Transparent wood-based materials: A new step toward sustainability and circularity

Next Materials 5 (2024) 100255

Contents lists available at ScienceDirect

Next Materials

journal homepage: www.sciencedirect.com/journal/next-materials

Research article

Transparent wood-based materials: A new step toward sustainability and circularity

Alberto Mariani [a], Giulio Malucelli [b,*]

[a] University of Sassari, Department of Chemical, Physical, Mathematical, and Natural Sciences, Via Vienna 2, Sassari 07100, Italy
[b] Giulio Malucelli, Politecnico di Torino, Department of Applied Science and Technology, Viale Teresa Michel 5, Alessandria 15121, Italy

ARTICLE INFO

Keywords:
Transparent wood
Delignification
Optical transmittance
Resin infiltration/ Polymerization/curing
Structural and functional applications
Sustainability

ABSTRACT

Wood is a natural composite material mainly consisting of three components, i.e., cellulose, hemicellulose, and lignin. It exhibits a complex hierarchical structure characterized by open channels, aligned in the growth direction, having specific porosity at micro-, meso-, and macro-scale, and an extended opacity, due to adsorption phenomena because of the presence of lignin and scattering, as different refractive indexes characterize its components. Even if during the historical ages some of its applications have been replaced by other materials, wood still covers a large part of common uses, which range from biomass for energy recovery to material for the building sector, or from artifacts to household/furniture manufacturing. Despite its real invention dating to 1992, only about ten years ago two independent research groups, one from the University of Maryland (USA) and the other from the Royal Institute of Technology (Sweden) rediscovered and started to thoroughly investigate the so-called transparent wood (TW). TW can be derived from almost any wood biomass through specific chemical treatments focused on lignin. These aim to completely remove this component from wood or to eliminate the chromophore groups present in the pristine material, hence obtaining, after direct densification or after infiltration with a suitable polymer resin, a new material with very high transparency, toughness, and lightness. These characteristics can further be combined with other specific features (such as environmental protection, flame retardancy, photoluminescence, and energy storage ability, among others), which open the way toward the development of new, up-to-date, advanced, and sustainable materials for both structural and functional purposes, fulfilling the current concepts of circular economy and sustainability. The present review is aimed at providing the reader with an overview of the characteristics of transparent wood, describing the latest applications and, finally, discussing some challenging issues and perspectives for possible developments in the forthcoming years.

1. Introduction

Wood, one of the most well-known non-polluting, sustainable, and carbon-fixing biomasses, has always been considered a reproducible source of materials and energy for everyday life [1]. It exhibits a mesoporous and hierarchical complex structure (Fig. 1), made of three main components, i.e., hemicellulose, cellulose, and lignin [2]. Unlike the first two constituents, which are colorless at visual inspection, lignin provides the biomass with a dark color, due to the presence of complex chromophores (i.e., C=C double bonds conjugated with aromatic rings [3]). Besides, the extended porosity of wood accounts for remarkable scattering phenomena of visible light, making the material opaque, hence with negligible optical transmittance [4–7]. The possibility of transforming wood into a transparent material was demonstrated by Fink in 1992 [8] but was abandoned until 2016 when two independent research groups, one from the University of Maryland (USA) [9] and the other from the Royal Institute of Technology (Sweden) [10], rediscovered the potential of this new material for different applications (Fig. 2).

The obtainment of TW requires specific procedures, as schematized in Fig. 3. Briefly, the first step refers to either removing or modifying the lignin of the pristine wood. The removal of lignin (a very well-established process in the paper industry [12]) can be carried out using acidic/alkali treatments or employing redox agents. Under acidic conditions, organic solvents can be employed [13]. Conversely, the lignin removal that is carried out in alkaline environments exploits quite high temperatures (usually between 140 and 170°C), and the use of ammonia or sodium hydroxide, often in combination with sulfites or

* Corresponding author.
E-mail address: giulio.malucelli@polito.it (G. Malucelli).

https://doi.org/10.1016/j.nxmate.2024.100255
Received 8 April 2024; Received in revised form 11 May 2024; Accepted 22 May 2024

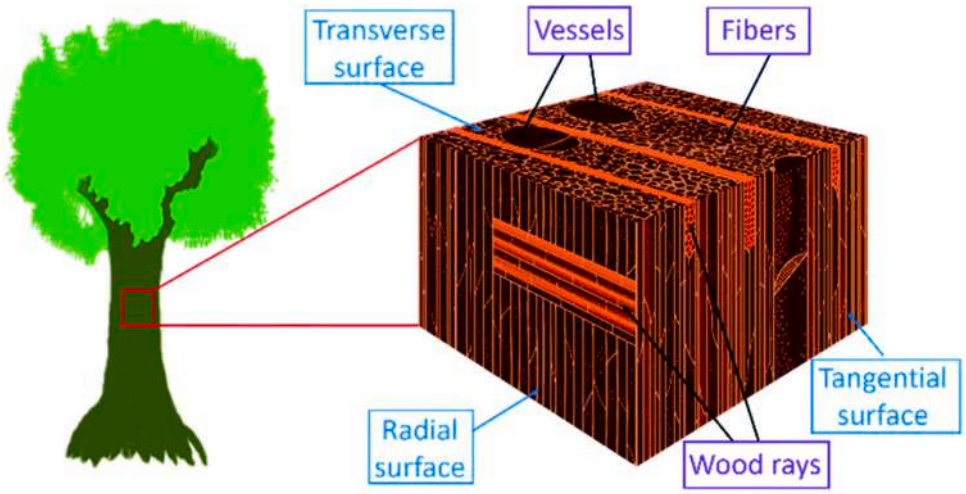

Fig. 1. Microstructure of hardwoods with vessels and fiber cells, as well as ray cells. In hardwoods, the typical fiber cell diameter is about 20 μm (fiber length: about 1 mm). Reproduced from [11] under CC-BY-NC license.

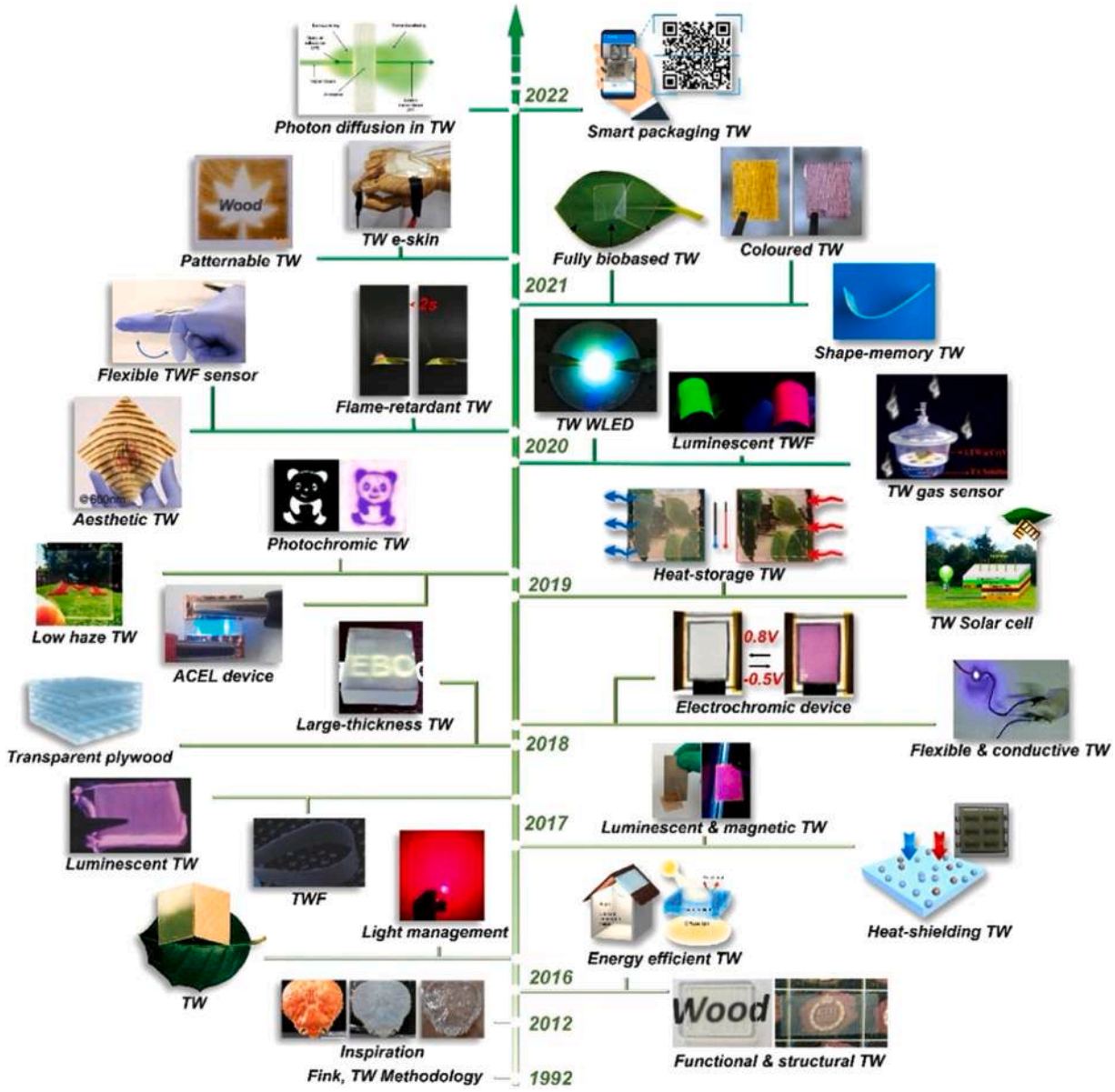

Fig. 2. Summary of the inspiration and research progress of transparent wood materials (TWF= Transparent wood films). Reproduced with permission [3]. Copyright 2023, Elsevier.

