Sustainability in materials science: the role of transparent wood

Maryann C. Wythers
EDITOR

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Chapter 3

Sustainability in Materials Science: The Role of Transparent Wood

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Abstract

Ten years ago, combining the word "wood" with "transparency" was an oxymoron since wood, a well-known natural composite material, does not allow light to pass through: indeed, light undergoes remarkable scattering phenomena and is completely absorbed by wood. The possibility of making wood transparent was discovered in parallel by two research groups (one American and one Swedish). It resulted in a new material that combines transparency, lightness, impact resistance, and low thermal conductivity. In fact, the removal of lignin (one of the three main components of wood along with cellulose and hemicellulose) allows for the obtainment, after infiltration with a monomer that possesses a refractive index similar to that of delignified wood, of a material with the above characteristics. Further, when the infiltrated monomer is bio-sourced, it is possible to attain a material that has sustainability characteristics and fits perfectly into the current concept of circular economy. Nowadays, transparent wood is finding applications both as a structural and functional material. This chapter describes transparent wood, how it is obtained, and the most recent applications in advanced fields.

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Introduction

Wood is one of the most well-known biomass materials; it possesses renewability, carbon-fixing, and sustainability and represents an energy source for everyday living (*Wood Handbook: Wood as an Engineering Material*, 2002; Wood, 1967; Chen et al., 2020; Lauri et al., 2014).

Native wood mainly consists of carbon, hydrogen, and oxygen; it shows a complex hierarchical and mesoporous structure (Figure 1), characterized by high anisotropy, in which the three main components (namely, hemicellulose, lignin, and cellulose) are organized as a peculiar network.

Cellulose (40-50 wt.%) and hemicellulose (15-35 wt.%) are polysaccharides made of β(1→4) linked D-glucose repeating units (molar mass between 10^4 and 10^5 g/mol) and complex mixtures (including mannans, xylans, glucomannans, and xyloglucans), respectively. While cellulose is organized as semicrystalline microfibrils (Cousins & Brown, 1995) originated by the reciprocal interactions of the polysaccharide macromolecular chains through weak bonds (i.e., van der Waals forces and hydrogen bonds), hemicellulose is responsible for reinforcing the cell walls through the development of interactions with lignin and cellulose (Scheller & Ulvskov, 2010). Besides, the further arrangement of microfibrils gives rise to the formation of larger fibrils and lamellae.

Finally, the polymerization of cinnamyl alcohols (i.e., monolignols, such as p-coumaryl alcohol, sinapyl alcohol, dihydroconiferyl alcohol, 5-hydroxyconiferyl alcohol, coniferyl alcohol, coniferaldehyde, ferulic acid, and coniferyl alcohol-9-acetate) leads to the formation of lignin (molar mass not exceeding 3 x 10^5 g/mol); the structure of this macromolecule varies as a function of the plant type. The cell walls of wood contain a substantial part of lignin that is responsible for providing the plants with mechanical strength. Unlike cellulose and hemicellulose, which show hydrophilicity, lignin is hydrophobic: consequently, lignin limits water absorption into the cell walls. Further, while hemicellulose and cellulose are colorless to the naked eye, lignin is responsible for the brownish color of wood, which is ascribed to the existence of complex chromophores (namely, unsaturated carbon-carbon double bonds conjugated with aromatic rings) in its structure (Zhu et al.,

2022). In addition, the structure of wood is highly porous, thus contributing to significant visible light scattering phenomena, providing the material with high opacity and limiting the optical transmittance (Zhu et al., 2016; Simelane et al., 2024; Mariani & Malucelli, 2024).

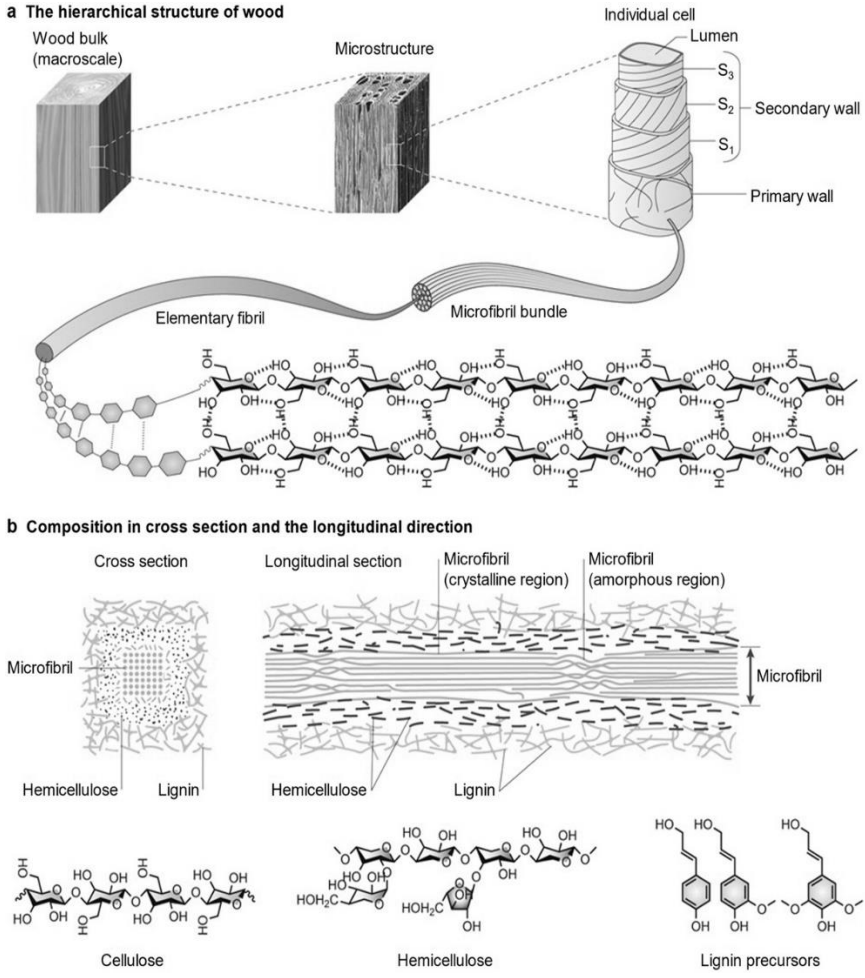

Figure 1. Hierarchical structure of native wood. (a) Wood exhibits a porous structure with longitudinal hollow channels; three-layered secondary walls (S_1-S_3) encircle the interior lumen. (b) The cross-section of wood reveals the presence of cellulose microfibrils embedded in the lignin and hemicellulose matrix. Cellulose microfibrils in the longitudinal direction give rise to both crystalline and amorphous regions. Reprinted from (Lee et al., 2025) under CC-BY 4.0 License.

