aesthetic wood is that, since only part of the lignin is removed, the material retains **most of the mechanical strength** of natural wood. This makes it more durable compared to Transparent Wood.

Additionally, **aesthetic wood can be produced in larger sizes**, exceeding 25–30 cm per side, whereas Transparent Wood is currently limited to smaller samples (typically around 15 × 15 cm²). This makes aesthetic wood a more practical option for **large-scale applications**.

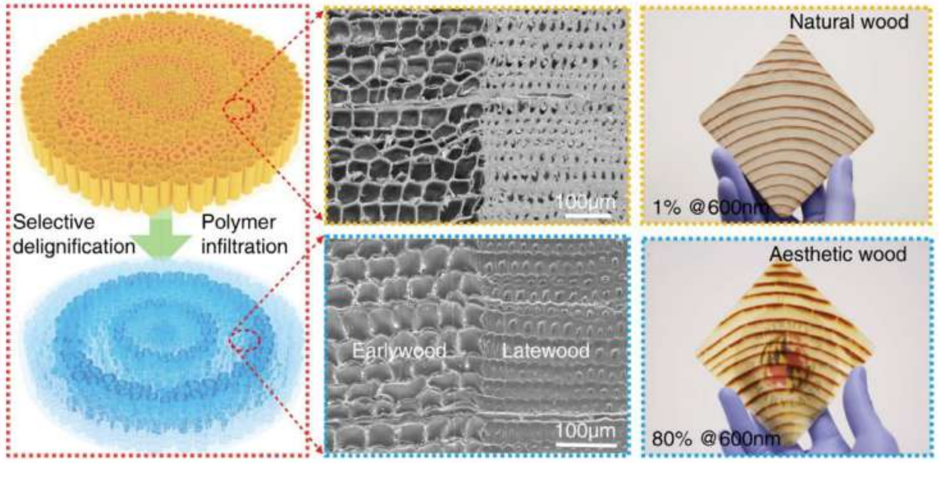

Figure 5: The making of aesthetic wood. Adapted from Mi et al., 2020 under CC-BY licence

Applications of Aesthetic Wood

Thanks to its **semi-transparent nature and preserved wood grain**, aesthetic wood is particularly suited for **interior design applications**, including:

- Decorative panels
- Flat surfaces for home design
- Furniture and artistic elements

Beyond decorative uses, aesthetic wood is also being explored for **innovative glazing**, offering a unique balance between **natural beauty and modern functionality** (Figure 6).

Indeed, compared with standard glass ceiling, aesthetic wood accounts for a controlled light diffusion that provides a uniform distribution of the light itself with the environment.

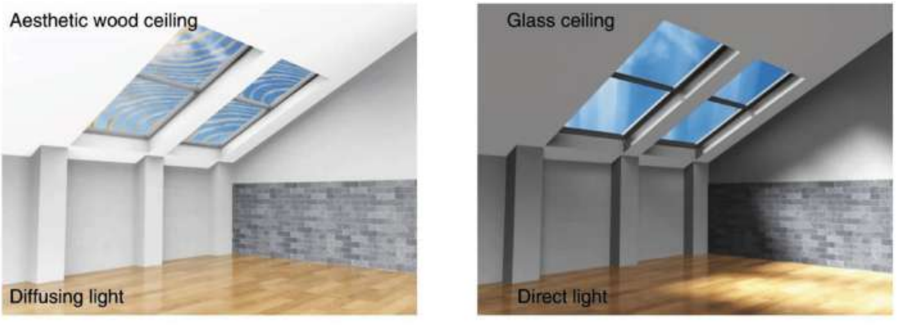

Figure 6: Comparing light diffusion through an aesthetic wood glazing with that through a standard glass ceiling. Adapted from Mi et al., 2020 under CC-BY licence

Photo by Daniele Nuvoli, UNISS, Italy

The making of Transparent Wood

Transparent Wood vs. Traditional Materials

To assess the potential use of Transparent Wood in different applications sectors, it becomes very important to evaluate its optical, mechanical, thermal, and environmental properties in comparison other traditional materials.