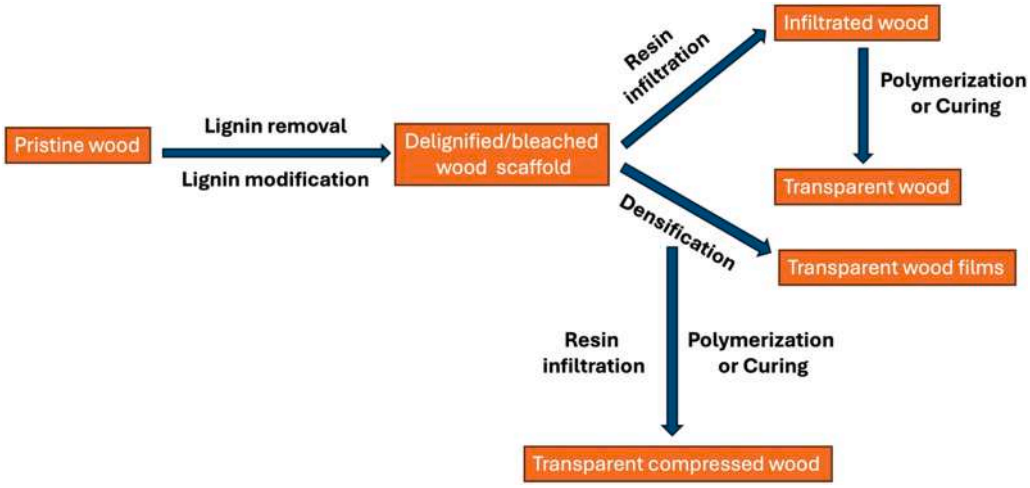

Fig. 3. Schematized paths for the obtainment of transparent wood.

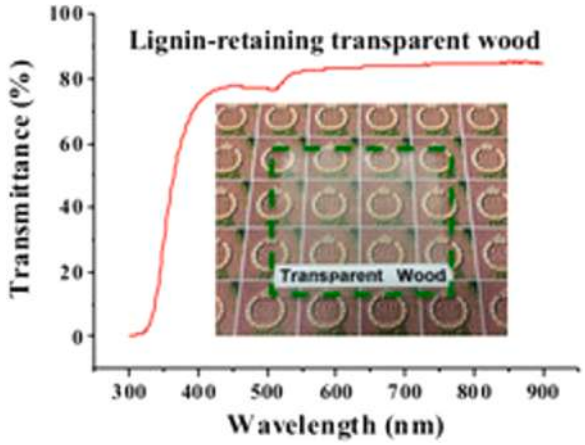

Fig. 4. Optical transmittance of TW (lignin content beyond 80%). Adapted from [25] under CC-BY-NC License.

Table 1
Main refractive index-matched polymers, suitable for obtaining transparent woods by infiltration and subsequent polymerization/curing.

Type of wood	Infiltrated polymer	Refractive index of the polymer	Ref.
basswood	epoxy resin	1.50	[4]
balsa wood	poly(methyl methacrylate)	1.49	[35]
basswood	poly(vinyl pyrrolidone)	1.53	[51]
natural wood	polyimide	1.45	[52]
balsa wood	thiol-ene thermosets	1.56	[40]
balsa wood	vitrimers	1.53	[53]
balsa wood	poly(limonene acrylate)	1.52	[46]
balsa wood	melamine-formaldehyde	1.50	[54]
balsa wood	poly(vinyl alcohol)	1.47	[55]
balsa wood	poly(N-isopropylacrylamide)	1.49*	[56]

* from [57]

sulfides.

Besides, it is essential to manipulate the wood structure by accurately controlling its nanopores in the cell walls through these chemical treatments, tuning, at the same time, the process conditions (namely: the concentration of the employed solutions, the treatment duration, the pH and temperature ranges) [14–17]. Further, during the above-mentioned treatments, it is very important to prevent the occurrence of dehydration

Table 2
Comparison of transparent wood strengths with other conventional materials.

Compared material	Main strengths of transparent wood
Glass	• Higher Lightness • Higher Toughness • Higher Impact resistance • Lower energy consumption for processing • Lower thermal conductivity • Lower carbon footprint
Fossil-based plastics	• Higher mechanical properties • Lower carbon footprint • Wider geographical availability
Wood	• Higher optical transmittance • Higher mechanical properties • Higher resistance to environmental conditions • Tailorable functional properties
Metal alloys	• Higher Lightness • Higher optical transmittance • Lower energy consumption for processing • No propensity to corrosion • Lower thermal conductivity • Lower surface hardness • Lower carbon footprint • Wider geographical availability
Ceramics	• Higher Lightness • Higher Toughness • Lower energy consumption for processing • Higher impact resistance • Lower thermal conductivity • Lower carbon footprint

reactions of wood polysaccharides, also avoiding the formation of undesirable chemical groups: indeed, these phenomena can impact the quality and the overall mechanical behavior of the final material [13].

The third effective method for removing lignin from wood takes advantage of the use of such bleaching agents as sodium chlorite [18] or hydrogen peroxide [19], which account for almost complete removal of the component (the residual lignin is as low as 0.8 and 0.6%, respectively). It is worth highlighting that, irrespective of the employed method, the thickness of the pristine wood is an important issue, as, usually, all the described processes are more effective when carried out on thin wood samples [20–24].

Aiming to limit both the decrease in bulk wood structural features due to the lignin removal and the production of toxic chemical by-products (such as methyl mercaptan, hydrogen and dimethyl sulfide, and chlorine), Li and co-workers [25] demonstrated the possibility of obtaining transparent wood without removing its lignin but changing the structure of the latter. In particular, the use of a bleaching solution

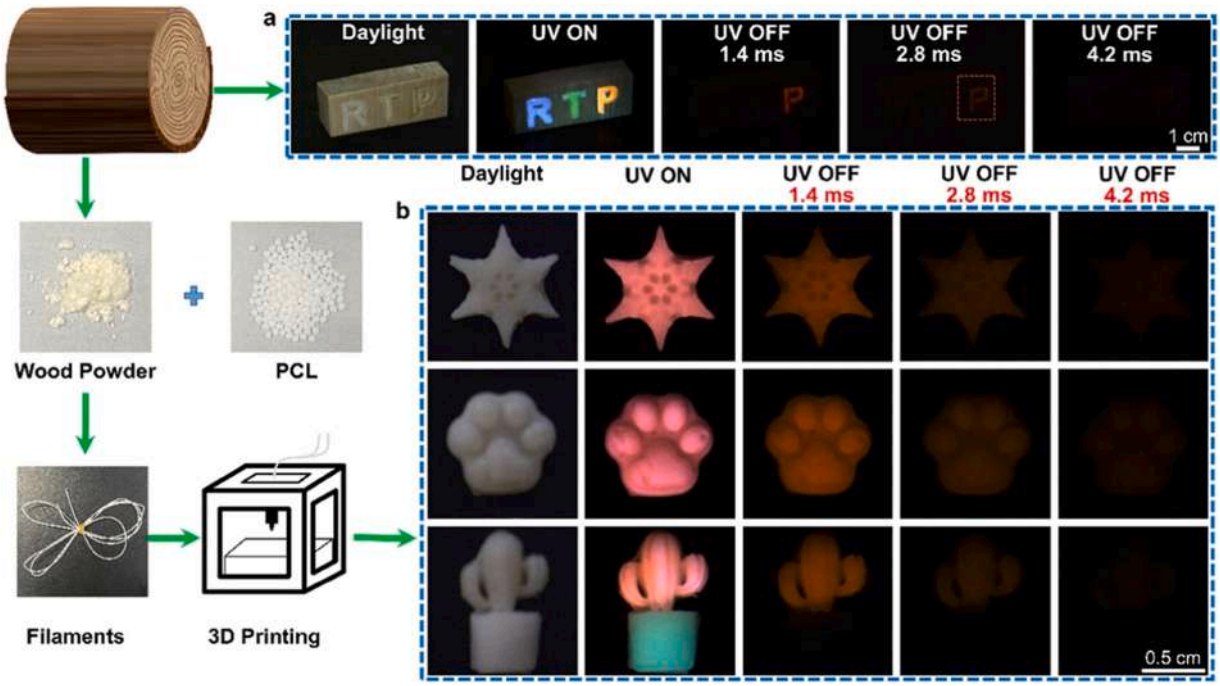

Fig. 5. Applications of wood-based room-temperature phosphorescent materials. Photographs of wood-based data anticounterfeiting devices using wood panels as the substrate material before and after photoactivation (a). Photographs of 3D-printed (with polycaprolactone, PCL) wood-based anticounterfeiting devices before and after photoactivation (b). Reproduced with permission [65]. Copyright 2024, American Chemical Society.