To overcome these limitations, in 1992, Fink demonstrated that it is possible to obtain transparent wood materials by removing the lignin from the wood channels, replacing it with a polymer that perfectly matches the refractive index of the obtained delignified material, hence overcoming the light scattering phenomena (Fink, 1992). Unfortunately, this concept was practically discarded till about 2016, when two independent academic research groups, one from the University of Maryland (USA) (Zhu et al., 2016) and the other from the KTH Royal Institute of Technology (Sweden) (Li et al., 2016) simultaneously took up the idea of making wood transparent.

From that point onwards, the research on transparent wood has grown impressively, as witnessed by the increasing number of scientific papers that appeared in peer-reviewed journals (Figure 2).

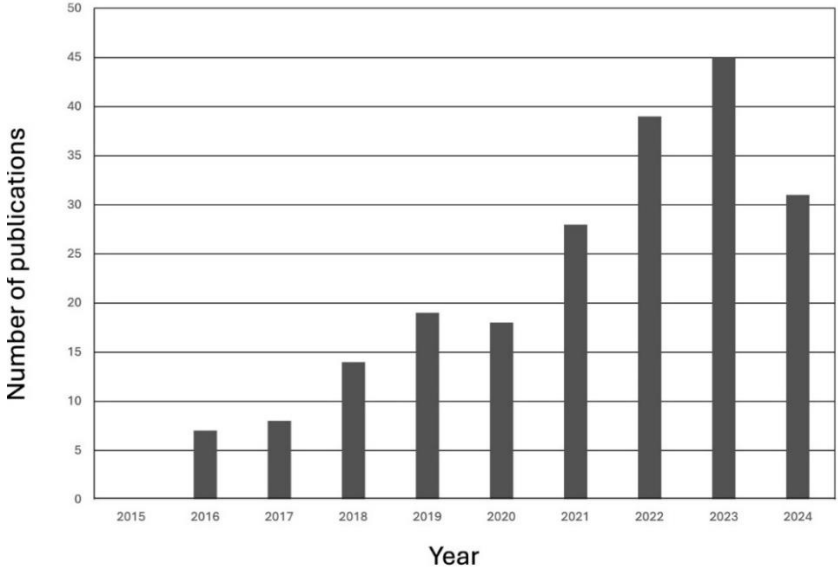

Figure 2. Number of publications (from 2015 to 2024) in peer-reviewed journals, dealing with "transparent wood" (data collected from the Web of Science™ database, accessed on Nov 10, 2024).

At present, transparent wood can rightly be considered a novel, green, and sustainable material with a big potential in different advanced application sectors comprising optoelectronics and electronic devices, solar cell windows, windows for innovative buildings (energy storage materials), and

ultrafiltration membranes, among others (Pandit et al. 2024; Simelane et al., 2024).

The present chapter aims to summarize the current state-of-the-art related to transparent wood, its fabrication, and some up-to-date applications, providing the readers (both experts and newcomers) with some perspectives about the possible further developments and implementations for the forthcoming years.

The Making of Transparent Wood

As mentioned in the previous paragraph, several factors concurrently contribute to the wood's opacity, namely its anisotropy, porosity, and hierarchical structure, which favor the visible light scattering and the presence of chromophores, able to absorb the incident light. However, it is possible to convert native wood into a highly transparent material by exploiting two different general strategies, namely, lignin removal and lignin modification.

The former approach relies on the use of different chemicals in acidic or alkaline conditions, able to diffuse within the wood channels and extract the lignin. There are some differences between working at high or low pH conditions, which will be summarized in the following paragraphs.

As the interactions between lignin and hemicellulose/cellulose do not tolerate high pH values, working in alkaline conditions may favor not only the lignin removal but also its degradation. Further, lignin removal is promoted by the conversion of the R-OH functionalities present in the native lignin into $R\text{-}O^-$ anionic groups during the alkali treatments: indeed, $R\text{-}O^-$ groups are more soluble in water and, therefore, can more effortlessly be removed from the wood channels.

The different alkaline conditions adopted for removing the lignin from wood can be derived from the pulping processes employed in the paper industry (Kumar et al., 2021); they are listed in Table 1.

Conversely, industrial lignin removal in acidic conditions relies on the use of quite high temperatures (up to about 240°C) in the presence of strong mineral acids and, possibly, organic solvents; Table 2 lists the main industrial processes. Further, to avoid the dehydration of the hemicellulose and cellulose, dilution effects are exploited.

As transparent wood must keep the integrity of hemicellulose and cellulose and avoid the formation of undesirable groups, only a few of the aforementioned delignification techniques can be utilized.

In particular, Mi and co-workers (Mi et al., 2019) were among the first to design an effective method for the almost complete removal of lignin from balsa wood: to this aim, the biomass was treated with $NaClO_2$ solution for almost 24 hours. This way, it was possible to achieve 0.8 wt.% of residual lignin; further, the treatment accounted for the obtainment of cellulose nanofibers, whose diameter was below the visible light wavelength, hence improving the final transparency of the delignified wood.