Table 1 compares the performance of **Transparent Wood** with other common materials, including **natural wood, plastics, glass/ceramics**, and **metal alloys**. Overall, Transparent Wood stands out as a **lightweight**, **strong**, and **environmentally friendly material** with **low thermal conductivity** and **high resistance to corrosion** and environmental factors. Additionally, it requires **less energy** for processing and is widely available, making it a promising alternative in various industries.

Photo by Caroline Grondin on Unsplash

04 PROPERTIES OF TRANSPARENT WOOD

Table 1: Performance of TW compared to other classes of materials. (Legend: =: similar performance; +/++: better performance of TW; -: worse performance of TW)

Property	Wood	Plastics	Glass / ceramics	Metal alloys
Lightness	=		++	++
Toughness			++	
Impact resistance			++	
Mechanical strength	+	+		
Surface hardness			–	–
Thermal conductivity			+	++
Corrosion resistance				++
Optical transmittance	++			++
Environmental resistance	+			
Processing energy consumption			++	++
Geographical availability		++		++
Carbon footprint		+		++

Transparent wood is a strong, sustainable, and versatile material, offering optical clarity, impact resistance, and thermal insulation.

Optical Properties: A Balance Between Transparency and Haze

One of the most **remarkable features** of Transparent Wood relies on its **optical transparency**, which sets it apart from natural wood and makes it a viable alternative to **glass and plastics**. Typically, TW exhibits a **high light transmission of 80–90%** in the visible spectrum, though this depends on the thickness and preparation method.

Unlike fully transparent glass, TW often displays a certain level of **haze**, caused by **light scattering** from **cellulose fibres and residual pores**. While this might seem like a drawback, it can actually be advantageous in applications requiring **diffused ligh**t, such as skylights, decorative panels, and energy-efficient windows.

The **optical properties of TW can be customized** by adjusting key processing parameters, including:

- **Delignification degree** – More lignin removal generally increases transparency.
- **Type of infiltrated resin** – Different polymers influence clarity and strength.
- **Material thickness** – Thinner samples reduce light scattering.
- **Additives like dyes or nanoparticles** – These can introduce colours or special optical effects, further enhancing TW's versatility.

Increasing the **polymer content** can improve transparency, while reducing thickness can **minimize haze** (Figure 7).

Properties of Transparent Wood

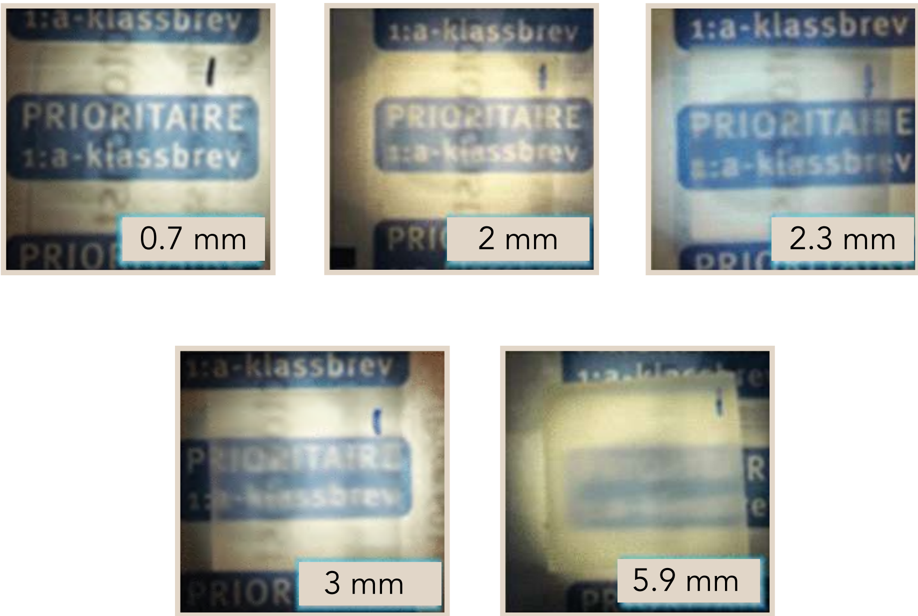

Figure 7: Transparency of TW samples with increasing thickness from left to right. Reproduced from Jele et al., 2024 under CC-BY licence.