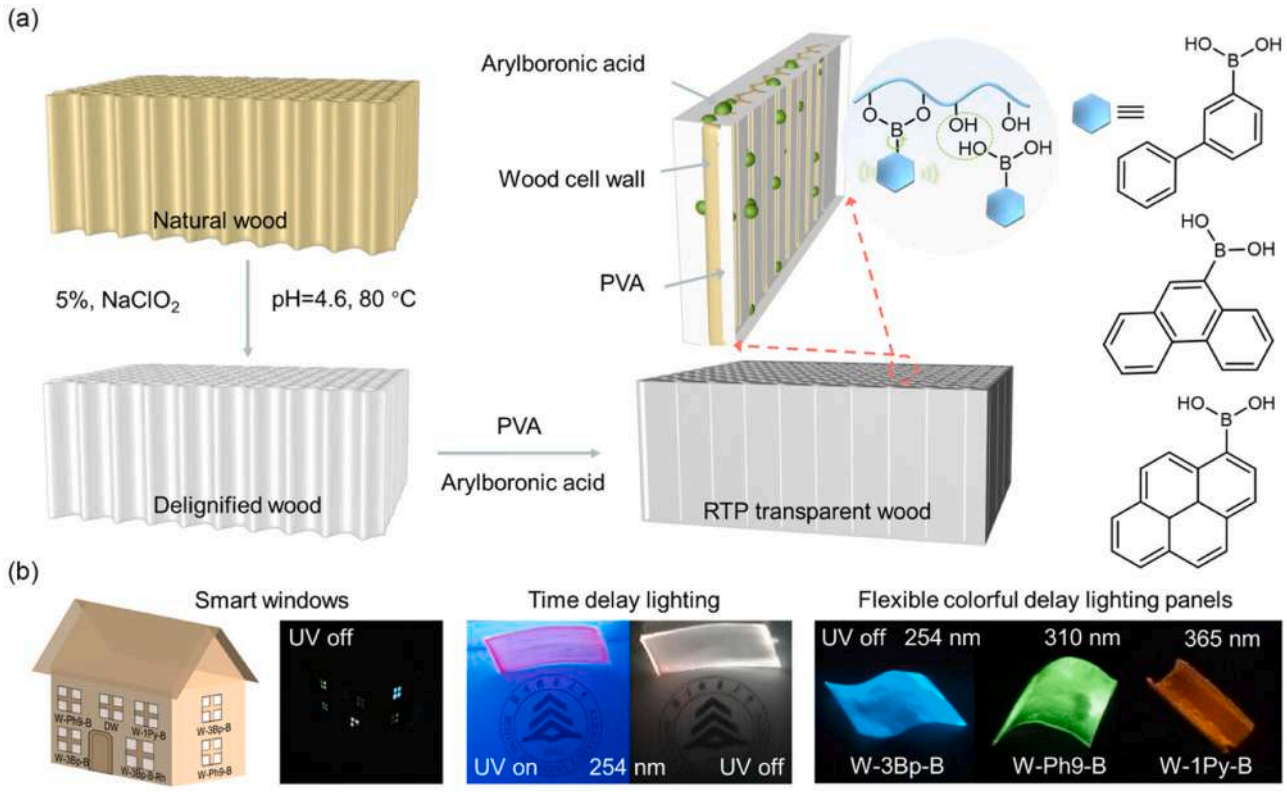

Fig. 6. Scheme of the room-temperature phosphorescent transparent wood. Its preparation, and chemical structures of different arylboronic acids employed (**a**). Photographs of multicolor smart afterglow windows, time delay lighting panels with white afterglow, and flexible colorful delay lighting panels made of various room-temperature phosphorescent transparent woods. Reprinted from [66] under CC-BY 4.0 license.

(Na_2SO_3/NaOH/H_2O_2) for removing only the chromophore groups allowed for retaining the lignin content beyond 80% and obtaining a stronger wood template compared to the delignified counterpart. Upon infiltration with methyl methacrylate and its subsequent in situ polymerization, the transmittance of the resulting TW was around 83%, as shown in Fig. 4.

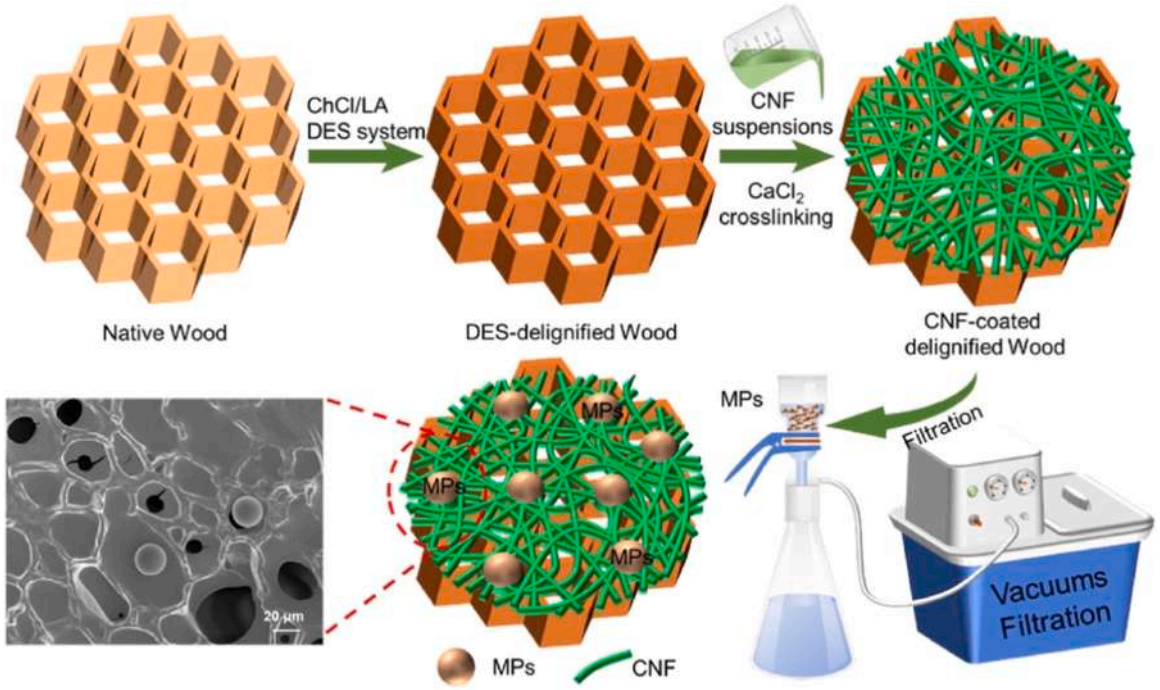

Fig. 7. Scheme of the preparation of cellulose nanofiber-coated, delignified wood for the removal of microplastics. Legend: ChCl= Choline Chloride; LA= lactic acid; DES= Deep eutectic solvent; CNF= Cellulose nanofibers; MPs= polystyrene microplastics. Reproduced with permission [71]. Copyright 2024, Elsevier.

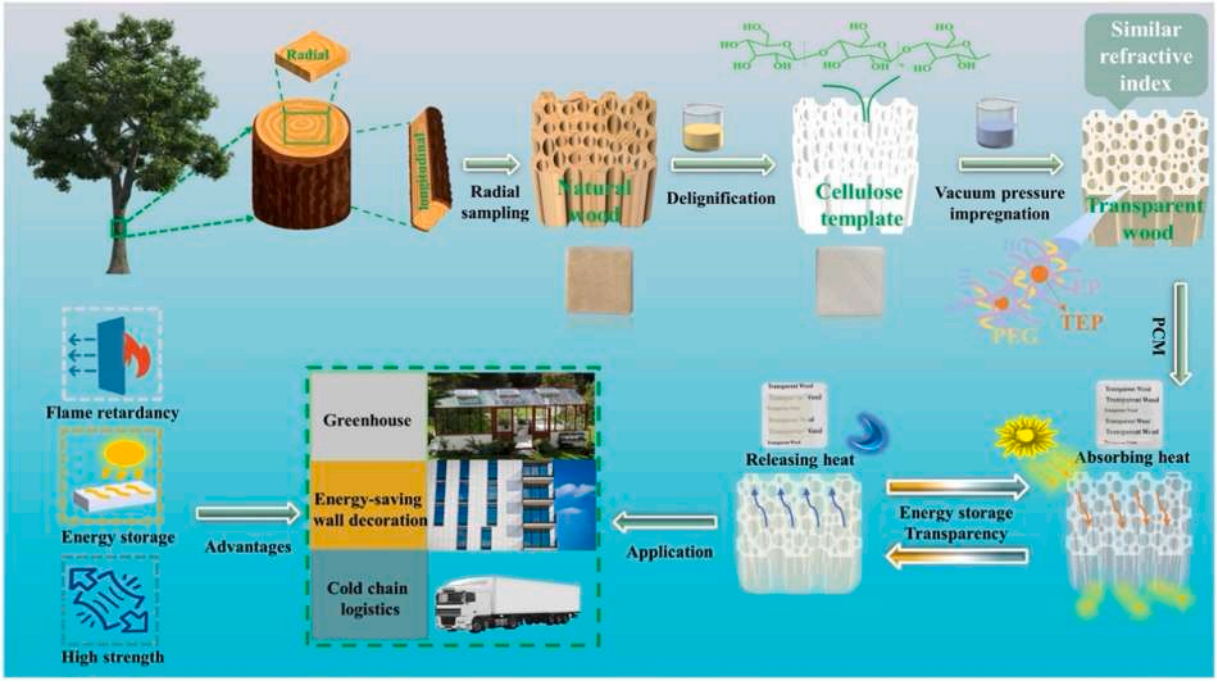

Fig. 8. Scheme of the preparation of multifunctional transparent woods, integrating flame retardance, good mechanical behavior, and phase change energy storage features. Legend: PCM= phase change material; TEP= triethyl phosphate. Reproduced with permission [72]. Copyright 2024, Elsevier.