Table 1. Some delignification processes carried out in alkaline conditions in pulp and paper industries

Type of process	Technique	Temperature range (°C)	Types of chemicals
Batch	Soda pulping	160-170	Aqueous solution of anthraquinone and NaOH
Batch	Kraft pulping	140-170	Aqueous solution of NaOH and Na_2S
Batch	Sulfite pulping	140-170	Aqueous solution of sulfite or bisulfite salts (Ca, Mg, Na, or ammonium)
Batch	Alkaline pretreatment	40-160	Aqueous solution of anthraquinone, NaOH and Ca $(OH)_2$
Batch	Anydrous ammonia pretreatment + extraction	60-160	Anhydrous NH_3 and dry biomass
Batch	Aqueous fiber explosion + extraction	100-130	Aqueous solution of NH_3 – quick decomposition
Flow-through	Ammonia recycle percolation	150-210	Aqueous solution of NH_3

Similarly, He and co-workers (He et al., 2019) proposed an effective treatment with water peroxide for lignin removal in basswood (0.6 wt.% residual lignin). Moreover, Li and co-workers (Li et al., 2019) achieved 0.8-1 wt.% of residual lignin in basswood through a steam-modified delignification method, using water peroxide and acetic acid.

After lignin removal, as schematized in Figure 3, there are two possibilities for obtaining transparent wood. The first involves the direct densification of the cell walls through compression, employing an external pressure: this way, the radial thickness of the delignified wood significantly decreases, giving rise to the formation of usually flexible transparent wood thin films (the flexibility of the final materials strictly depends on the type and initial thickness of native wood). The final material can be used as it is or further vacuum-infiltrated by an appropriate polymer resin, hence giving rise to transparent compressed wood material (Wang et al., 2022).

The second strategy (and the most employed one) exploits the infiltration of a liquid resin system into the delignified wood template; the infiltrated resin, according to its chemical structure, subsequently undergoes *in situ* thermal/photoinduced polymerization or curing, depending on whether it is thermoplastic or thermosetting, respectively (Li et al., 2021; Wu et al., 2020; Qin et al., 2018; Wang et al., 2021; Chen et al., 2022).

Table 2. Some delignification processes carried out in acidic conditions in pulp and paper industries

Type of process	Technique	Temperature range (°C)	Types of chemicals
Batch	Steam explosion pretreatment + extraction	100-210	H_2O, (SO_2), – quick decomposition
Batch	Organosolv pulping	120-210	Organic solvents (MeOH, EtOH, BuOH, or EtGly, glycerol, or THF, dioxane, HCOOH, CH_3COOH), (H_2O), H_2SO_4
Batch	Formaldehyde-assisted fractionation	80-100	H_2O, dioxane, formaldehyde, HCl
Flow-through	Diluted acid pretreatment	120-210	Aqueous solution of mineral acid (H_2SO_4, HCl)
Flow-through	Hot water pretreatment	160-240	H_2O

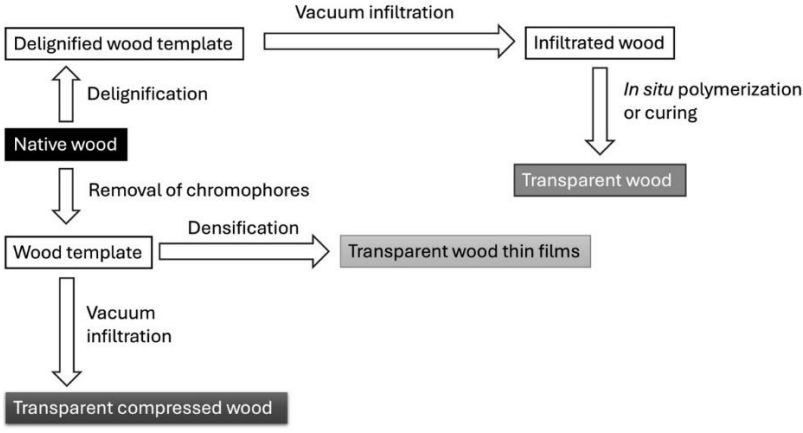

Figure 3. The obtainment of transparent wood starting from a delignified native wood.

The first successful attempt to obtain transparent wood without exploiting the removal of lignin was proposed by Li and co-workers (Li et al., 2017). This strategy (Figure 4) was motivated by the unavoidable worsening of the mechanical behavior of wood after delignification and the need to avoid i) the use of toxic chemicals and ii) the development of (by-)products impacting the environment (like chlorinated compounds and sulfides, among others). In particular, they employed an aqueous bleaching solution ($NaOH/H_2O_2/Na_2SO_3$/diethylene triamine pentaacetic acid), which allowed for the removal of the chromophores only (residual lignin was more than 80 wt.%) and accounted for the obtainment of a final wood template that was mechanically stronger than the delignified wood counterpart. Then, methyl methacrylate was infiltrated and subsequently *in situ* polymerized, giving rise to the formation of transparent wood (about 83% of transmittance in the visible wavelength region, Figure 5).