Its eco-friendly nature and unique properties make it a promising alternative for construction, design, and advanced technologies.

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Mechanical Strength and Impact Resistance

The impressive **mechanical performance** of Transparent Wood comes from **its hierarchical structure**. The **polymer matrix** further strengthens the structure by **filling voids and bonding with wood fibres**, resulting in:

- **High tensile strength**, often comparable to or exceeding natural wood.

- **Tunable stiffness**, depending on the polymer type and material thickness.

- Superior **toughness** compared to glass, making TW resistant to impact and less prone to shattering.

While glass is brittle and can break easily, **Transparent Wood absorbs impact energy through plastic deformation**, making it a safer alternative for applications **where impact resistance is crucial**. Furthermore, TW's flexibility allows it to be bent or shaped without breaking, making it ideal for curved structures and flexible electronic devices.

Thermal Insulation and Sustainability

Beyond its strength and transparency, transparent wood also offers significant advantages in **thermal insulation** and **environmental sustainability**, namely:

- **Low thermal conductivity** – TW helps reduce heat loss, making it ideal for windows and building facades that improve energy efficiency.

- **Passive solar heating** – Its ability to diffuse light contributes to natural heating, further enhancing its thermal performance.

- **Sustainable production** – TW is derived from renewable resources, and the polymer matrix can be selected from biodegradable or recyclable sources.

Compared to glass or plastics, TW produces lower carbon emissions during manufacturing, **contributing to a smaller environmental footprint** (Mariani & Malucelli, 2024; Chutturi et al., 2023).

Photo by Giorgio Trovato on Unsplash

Properties of Transparent Wood

Potential Applications of Transparent Wood

Scientific research has identified numerous **innovative uses** for transparent wood across various technological fields. Its unique combination of **mechanical strength, optical transparency, and sustainability** makes it a promising alternative to traditional materials like **glass, plastics**, and composites. Below are four major areas where transparent wood is expected to have a significant impact:

1) Architectural Glazing & Building Materials

Transparent wood's **strength and insulating properties** make it ideal for **windows, facades, and skylights**, allowing natural light while reducing heat loss. Compared to glass, TW offers better thermal insulation, improving **energy efficiency** in buildings (De Ranieri, 2016; Mi et al., 2020; Du et al., 2023). Figure 8 highlights its superior insulation performance.

Additionally, TW can be integrated into **smart windows**, offering UV protection, light control, and self-tinting capabilities for modern, energy-efficient architecture.

Photo by Ausanee Binney on Unsplash

05 POTENTIAL APPLICATIONS OF TRANSPARENT WOOD

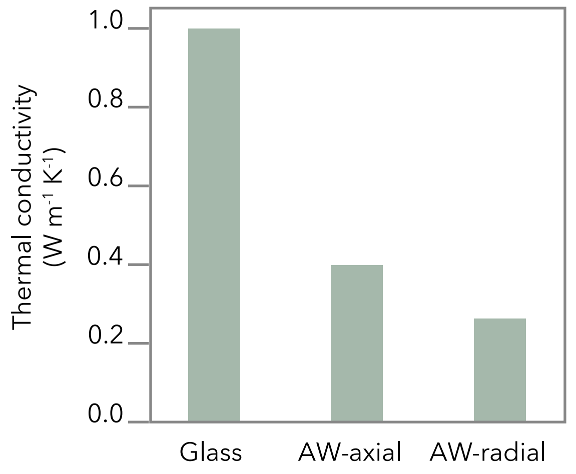

Figure 8: Thermal conductivities of "standard" glass and aesthetic TW (both considering axial and radial wood cut). Adapted from Mi et al., 2020 under CC-BY licence.

2) Lightweight Structures & Composites

With its **high strength-to-weight ratio**, TW is an excellent material for aerospace and automotive applications, where **reducing weight** improves fuel efficiency. It also works well as a reinforcement material, combining mechanical strength with optical functionality (Wu et al., 2024).

Potential applications include **lightweight car windows**, aircraft interiors, and impact-resistant panels, offering durability and **energy savings in transportation**.