After lignin removal, two possible pathways can be followed to obtain the final TW showing the envisaged properties, namely: the direct cell wall densification or the infiltration of delignified wood by a resin and its subsequent polymerization/curing. The first approach is suitable for obtaining transparent wood thin films, which exhibit high transparency and even flexibility, according to the employed type of pristine wood. For this purpose, the delignified wood template is simply compressed using external pressure, aiming at making the radial thickness of the wood template smaller; as a result, a more uniform and compact wood template with a cell wall skeleton is produced.

This dense wood template can be used as it is (i.e., as a thin transparent wood film), or can be further vacuum infiltrated by a suitable polymer resin, thus obtaining transparent compressed wood [26].

The second approach, which is the most utilized, exploits the infiltration of the delignified wood with a suitable resin (i.e., bearing a refractive index that perfectly matches that of delignified wood, which is

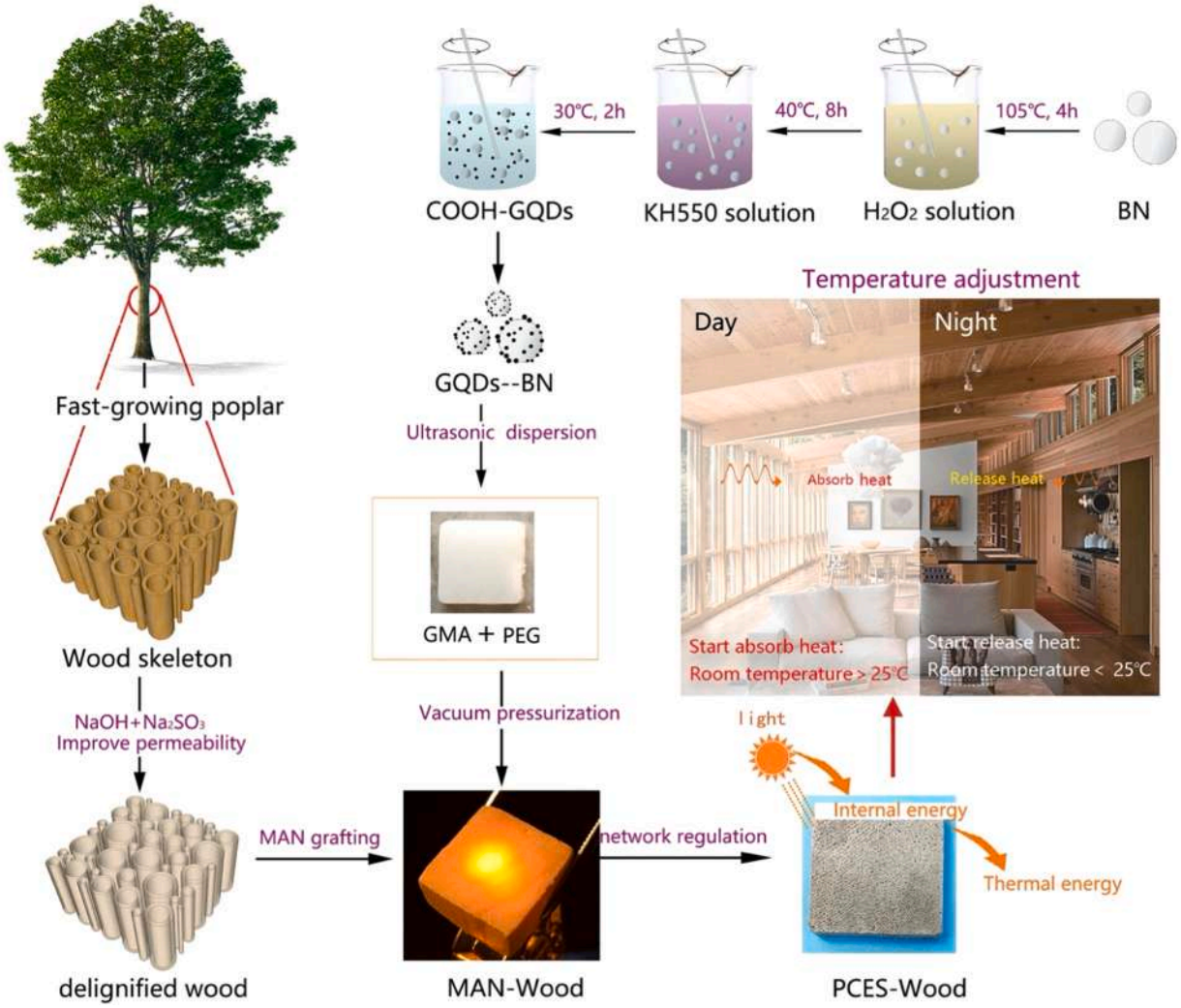

Fig. 9. Scheme of the preparation of phase change energy storage wood. Legend: BN= Boron nitride; COOH= oxalic acid; GMA= glycidyl methacrylate; GQDs= graphene quantum dots; KH550= γ-aminopropyltriethoxysilane; MAN: maleic anhydride; PCES= phase change energy storage; PEG= poly(ethylene glycol). Reproduced with permission [73]. Copyright 2024, Elsevier.

often around 1.5) and the successive polymerization/curing [27–31]. To speed up the process and save time, infiltration may be carried out under vacuum; both thermal and photoinduced polymerization strategies can be employed for the successive step [3,32–34].

The first pioneering works paving the way toward highly transparent, thermally insulating, and tough infiltrated transparent woods come from Hu's and Berglund's groups, who respectively succeeded in obtaining transparent epoxy-backfilled basswood [4] and poly(methyl methacrylate)-infiltrated balsa wood [35].

Since then, the seeking for other refractive index-matched polymers, suitable for obtaining TW composites, has grown remarkably [36–38]. Table 1 collects the main research outcomes achieved so far.

However, both mechanical and optical features of the resulting TW can be worsened due to shrinking phenomena, which the infiltrated polymers may undergo during their polymerization/curing: consequently, cracks or defects alongside the interface between the bleached wood scaffold and the infiltrated resin may originate [39]. Some strategies have been proposed to overcome these issues. They include: i) the use of refractive index-matched resins that exhibit a low shrinkage upon curing [40–45], and ii) the modification, usually by esterification, of the hydroxyl-rich inner surfaces of the channels in the bleached wood scaffold to improve the compatibility between this latter and the infiltrated resin [46–48]. This way, it is possible to obtain defect-free, highly transparent materials combining lightness, toughness, and outstanding mechanical properties [3,49,50].

2. Recent advances in transparent wood applications

The world that revolves around transparent wood is changing very rapidly, achieving new performance targets that were unpredictable a few years ago and envisaging new potential applications of this up-to-date material. Indeed, as an innovative transparent material, transparent wood exhibits not only outstanding optical features but also exceptional mechanical behavior (in terms of strength, toughness, and impact resistance), which plays a key role in providing the viability and safety of its uses in the building sector [58]. Besides, its high optical transmittance in a wide wavelength range and tunable haze make transparent wood an appealing alternative to such conventional materials as glass for architectural uses. In addition, the structure and morphology of TW allow for its use as a functional material, making it suitable to replace conventional materials (i.e., fossil-derived plastics) in advanced sectors including ultrafiltration membranes, solar cells, superflexible electronic devices, thermal insulators, energy storage materials, and phase-change materials, among others [59–62].

Table 2 lists the main strengths of transparent wood over other conventional materials.