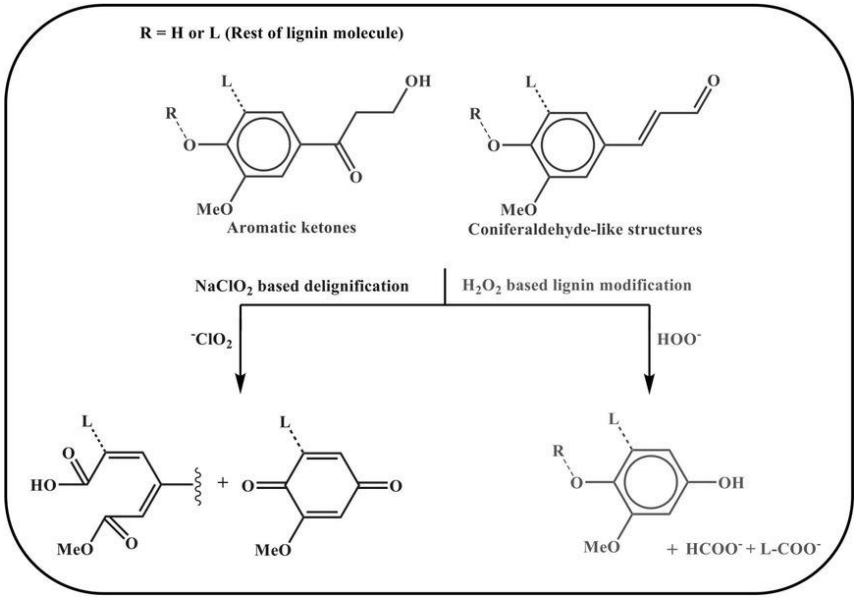

Figure 4. Illustrative lignin reactions and structures contributing to wood color, and main products of the two routes (delignification with $NaClO_2$ solutions and lignin modification through bleaching with $NaOH/H_2O_2/Na_2SO_3$. Reprinted from (Li et al., 2017) under CC-BY License.

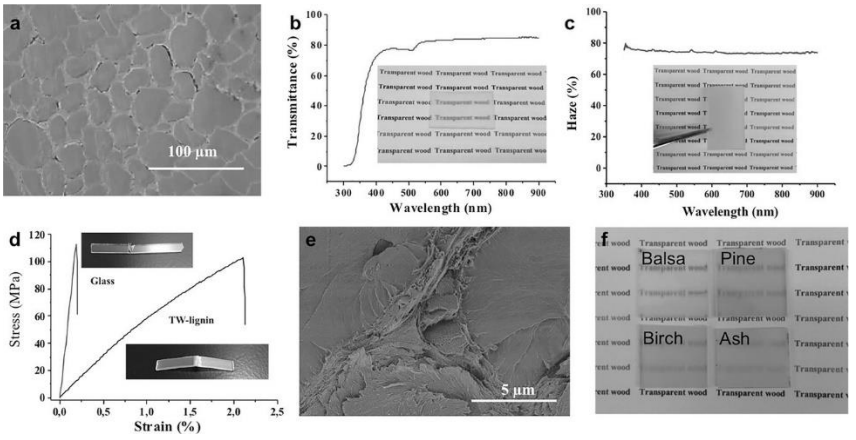

Figure 5. (**a**) Typical SEM image of transparent wood after the removal of the chromophores, infiltration with methyl methacrylate, and subsequent in situ polymerization: the distribution of poly(methyl methacrylate) in wood lumen space is evident. (**b**): Optical transmittance of the so-obtained transparent wood; the inset is a photograph of transparent wood with a thickness of 1.5 mm. (**c**) Optical haze of the so-obtained transparent wood; the inset is a picture of the material with a 5 mm gap between the sample and the underlying paper. (**d**) Three-point bending curves of the so-obtained transparent wood and glass; inset images are the fractured samples after the test. (**e**) Typical SEM image of TW-lignin after fracture, demonstrating the ductile fracture (**f**): Typical photographs of lignin-retaining transparent woods obtained from different native woods. Reprinted from (Li et al., 2017) under CC-BY License.

Recent Advances in Transparent Wood

The next paragraphs will highlight the potential of transparent wood as a sustainable and effective material for different applications sectors, providing the reader with some up-to-date case studies.

Functional Applications of Transparent Wood

Transparent wood has recently gathered great attention in optoelectronics, for the design of photoluminescent transparent films (thickness of about 90 µm) (Zou et al., 2022). To this aim, very thin poplar wood veneer slices were delignified and subsequently treated with quantum dots solutions at different loadings. The final step was to soak the so-treated material in a flexible epoxy

resin under vacuum and cure it for 1 day at room temperature. The transparent wood films showed high transparency and flexibility (Figure 6). In addition, the incorporation of quantum dots (three different colors, namely blue, green, and red) was responsible for the photoluminescent effects (Figure 7).

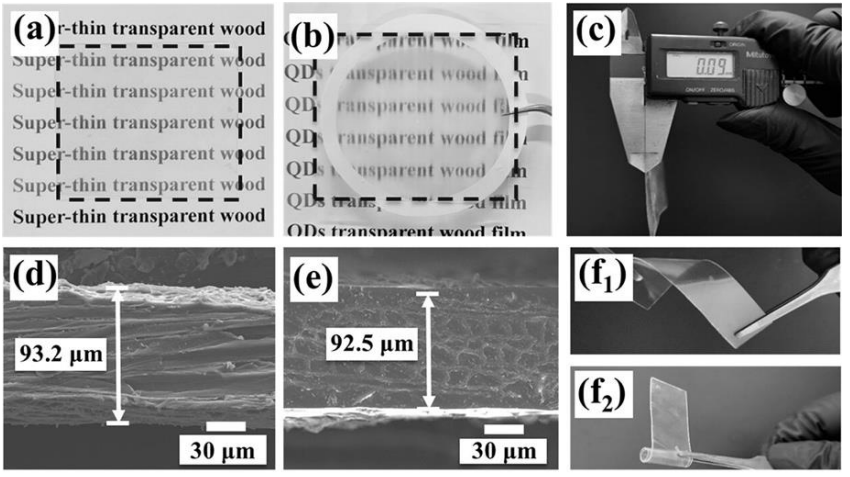

Figure 6. (a, b) Superthin transparent wood films placed directly on substrates and 10 mm above the substrate, respectively. (**c**) The thickness of the superthin transparent wood films measured with vernier calipers. (d, e) The thickness of superthin transparent wood films from SEM analyses. (f_1, f_2) The high flexibility of the superthin transparent wood films. Reprinted with permission from (Zou et al., 2022). Copyright 2022, American Chemical Society.