3) Energy Storage & Solar Applications

TW is gaining interest in **energy storage and solar energy technologies**, particularly in the development of batteries, supercapacitors, and solar cells. Due to its high surface area and conductivity, TW can serve as an efficient substrate material for batteries and supercapacitors, improving energy storage performance while keeping devices lightweight and flexible (Montanari et al., 2023; Hou et al., 2023). In **solar energy applications**, TW acts as a light-guiding material, helping solar panels capture more sunlight and enhancing energy conversion efficiency (Zhu et al., 2016; Li et al., 2019). As shown in Figure 9, this property allows TW to optimize **solar energy absorption**, making it a strong candidate for future renewable energy solutions.

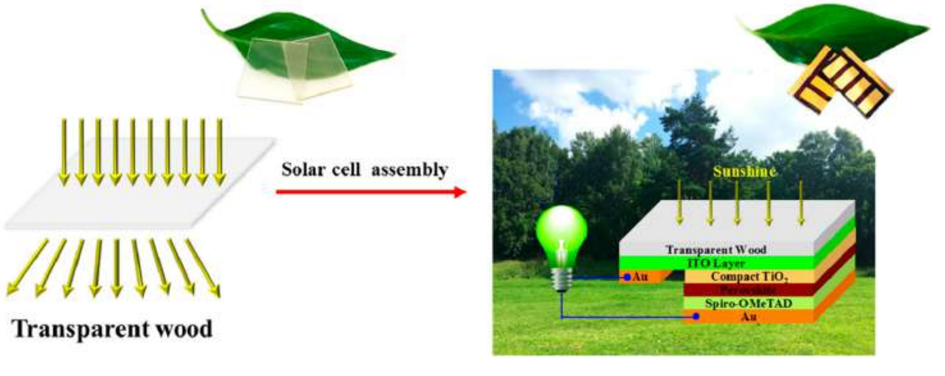

Figure 9: Schematic sketch showing the process of TW preparation and assembling of a solar cell on the TW substrate. Reproduced from Li et al., 2019 under CC-BY licence.

TW combines strength, flexibility, and sustainability, making it a versatile material for construction, energy, and technology.

4) Electronics & Optoelectronics

The **flexibility, durability, and optical properties** of transparent wood make it a valuable material for emerging electronic and optoelectronic devices. Research is exploring its use in flexible displays and touchscreens, where TW could **replace conventional plastic screens** in smartphones, tablets, and laptops, offering a more durable and sustainable alternative. Wearable technology is another promising field, as TW's lightweight and **bendable nature** allow for integration into smart clothing, medical sensors, and fitness trackers (Li et al., 2017). Additionally, its ability to manipulate light makes it ideal for optoelectronic applications, such as LEDs, sensors, and transparent circuits, enabling the development of more efficient and adaptable electronic systems (Wan et al., 2021). Figure 10 and 11 illustrate how TW is already being incorporated into cutting-edge flexible electronics.

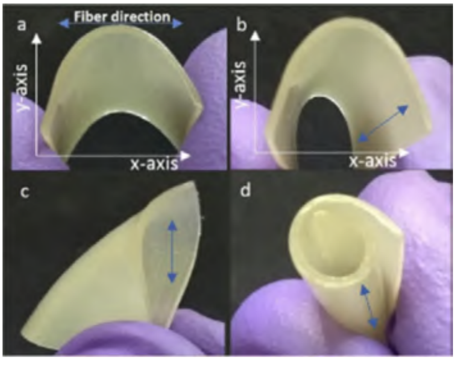

Figure 10: Example of the high flexibility that can be achieved in TW. Reproduced from Jele et al., 2024 under CC-BY licence.

Figure 11: Luminescent and flexible TW. Adapted from Zou et al., 2022 under CC-BY licence.

Modelling the Properties of Transparent Wood

Despite significant progress in research, accurately predicting the properties of Transparent Wood remains a complex challenge. So far, only a few studies have tackled this issue, using different modelling approaches (for example, Figure 13) to simulate mechanical and fire-retardant behaviour.