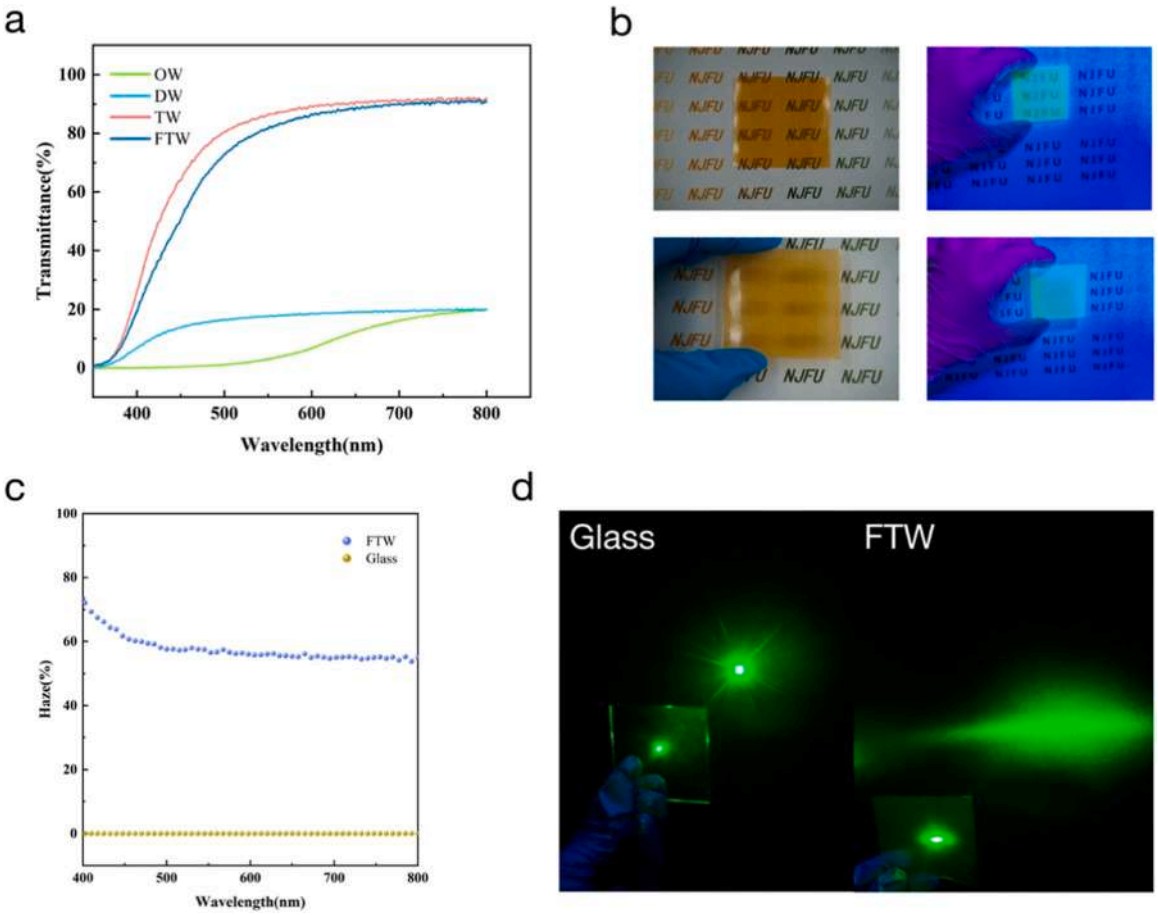

Fig. 10. Transparency and haze display of fluorescent transparent wood (FTW); transmittance curves of Canadian white maple (OW), delignified wood template (DW), epoxy-infiltrated transparent wood (TW), and FTW (a); optical transmittance and haze performance of FTW under sunlight and 395 nm UV lamp irradiation (b); haze curves of FTW and glass (c); comparison of light scattering ability between FTW and glass (d). Reprinted from [75] under CC BY-NC-ND 4.0 License.

The present paragraph will summarize the latest research outcomes achieved.

Du and co-workers [63] developed an optically switchable and mechanically resistant perovskite-coated thermochromic transparent wood (derived from delignified balsa wood that was subsequently infiltrated with poly(methyl methacrylate)) to be employed as an effective smart window. This latter exhibited not only enhanced mechanical behavior (i.e., enhanced tensile and flexural strength – about 71 and 93 MPa, respectively) but also a significant solar modulation capability and an optical transmittance as high as 78%, suitable for the design of novel glazing materials having enhanced thermal regulation and energy-saving potential.

Zhang and co-workers [64] designed and produced an all-wood-based flexible electronic device, derived from the self-densification of balsa wood that was converted into self-densification-wood-derived-paper, operating at room temperature, and exploiting the occurrence of capillary forces simply generated by water evaporation. The obtained material showed a suitable optical transmittance (beyond 40%), a very high haze (around 93% at 800 nm wavelength), as well as an outstanding tensile strength (about 230 MPa) in the fiber direction, much higher than pristine balsa wood and standard cellulose paper. Besides, thanks to its high wettability, the self-densification-wood-derived-paper was appropriate for being written with a conductive carbon ink (obtained from the carbonization of balsa wood) to get customized patterns: this way it was possible to produce cheap and biodegradable flexible sensors, suitable for stably monitoring finger movements.

The possibility of using delignified balsa wood nanopores as a confinement template for activating the room-temperature phosphorescence of organic dyes was thoroughly demonstrated by Zhu and co-workers [65]. More specifically, the delignified template gave rise to a three-dimensional nanostructure bearing stable H-bonds and a stiff network, which accounted for the suppression of the nonradiative transition of the selected organic dye molecules (namely, gallic and ellagic acid, quercetin, and vanillin), facilitating the room-temperature phosphorescence emission. Further, the authors demonstrated the appropriateness of the wood-based organic room-temperature phosphorescent composite materials for the fabrication of 3D-printed high-precision devices, potentially suitable for data encryption and anticounterfeiting (Fig. 5).

In a further research effort, Lü and co-workers [66] exploited delignified balsa wood for preparing colorful room-temperature phosphorescence materials that may find potential applications as afterglow windows, anticounterfeiting labels, and time delay lightings. In particular, after delignification in an acidic aqueous sodium chlorite solution, the resulting wood scaffold was infiltrated with poly(vinyl alcohol) solutions containing arylboronic acids with different π conjugations (Fig. 6). The concurrent stiffening action provided by the formed H-bonds and the B—O covalent bonds ensured an ultralong lifetime of 2.13 s and a highly stable room-temperature phosphorescence emission, together with 90% optical transmittance and high tensile strength (about 150 MPa). This approach was further implemented, using rare-earth strontium aluminum oxide nanoparticles dispersed in the monomer (methyl acrylate) employed for the infiltration of basswood slabs [67], or vacuum-impregnating basswood slices with a UV-curable resin – namely, a mixture of poly(urethane acrylate), poly(ester

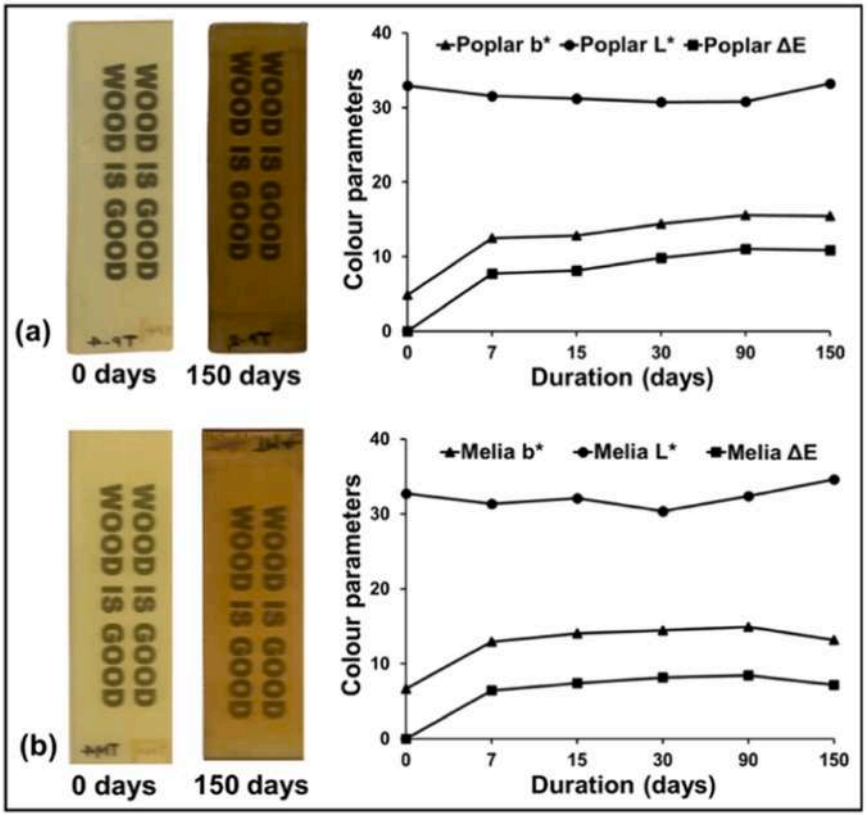

Fig. 11. Typical pictures showing color changes in unexposed (i.e., 0 days) and 150 days exposed woods: transparent wood composite from poplar wood (a) and melia wood (b). Respective variations in CIELab color parameters (namely, lightness L*, chromaticity parameter b*, and total color change ΔE) are also presented. Reproduced with permission [76]. Copyright 2024, Elsevier.

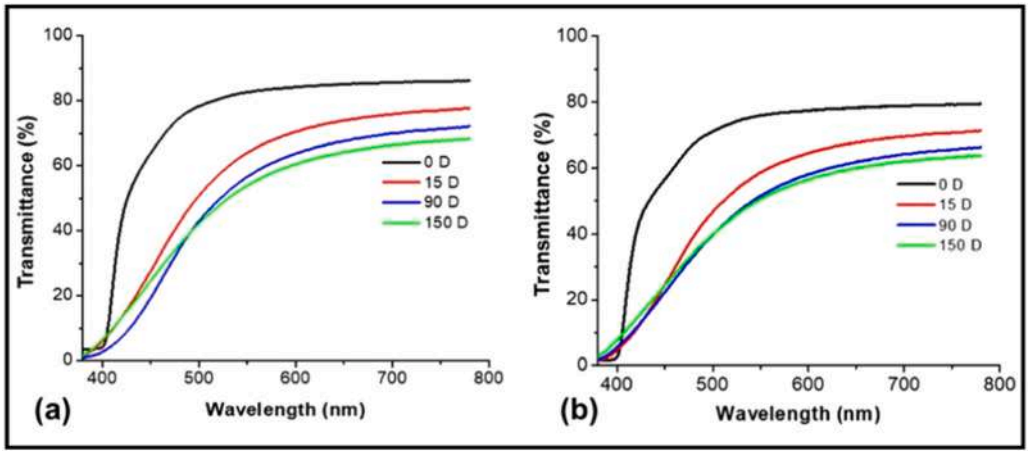

Fig. 12. Effect of natural weathering on the optical transmittance spectra of TW composites derived from poplar wood (a), and melia wood (b). Legend: D= days of exposure to solar radiation. Adapted with permission [76]. Copyright 2024, Elsevier.

acrylate), epoxy acrylate, and acrylamide morpholine – containing a reactive red X-3B dye [68].