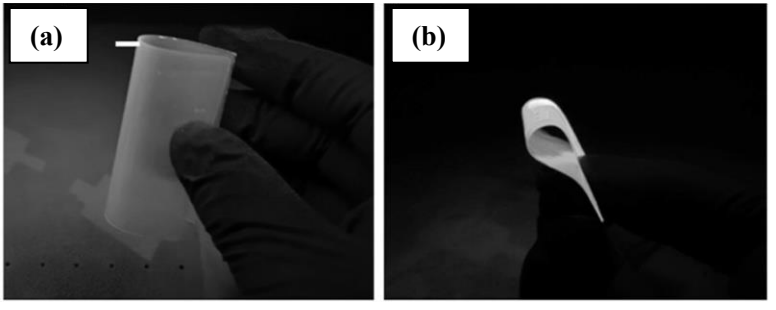

Figure 7. (a) Digital image of superthin transparent wood film and (b) Quantum dots/superthin transparent wood film UV-irradiated and exhibiting photoluminescence (concentration of quantum dots: 0.50 mg/mL). Adapted with permission from (Zou et al., 2022). Copyright 2022, American Chemical Society.

Liu et al. dispersed 1,2-bis(5-chloro-2-methylthiophen-3-yl) cyclopent-1-ene (CMCE, a photochromic dye) in PMMA that, in turn, was infiltrated into delignified poplar wood (Liu et al., 2022). The photochromic dye accounted for reversible structural changes upon exposure to visible or UV radiation, thanks to the opening or closure of the CMCE rings, respectively. This finding suggested the utilization of the designed photochromic transparent wood in the packaging sector, as sensor material for anticounterfeiting purposes.

Quite recently, transparent wood has also been proposed as an effective thermochromic system, potentially suitable for the design of smart windows: in particular, Liu et al. vacuum-infiltrated delignified balsa wood films with an aqueous suspension of VO_2 nanoparticles (1-6‰ concentration) in poly(vinyl alcohol) (Liu et al., 2021). The so-obtained transparent wood further underwent treatment with octadecyltrichlorosilane, hence becoming hydrophobic (with static water contact angles beyond 120°) and exhibiting self-cleaning properties. In addition, the films showed very good thermochromic features, witnessed by the significant temperature-dependent transmittance over the visible wavelength range, as well as good mechanical properties and very low thermal conductivity (around 0.29 W(mK)): all these findings clearly supported their potential use in the design of efficient smart glazing systems.

In a further research effort, Al-Qahtani and co-workers (Al-Qahtani et al., 2024) infiltrated (and then polymerized) electrospun silanized glass nanofibers-reinforced styrene into delignified basswood. Before infiltration, rare-earth strontium aluminate was added to styrene at different loadings (up to 11 wt.%), hence attaining a photochromic nanosystem. The so-obtained transparent wood turned green when exposed to UV radiation, conversely remaining colorless under visible light. This photochromic effect was fully reversible and fast.

To obtain luminescent transparent wood, Zhou et al. exploited the incorporation of carbon quantum dots (exhibiting yellow or red fluorescence) into delignified balsa wood; afterward, the so-treated wood was infiltrated with an epoxy resin (Zhou et al., 2024). The final materials showed high mechanical behavior and UV-blocking features, as well as remarkable water repellency, high durability, and good insulation, envisaging their potential for the design of smart windows.

A similar approach was recently exploited by Xu and co-workers (Xu et al., 2024), who prepared a fluorescent transparent wood showing UV-shielding features through the infiltration of an epoxy resin containing carbon quantum dots into delignified Canadian white maple. Indeed, compared to

glass, the so-obtained transparent wood not only showed improved mechanical properties (in terms of higher tensile strength and impact resistance) but also enhanced UV-shielding capability and haze.

Tian et al. succeeded in obtaining flexible and reversible photoresponsive transparent woods through the infiltration of an epoxy resin mixed with a spiropyran solution into balsa wood (Tian et al., 2024). Owing to the break of carbon-oxygen bonds, the photosensitive dye provided the transparent wood with photoresponsive features upon exposure to UV radiation for 1 min.

The modification of delignified sonokeling wood with a poly(vinyl alcohol)/gelatin solution, containing up to 0.5 g of $BaCO_3$, provided the material with X-ray shielding features (Muhammad et al., 2022). Indeed, the linear attenuation coefficients evaluated in the tests using different photon energies (within 55 and 90 eV) were high, and a linear correlation between the mass attenuation coefficients and the Barium carbonate content was observed, hence demonstrating the suitability of transparent wood for the envisaged application.

Another functional application in which transparent wood is currently emerging refers to its use for the design of efficient materials suitable for sensor applications and flexible electronic devices. In this context, Yang et al. infiltrated delignified balsa wood with a deep eutectic solvent (DES) made of choline chloride and acrylic acid; then, the infiltrated DES underwent polymerization (Yang et al., 2021). The so-obtained material not only exhibited high stretchability/flexibility but also acceptable transmittance (beyond 60% in the entire visible wavelength range). Further, thanks to the high mobility of cations and anions in the DES mixture, the flexible transparent wood showed temperature-sensing properties, evidencing high stability of the electrical signal even after repeated heating-cooling cycles.

Energy-Saving Applications

Owing to its intrinsic toughness and low thermal conductivity, transparent wood has also been investigated as a potential replacement for glass in the construction sector, aiming to design new materials with passive radiative cooling features and enhanced energy-saving effectiveness. To this aim, Hu et al. sonochemically treated an epoxy-infiltrated transparent balsa wood with a ZnO coating (Hu et al., 2022). The coated material showed good mechanical properties, solar reflectance, and, very interestingly, very low thermal conductivity (about 0.157 W(mK)) and high emissivity (around 90% in the

infrared region). Besides, compared to standard commercial glasses and low-emissivity (i.e., Low-E) glasses, the ZnO-coated transparent wood allowed for an important cooling energy saving, as evaluated by some simulations in Chongqing, Hongkong, and Shanghai. This concept was further demonstrated by the same group very recently (Hu et al., 2024).