Foster and colleagues (Foster et al., 2019) investigated the mechanical properties of TW laminates made from **one or two plies of delignified basswood** (*Tilia americana*). They applied classical lamination plate theory to **predict the material's elastic modulus and tensile strength**.
Additionally, they used Monte Carlo simulations (n=100,000, a computational method based on **repeated random sampling**, **to refine their predictions**. The simulated tensile strength values closely matched the experimental results, confirming the reliability of this approach.

Photo by James Haworth on Unsplash.

06 MODELLING OF TRANSPARENT WOOD

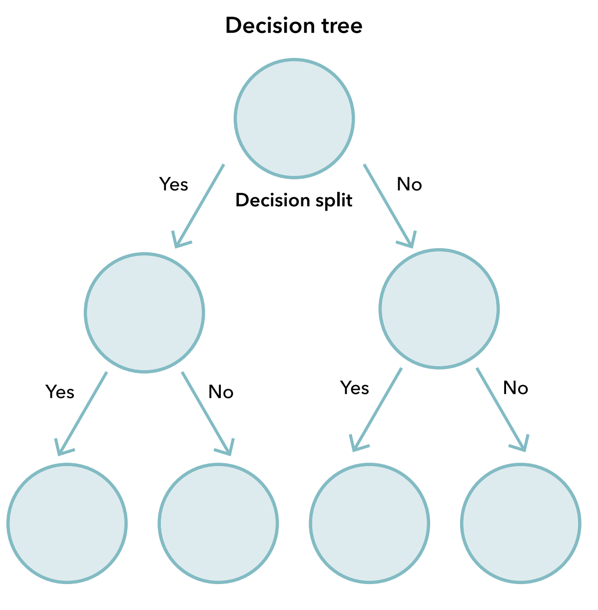

Figure 13: An example of decision tree.

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In another study, Martinka et al. (2023) explored the **fire-retardant properties of epoxy-based TW** made from *Tilia cordata Mill.* using Artificial Intelligence (AI) modelling. They trained neural networks to predict the **heat release** rate of the material based on its mass loss rate. Their model achieved a **high prediction accuracy** ($R^2 > 0.90$), demonstrating that AI can be a powerful tool for assessing TW's fire performance.

Kanocz and colleagues (Kanocz et al., 2020) focused on the **mechanical behavior** of TW in structural applications. Using numerical simulations in ANSYS Workbench 17.2, they analyzed I-beams made of veneer transparent wood (Figure 13). Their results confirmed that TW maintains high mechanical strength, making it suitable for load-bearing structures in construction.

These studies highlight the potential of computational modeling and AI in **predicting TW's properties**, paving the way for more efficient material design and optimization. However, further research is needed to improve modeling accuracy and expand its applications in engineering and industry.

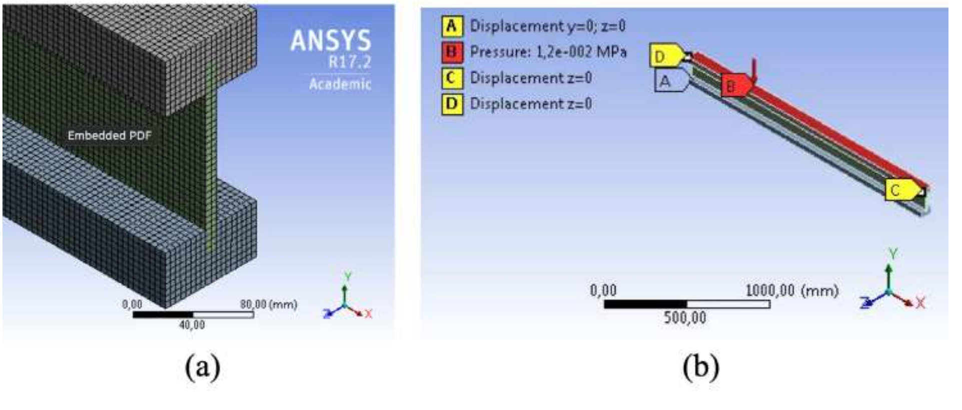

Figure 13: Numerical model of I-beam (a) Mesh; (b) Analysis parameters. Reproduced from (Kanócz et al. 2020) under CC-BY licence.

Photo by Uriel SC on Unsplash.

Modelling of Transparent Wood

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