Within the goals of sustainability and environmental protection, one of the current most challenging and impacting issues refers to the management and removal of microplastics from the aquatic environment, as they represent a severe threat not only to aquatic organisms but also to human health [69,70]. In this context, Liu and co-workers [71] assessed the possibility of using cellulose nanofiber-coated delignified balsa wood as a green, effective, renewable filter for the removal of microplastics. To this aim, balsa wood chips underwent delignification through three different methods (i.e., employing a deep eutectic solvent made of lactic acid and choline chloride, using $NaClO_2$, or a solution of Na_2SO_3 and NaOH). The mechanical properties and the porosity of the delignified balsa wood were optimized. Then, the delignified wood was dipped in suspensions of cellulose nanofibers at different loadings (namely, 0.25, 0.50, 0.75, and 1.0 wt%) and finally crosslinked with $CaCl_2$ solutions (Fig. 7). The formation of a film of cellulose nanofibers on the delignified wood surface was responsible for the high observed efficiency in filtering and removing polystyrene microplastics: in particular, when the average particle size of these microplastics was 25 μm, the use of 10 mm thick delignified wood, coated in a 0.5 wt% cellulose nanofiber suspension and subsequently crosslinked in 1 mol/l

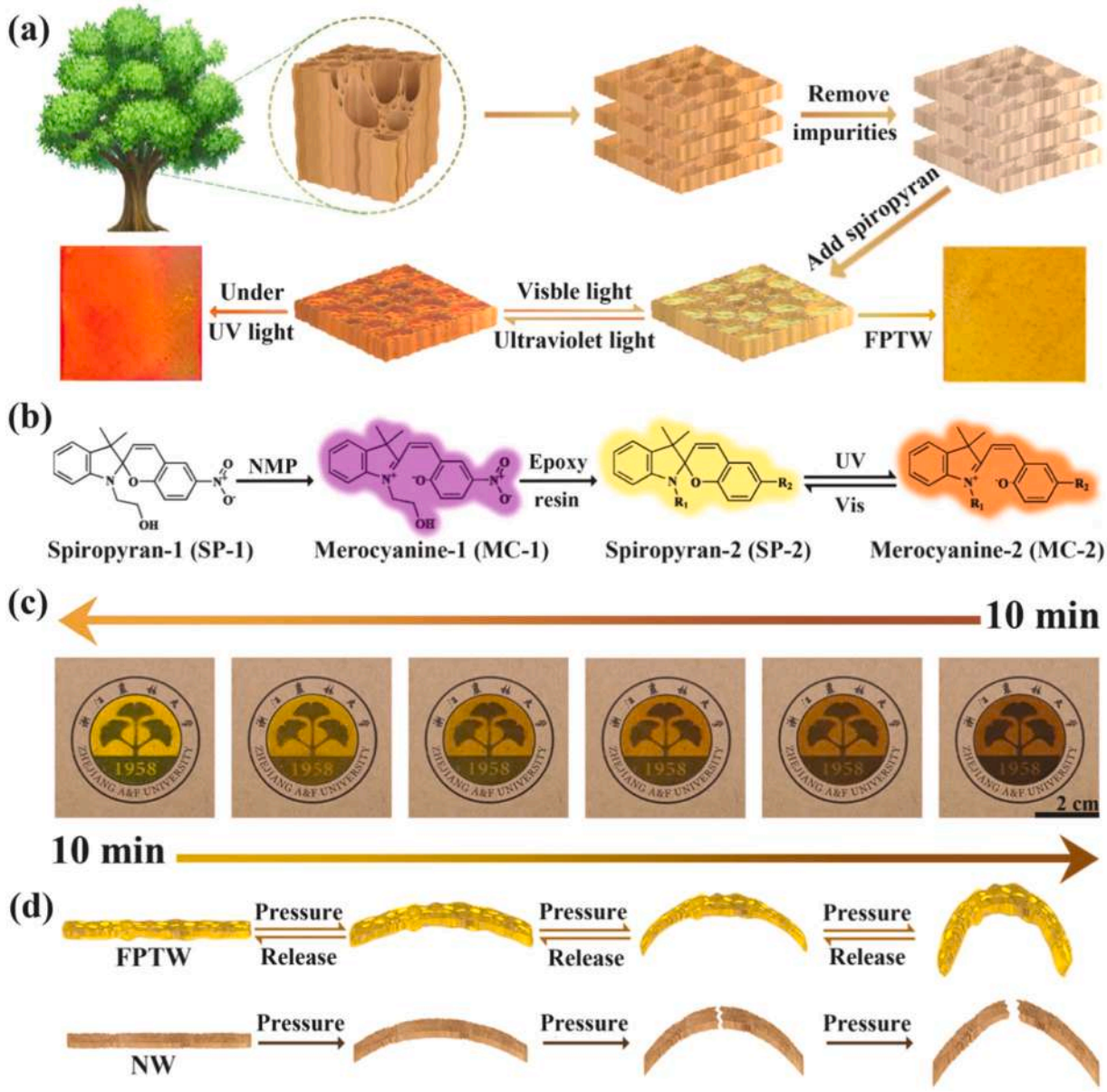

Fig. 13. Preparation procedure of flexible photoresponsive transparent wood (FPTW) (a); Structural change process of spiropyran (b); Discoloration of the flexible photoresponsive transparent wood upon irradiation of UV and visible light (c). The difference in flexibility between FPTW and the pristine balsa wood (NW) (d). Reproduced with permission [77]. Copyright 2024, Elsevier.

$CaCl_2$ solution, accounted for a removal efficiency as high as 96% and a high filtration rate (measured flux: 1146 L/m^2·h).

At present, the multifunctionality of transparent wood is emerging as a demanding topic, aiming to widen its potential applications. This challenge was taken up by Li et al. [72], who succeeded in producing bio-based transparent wood exhibiting flame retardance, mechanical strength, and phase change energy storage properties. To this aim, balsa wood was delignified with sodium chlorite and subsequently impregnated under vacuum with a mixture of epoxy resin, poly(ethylene glycol), and triethyl phosphate. A general scheme of the adopted procedure is presented in Fig. 8. The obtained wood self-extinguished in flammability tests (thanks to the presence of triethyl phosphate), and exhibited the envisaged phase change energy storage features (provided by the embedded poly(ethylene glycol)), keeping high optical transparency (about 95%), high tensile strength (around 2 MPa), and impact resistance (around 8 kJ/m^2).

A similar approach was exploited by Li and co-workers [73], who obtained phase change energy storage woods exhibiting high photo-thermal conversion effectiveness through delignification of balsa wood and its subsequent impregnation with a poly(ethylene glycol)-based composite containing graphene quantum dot-grafted boron nitride as a thermal conductive filler. The overall process is schematized in Fig. 9. Even 6 wt% of graphene quantum dot-grafted boron nitride guaranteed high optical transparency and thermal conductivity (around 0.392 W/(m·K); besides, for the same system, solidification and melting enthalpies achieved about 114 and 115 J/g, hence indicating a high latent heat value. Finally, the temperature of phase transformation was in the range between 20.3 and 36.3°C, i.e., compatible with that of the human body.

A nice example of the use of functional transparent wood for smart window applications was proposed by Zhou and co-workers [74], who prepared epoxy-based balsa wood TW composites containing carbon quantum dots (derived from chitosan or *o*-phenylenediamine) showing yellow or red fluorescence, respectively. The so-obtained materials exhibited a good optical transmittance of around 70%, a high UV blocking rate (about 80% for the yellow and 89% for the red