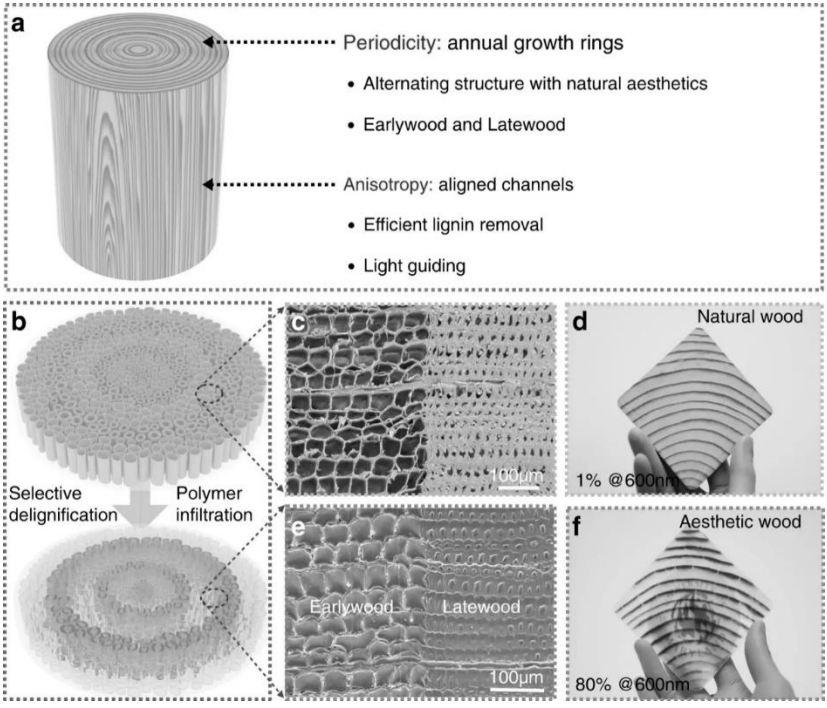

Figure 8. (a) Combination of wood periodicity (annual growth rings) with anisotropy (aligned channels) to produce a new kind of transparent wood composite. (b) Scheme of the procedures for producing aesthetic transparent wood from native Douglas fir wood with vertically aligned cells and annual growth rings after fast spatially selective delignification and polymer infiltration. (c, e) Typical SEM images of the cross-section of native wood and dense aesthetic wood microstructures after polymer infiltration. (d, f) Photos to show a piece of aesthetic wood-R ($86 \times 86 \times 2$ mm^3) with preserved wood patterns and high average transparency. Reprinted from (Mi et al., 2020) under CC-BY License.

Mi et al. were among the first to assess and verify that the selective/partial delignification of wood, followed by infiltration with an epoxy resin, allows for obtaining the so-called “aesthetic transparent wood” (Figure 8). This material, which keeps the growth ring patterns of native wood, is suitable (and

even scalable) for designing effective energy-saving building glazing (Figure 9 shows the light distribution and aesthetic appeal inside a building using the aesthetic transparent wood). Indeed, the aesthetic transparent wood exhibited 93% haze and around 80% transmittance (at 600 nm wavelength), interesting mechanical features (particularly referring to toughness – beyond 270 MJ/m^2 - and strength – around 92 MPa), and very low thermal conductivity (about 0.24 W(mK)) (Mi et al., 2020).

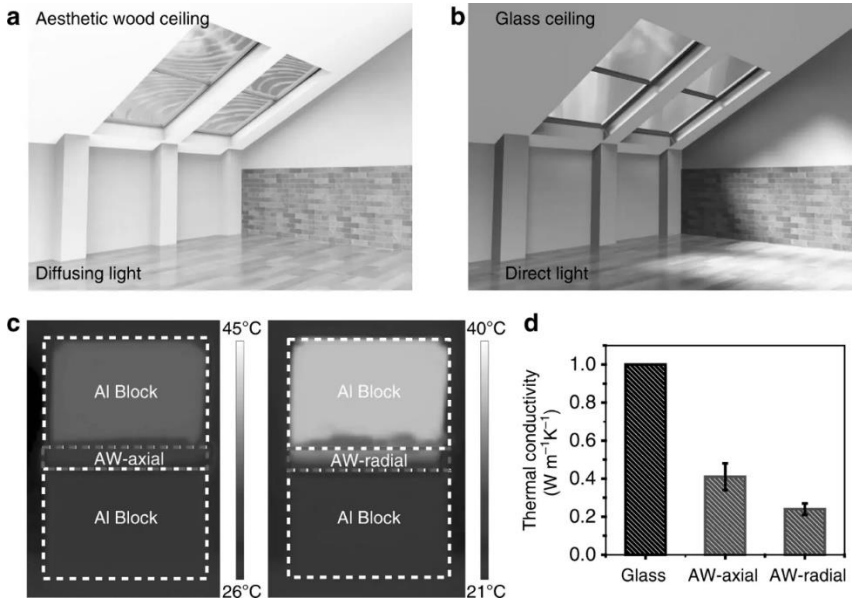

Figure 9. (a, b) The schematic scene showing the light distribution and aesthetic appeal inside a building using the aesthetic transparent wood (abbreviated as AW in the (d) ceiling), compared with the glass ceiling. (**c**) IR images of aesthetic wood with temperature distributions in the axial (AW-axial - heat transfer direction is parallel to the aligned wood microchannels) and radial (AW-radial - heat transfer direction is perpendicular to the aligned wood microchannels) directions. (d) Thermal conductivities of glass, AW-axial, and AW-radial transparent aesthetic wood. Error bars denote standard deviation. Reprinted from (Mi et al., 2020) under CC-BY License.

Tan et al. successfully infiltrated stimuli-responsive vitrimers (made of covalently adaptive networks based on thiocarbamate linkages) into delignified balsa wood; then, the infiltrated wood was cured at 60°C, employing a click reaction between thiol and isocyanate (Tan et al., 2022). The resulting transparent wood showed around 90% transverse transmittance

and haze; in addition, the measured thermal conductivity values were about 0.30 W(mK), and the overall mechanical behavior was acceptable (49 and 37 MPa for flexural and tensile strength, respectively). Very interestingly, the presence of the vitrimeric resin was responsible for the high shape manipulation capability of the material, which was able to almost recover its original flat shape through a thermal treatment performed at 60°C for 5 min.

Very recently, Binyaseen and co-workers (Binyaseen et al., 2024) designed long-persistent photoluminescent transparent basswood with color-changing capabilities and photo-switchable transmittance, suitable for effective smart window applications. In particular, an aqueous bleaching solution ($NaOH/H_2O_2/Na_2SO_3$/diethylene triamine pentaacetic acid) allowed for the removal of the lignin chromophores only; then, the modified wood was vacuum infiltrated with pre-polymerized methyl acrylate containing rare-earth strontium aluminum oxide nanoparticles (7-15 nm). The incorporation of the nanoparticles accounted for superhydrophobic properties, witnessed by water contact angles beyond 150°: this finding was ascribed to the increase of the surface roughness as the nanoparticle loadings increased. Further, the so-obtained transparent wood (69% transmittance over the visible wavelength range) displayed stable and reversible photoswitchable luminescent features (changing color from colorless in daylight to greenish when exposed to UV radiation).

Pursuing this research, Al-Qahtani et al. designed a photochromic and fluorescent transparent wood, infiltrating basswood with a room-temperature vulcanizing polysiloxane embedding europium- and dysprosium-activated strontium aluminum oxide nanoparticles (average size: 8–13 nm). This way, it was possible to obtain a transparent (about 70% transmittance) and superhydrophobic material (water contact angles between 146 and 157°), showing photoluminescent (i.e., colorless in daylight, green under UV exposure, and greenish-yellow in the darkness) and UV-blocking features. All these findings suggested the potential use of the material in the design of novel effective smart windows (Al-Qahtani and Attia, 2024).

Zhang and co-workers (Zhang et al., 2023) proposed the use of transparent wood as an efficient electromagnetic absorption material. For this purpose, they delignified balsa wood and subsequently vacuum-infiltrated it with pre-polymerized acrylamide containing 0.1 wt.% Ag nanowires, 0.1 wt.% carbon nanotubes and CNTs), and 0.1 wt.% reduced graphene oxide. The optical transmittance of the final material was around 83% within the visible wavelength range. More interestingly, 2 mm thick transparent wood exhibited an effective absorption bandwidth of 9.5 GHz, almost covering the entire X

band (8.2–12.4 GHz) and Ku band (12.4–18 GHz); besides, its thermal conductivity was as low as 0.45 W(mK). These findings highlighted the big potential of transparent wood for the design of smart energy-efficient windows.

Very recently, Cheng et al. designed a flexible transparent wood-based triboelectric nanogenerator (TW-TENG) combining excellent triboelectric properties, optical features, energy-harvesting capability, and wood aesthetics (Cheng et al., 2024). To this aim, maple wood was delignified and subsequently vacuum-infiltrated with an epoxy resin. After curing, the transparent wood (about 89% transmittance) was able to reach an open-circuit voltage of up to 127 V, highlighting a significant 530% improvement with respect to the native wood (Figure 10). In addition, the nanogenerator showed high stability and durability during 10000 working cycles, highlighting its suitability for the design of novel self-power supply, motion sensing, and smart home devices.

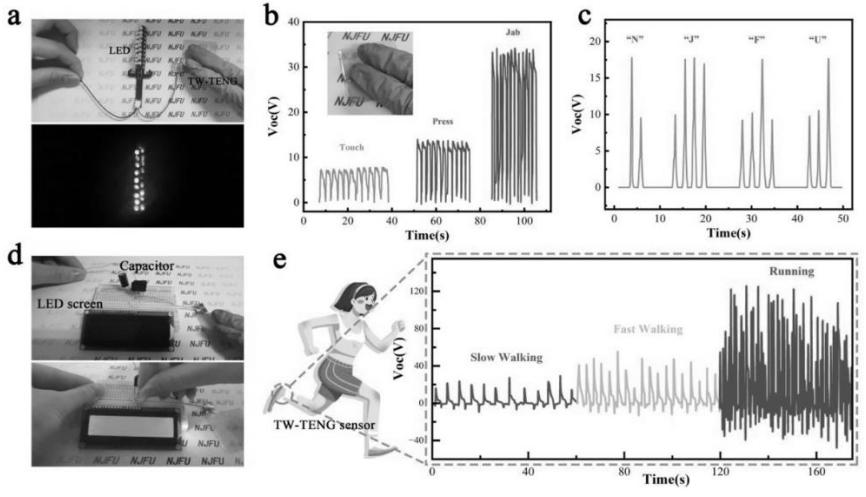

Figure 10. Demonstration of the practical application of the transparent wood-based triboelectric nanogenerator (TW-TENG). (a) The nanogenerator can light up 19 small LED bulbs. (b) Open-circuit voltage (Voc) is generated by triggering the TW-TENG in different motion modes. (c) The TW-TENG can transmit the message of "NJFU" in Morse code. (d) The TW-TENG charges a capacitor and lights up an LED screen with the capacitor as the power source. (e) The TW-TENG serves as a motion sensor to monitor human movement. Reprinted from (Cheng et al., 2024) under CC-BY License.

Applications of Transparent Wood in Flame Retardancy

Both native woods and related transparent woods can effortlessly be ignited by exposure to an irradiative heat flow or a direct flame. Therefore, it becomes necessary to provide these materials with flame retardant properties. The main recent outcomes on flame retarded transparent wood are summarized in the following.

Zhang et al. infiltrated a poly(vinyl alcohol)/MXene® nanosheets dispersion into delignified balsa wood. Even in the presence of 3 wt.% MXene® nanosheets, the so-obtained transparent wood showed good transparency over the entire visible light wavelength, enhanced UV resistance, and remarkably low thermal conductivity (about 0.31 W/(mK)). Interestingly, 2 wt.% MXene® nanosheets in the infiltrated polymer promoted a remarkable lowering in total heat release (by around 22%) and peak of heat release rate compared with the delignified material, as revealed by microscale combustion calorimetry measurements (Zhang et al., 2022).