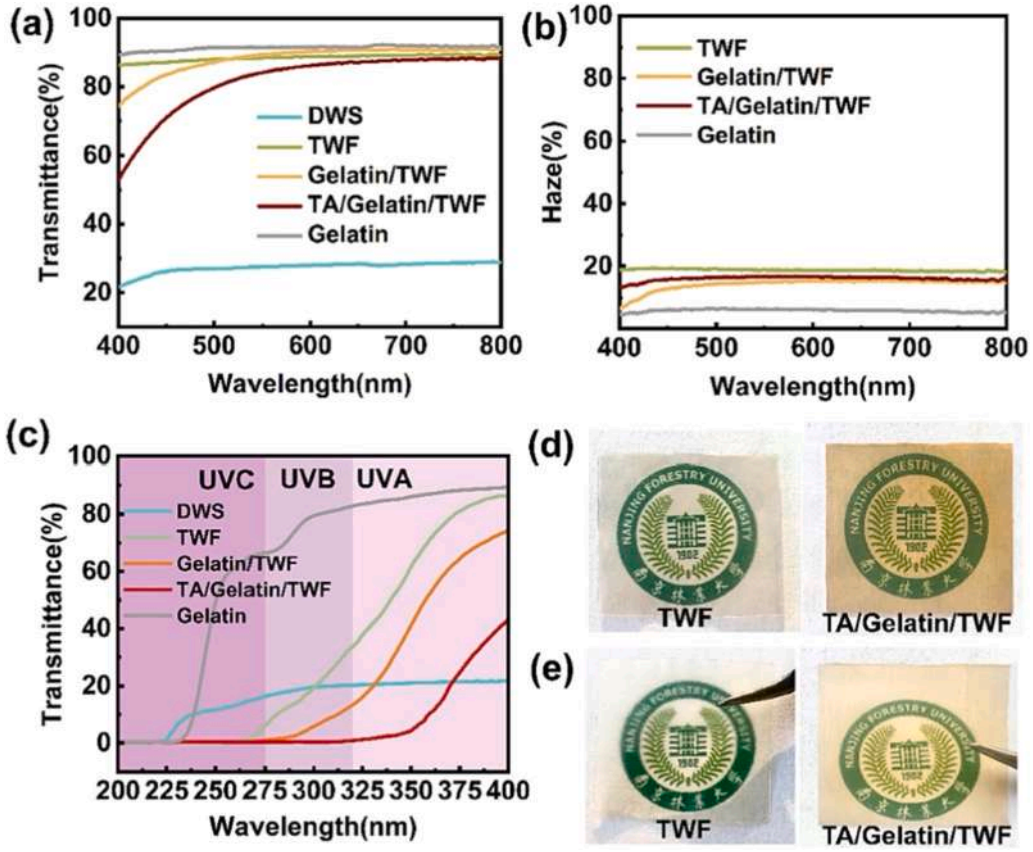

Fig. 14. Optical transmittance (a) and haze (b) of the wood samples (DWS= delignified and densified wood sample; TA= Tannic acid; TWF= transparent wood film; TA/Gelatin/TWF= fully biobased TW composite film). UV transmittance curves of the wood samples (c). Typical images of transparent wood film and fully biobased TW composite film (d). Photographs of transparent wood film and fully biobased TW composite film taken with an angle of 45° to the paper (e). Reproduced with permission [78]. Copyright 2024, Elsevier.

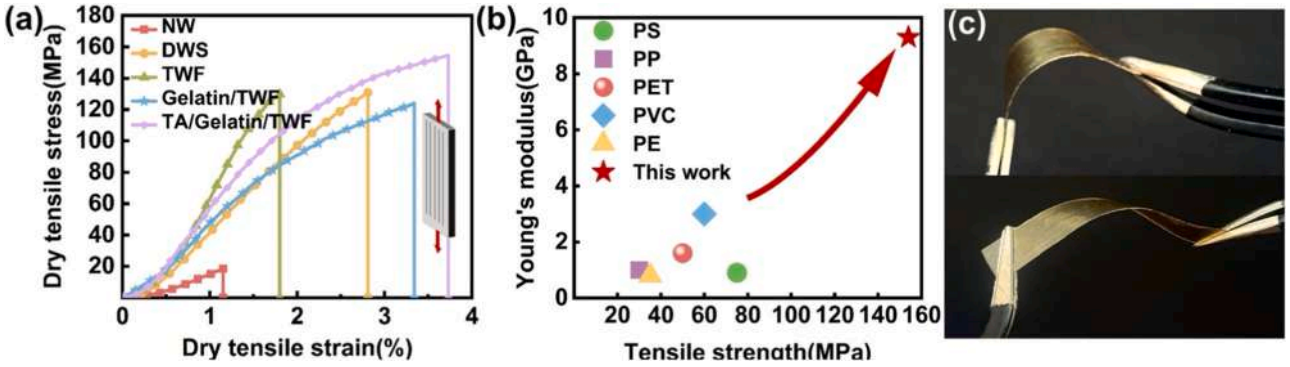

Fig. 15. Tensile performance of the investigated wood samples (NW= pristine balsa wood; DWS= delignified and densified wood sample; TA= tannic acid; TWF= transparent wood film; Gelatin/TWF= gelatin-grafted TW film; TA/Gelatin/TWF= fully biobased TW composite film). Typical tensile stress-strain curves for the wood samples in dry state (a). Comparison of tensile strength and Young's modulus of the developed fully biobased TW composite films with other typical plastics (b). Photographs showing the flexibility of fully biobased TW composite films along fiber direction (c). Reprinted with permission [78]. Copyright 2024, Elsevier.

fluorescence TW), excellent water resistance, high durability, and thermal insulation.

In a further research effort [75], delignified Canadian white maple template was infiltrated with an epoxy resin embedding carbon quantum dots and cured at room temperature.

The so-obtained composite films (0.5 mm thickness) exhibited high optical transmittance (about 91%), water absorption stability (weight gain rate below 9%), good longitudinal tensile strength (about 140 MPa), and UV-shielding properties (Fig. 10).

Bisht and co-workers [76] assessed the effect of environmental conditions (in particular, of natural weathering) on the properties of TW composites (derived from delignified melia and poplar woods, further infiltrated with an epoxy resin), considering possible changes in color, optical transmittance, visual appearance, and chemical structure. Solar radiation was responsible for photo-oxidative degradation phenomena that occurred soon after the start of the tests. As shown in Figs. 11 and 12, both color darkening and optical transmittance losses (by about 34%) occurred. Conversely, these photo-oxidation phenomena were quite significantly reduced through the incorporation (at 1.75 wt% loading) of a benzotriazole-derived UV absorber in the formulation of

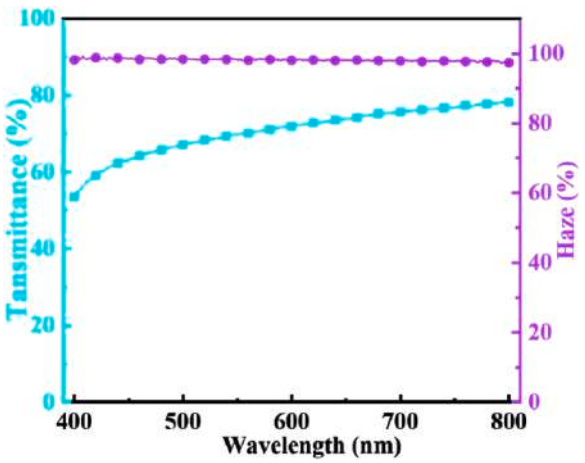

Fig. 16. Optical transmittance and haze of the prepared transparent wood composites. Adapted from [79], under CC-BY License.

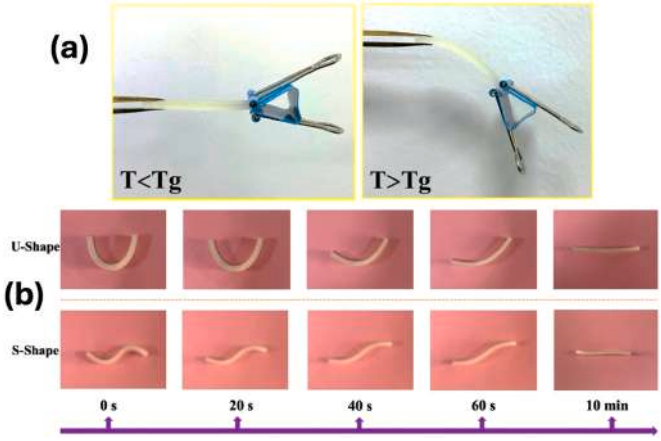

Fig. 17. Stiffness tunability (a) and shape-recovery capability (b) of the transparent wood composites. Adapted from [79], under CC-BY License.

the infiltrated epoxy resin, limiting the optical transmittance loss to about 15%.

A flexible reversibly photoresponsive transparent wood, suitable for the design of sensors and electronic devices, was recently proposed by Tian and co-workers [77]. To this aim, a delignified balsa wood template was infiltrated with a flexible epoxy resin (namely, Hasuncast 3016LV from Huasheng Tongchuang Technology Co., China) and a spiropyran solution, as schematized in Fig. 13. As a photosensitive dye, spiropyran was able to break the carbon-oxygen bond upon UV irradiation, hence promoting a remarkable color change.

Zhou et al. [78] thoroughly investigated the performance of a fully biobased, biodegradable, and flexible transparent wood, suitable for replacing traditional plastics in flexible electronics, anti-counterfeiting, and UV protection applications. To this aim, gelatin was grafted onto delignified balsa wood and subsequently crosslinked with tannic acid: the so-obtained films (thickness of about 100 μm) combined high tensile strength (around 155 MPa) and optical transmittance (86.2% at 600 nm), low haze and UV blocking effectiveness (Figs. 14 and 15), as well as remarkable stability in water.

Liu and co-workers [79] succeeded in preparing transparent wood (from balsa wood) with soft-/hard-switchable and shape recovery capabilities by infiltrating an epoxy-based polymer (whose T_g – glass transition temperature – was around 0°C) into the delignified wood template. The resulting material showed high optical transparency and haze (70 and 95%, respectively, for TW samples 2.0 mm thick, Fig. 16), tunable stiffness, and shape-recovery capability (Fig. 17).