The current chemistry of flame retarded polymers widely relies on the use of phosphorus-based additives (Singh and Sivaramakrishna, 2024; Malucelli, 2024; Attia et al., 2024). In this context, Fan and co-workers (Fan et al., 2022) made balsa wood transparent through oxidation of the chromophores in the presence of H_2O_2; then the resulting material was infiltrated with a melamine-formaldehyde resin incorporating a phosphorus-containing flame retardant derived from the reaction of a cyclic phosphate ester with poly(ethylene glycol). 95% transmittance was achieved in the final transparent wood, which showed enhanced mechanical strength, as well as a high Limiting Oxygen Index (LOI=36%). Further, as assessed by forced combustion tests, the presence of the P-containing flame retardant accounted for a significant lowering in the fire growth rate index (-83% compared to the transparent counterpart not incorporating the flame retardant additive), the peak of heat release rate (-81%), the peak mass loss rate (-69%), and the effective heat of combustion (-74%). The observed flame retardant outcomes suggested the use of this transparent wood in the sector of civil engineering.

Samanta and co-workers (Samanta et al., 2022) operated on two different kinds of wood, namely birch wood (delignified with sodium chlorite) and balsa wood (bleached with a solution comprising H_2O_2, Na_2SiO_3, $MgSO_4$, and NaOH). After the modification, both the woods were infiltrated with a water-soluble and flame-retardant melamine-formaldehyde resin and finally underwent curing. Despite a quite limited transmittance (not exceeding 50% in the visible wavelength interval), the transparent woods were able to achieve

self-extinction in both vertical and horizontal flammability tests; in addition, compared with the non-infiltrated material, around 84 and 14% decrease in total smoke release and peak of heat release rate, respectively, was observed during cone calorimetry tests. Finally, it was possible to obtain quite large size (i.e., 200 x 100 x 1 mm^3, Figure 11) transparent wood specimens from birch wood, following the delignification/infiltration/curing experimental steps: these specimens optically performed similarly to small size counterparts, hence envisaging the possible scaling up of the production process, with a view to industrial exploitation.

Figure 11. Scale-up demonstration of transparent birch wood infiltrated with melamine-formaldehyde resin. The sample was placed on top of printed paper. Reprinted from (Samanta et al., 2022) under CC-BY 4.0 License.

Ninety-eight and 93% of haze and transmittance, respectively, were measured for a delignified balsa wood infiltrated with a flame retardant phosphate ester-poly(ethylene glycol) and finally cured (Chu et al., 2022). The final material was self-extinguishing in flammability tests carried out in horizontal configuration; in addition, its LOI achieved 37%. To complement the outstanding flame retardant behavior, cone calorimetry tests (50 kW/m^2 irradiative heat flux) revealed a remarkable decrease in total heat release (around -84% compared with the same delignified material infiltrated with an

epoxy, not flame retarded, system), heat of combustion (around -81%), and peak of heat release rate (about -82%).

Very recently, Li et al. infiltrated delignified balsa wood with epoxy resin, triethyl phosphate, and poly(ethylene glycol), using a vacuum-assisted technique (Li et al., 2024). This way, they obtained a multifunctional material capable of combining different properties, namely transparency (up to 95% in the visible wavelength range), phase-change energy-storage performance (thanks to the high enthalpy of phase change - 54.25 J/g - and the low melting temperature - 6.6°C-), mechanical strength (with enhanced ductility and toughness), and flame retardancy (with self-extinction in horizontal flame spread tests, thanks to an extended charring effect in the condensed phase).

Applications in Home Design and Manufacturing

The potential of transparent wood also began to be explored in home design and manufacturing. In this context, Zhou and Xu succeeded in improving the interface between partially delignified Chinese fir and the epoxy resin employed for the impregnation step utilizing a chemical treatment with γ-aminopropyl triethoxysilane (silane coupling agent). This latter accounted for the formation of a good interface between the cured epoxy and the wood channels, leading to enhanced ductility (+154% elongation at break, compared with native wood) and tensile strength (+72%). Besides, the so-obtained transparent wood showed good optical transmittance and low haze, which indicated its appropriateness for home design and manufacturing applications (Zhou and Xu, 2022).

Conclusion and Future Perspectives

At present, transparent wood is becoming more and more appealing not only because of the peculiar features that make it a potentially advantageous replacement for “traditional” materials (i.e., plastics, metal alloys, ceramics, and even wood itself) but also for its intrinsic sustainability. Indeed, transparent wood derives from biomass (i.e., native wood), hence fulfilling the current demand for the use of bio-sourced and renewable materials. Transparent wood is progressively fitting well into the circular economy

concept and may represent a good and reliable answer to the need for more intelligent exploitation of the limited planet's resources.

Surely, transparent wood materials can potentially be used in different advanced applications comprising sensoring, optoelectronics, energy-saving and smart glazing, flame retardancy, home design, and X-ray shielding, among a few to mention

However, despite the potential that has been described in the present chapter, transparent wood still has some challenges to overcome. First, the scaling up and industrialization of transparent wood are severely limited by the difficulties in producing materials of great thickness and sizes: in fact, the delignification/bleaching methods that are currently employed do not allow for satisfactory treating large and thick wood native samples. Further, the chemicals utilized for the aforementioned treatments are somehow environmentally impacting (even though their toxicity is not very high): therefore, they should be replaced with more environmentally friendly products, which requires a greater effort.

Then, replacing the infiltration resin systems with more bio-sourced products would pave the way for the development and implementation of fully biobased transparent wood materials. At variance, the availability of highly bio-sourced resin systems is still quite limited, hence negatively affecting the possibility of designing totally “green” materials.

In spite of all these limitations, it is expected that materials and technologies related to the production of transparent wood can be significantly improved in the near future, thus fostering a significant development of this emerging material.

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