One very recent application of transparent wood refers to the design of effective electromagnetic wave absorption materials characterized by small thickness and wide effective absorption bandwidth, which may contribute to alleviating electromagnetic pollution. In this context, Zhang and co-workers [80] produced a highly transparent wood composite (optical transmittance beyond 83%) derived from delignified balsa wood. This latter was infiltrated with refractive-index-matched partially polymerized acrylamide, in the presence of very small amounts of nanofiller, namely: Ag nanowires (0.1 wt%), carbon nanotubes (0.1 wt%), and reduced graphene oxide (0.1 wt%). The resulting TW composite exhibited a very low thermal conductivity (around 0.45 W/(mK)) and a remarkable electromagnetic absorption performance. In particular, as shown in Fig. 18 for 2.0 mm thick samples, the effective absorption bandwidth achieved 9.5 GHz, almost seizing the whole X (8.2–12.4 GHz) and Ku (12.4–18 GHz) bands.

Finally, Table 3 collects the main properties and performance indicators of the recently developed transparent wood materials summarized in the present paragraph.

3. Conclusions and perspectives

The idea of creating transparent wood was born to study the anatomical characteristics of the wood itself [3,5]. However, the growing awareness of energy saving, the need to create a virtuous system based on the recyclability of materials and the circular economy, and the urgent demand for limiting global warming have recently proposed TW as one of the possible answers to these problems. The possibility of creating windows that would allow light to pass through but which, at the same time, would act as a thermal barrier, immediately appeared as an obvious but essential application of TW. In addition, the advantage represented by the enhanced impact resistance properties compared to traditional glass has made it a potential replacement for both practical and commercial interest.

On the other hand, even the material obtained when the internal structure of the wood remains visible soon aroused the economic interest of furniture manufacturers, who immediately appreciated its aesthetic characteristics.

At present, the growing interest in this material is beginning to involve more advanced sectors, in particular electronics [14,15]: indeed, TW is proving to be an appealing material in the fields of solar cells, luminescent devices, photonics, and LEDs, among others.

However, it seems necessary to think out of the box. Indeed, as fascinating as it is, the current configuration of the TW can limit its usage and performance.

For example, the use of sawdust instead of wooden slabs could make the processes of removing or modifying lignin more effective. Moreover, the material obtained, not being characterized by the presence of channels oriented along preferential directions, unlike the current one, would be isotropic.

The use of already purified cellulose or lignin would allow for the exploitation of the current paper supply chain, thus eliminating both the process of removal/modification of lignin and that of infiltration of monomers and resins inside the wood channels.

In addition, biomass with a high growth rate (e.g., bamboo, grasses), which are more efficient for CO_2 sequestration and whose harvesting does not imply deforestation, should be preferred.

A huge amount of work must also be devoted to the organic polymer. Although there is a wide availability of structural properties, from a functional point of view the aspects to be considered make the choice more complex and even more challenging. The first problem is related to the infiltration phase: the monomer or resin to be infiltrated must have a viscosity that is not too high.

Then, the compatibility between the inner walls of the wood channels and the infiltration system is not always optimal. It is therefore necessary to find low-viscosity alternatives, maybe using reactive

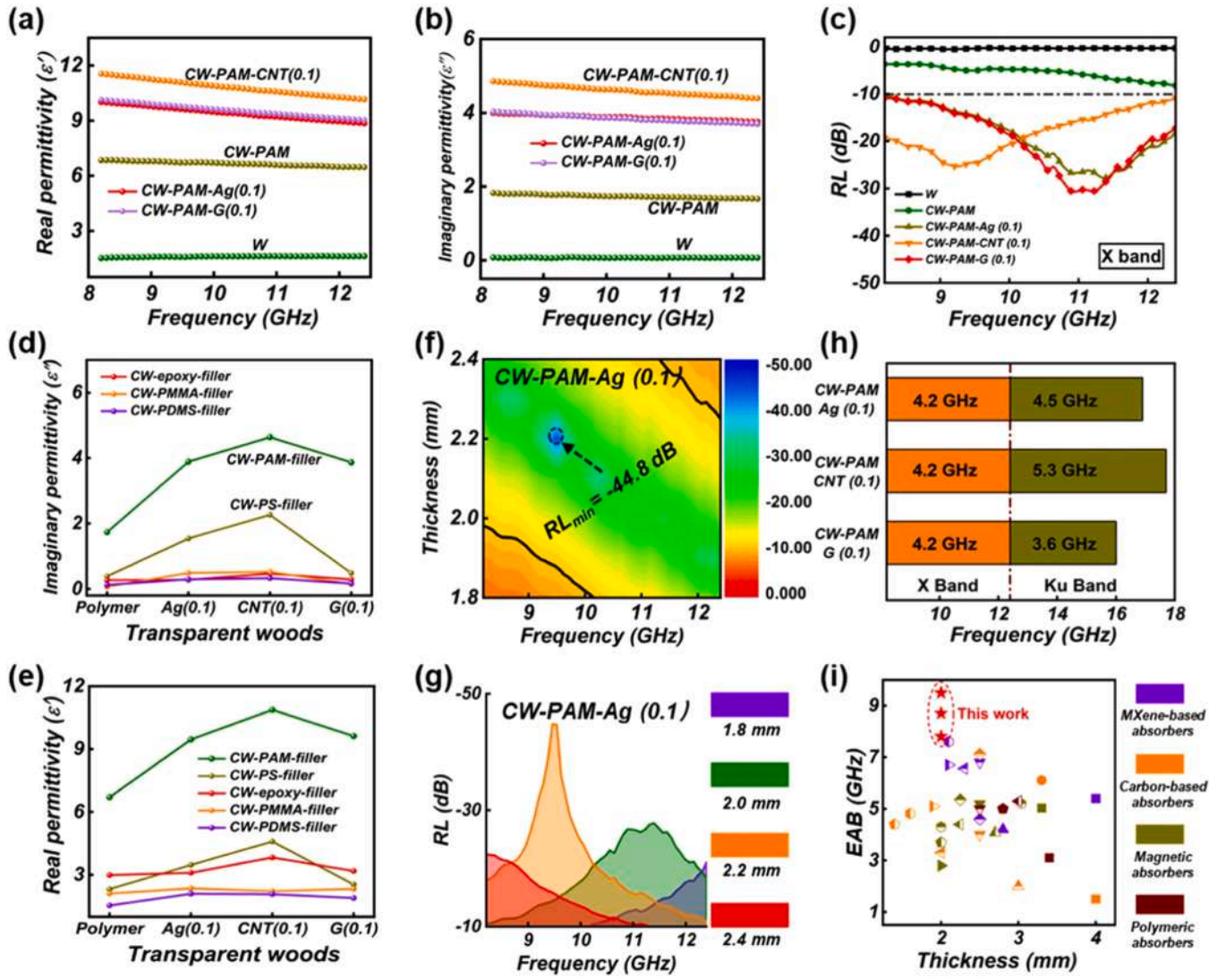

Fig. 18. Electromagnetic wave absorption properties of the investigated transparent wood composites. Real permittivity (a); imaginary permittivity (b), reflection loss of pristine wood and delignified- transparent wood composites (CW-PAM= TW composite infiltrated with unfilled polyacrylamide; CW-PAM-CNT(0.1)= TW composite infiltrated with polyacrylamide filled with 0.1 wt% of carbon nanotubes; CW-PAM-Ag(0.1)= TW composite infiltrated with polyacrylamide filled with 0.1 wt% of silver nanowires; CW-PAM-G(0.1)= TW composite infiltrated with polyacrylamide filled with 0.1 wt% of reduced graphene oxide) at the frequency of 8.2–12.4 GHz (X band) (c). Comparison of the average real permittivity (d) and imaginary permittivity (e) of diverse transparent woods (CW-*XX*-filler, where *XX* stands for polyacrylamide – PAM, polystyrene – PS, epoxy resin – epoxy, poly(methyl methacrylate) – PMMA, poly(dimethyl siloxane) – PDMS) in X band. Reflection loss (RL) of CW-PAM-Ag(0.1) transparent wood in X band with various thicknesses (f, g). Effective absorption band (EAB) of CW-PAM-Ag(0.1), CW-PAM-CNT(0.1), and CW-PAM-G(0.1) in the frequency of 8.2–18 GHz (X band + Ku band) (h). EAB versus thickness of transparent CW-PAM-Ag(0.1), CW-PAM-CNT(0.1), and CW-PAM-G(0.1) wood composites and other MXene-based, carbon-based, magnetic and polymer absorbers (i). Reproduced with permission [80]. Copyright 2024, Elsevier.

diluents. In addition, it might be useful to modify the functional groups of the inner walls of the channels to increase the compatibility between wood scaffold and polymer. However, any chemical or physical transformation must preserve the principle of maintaining the same refractive index of all the constituents of the final composite. Further, the infiltrating material should also be of biological origin (i.e., bio-sourced or bio-based). Then, given the nature of the components, it is necessary to use both stabilizing additives and appropriate flame-retardant materials, to prolong the life span of TW composites: indeed, as a biomaterial, transparent wood is prone to degrade over time. This may be attributed to such factors as temperature fluctuations, fire occasions, microbial activity, photo-oxidation, moisture and humidity adsorption, and exposure to aggressive chemicals as well. Fixing these issues involves a combination of design considerations, material improvements, and industrial practices.

Finally, there is an urgent need for the development of scalable manufacturing processes: indeed, it is highly necessary to design and process large-size and thick transparent wood structures for industrial production and exploitation. This is currently impossible and remarkably limits the use of the big potential offered by TW. It is worth noticing that the processing techniques that work on a small scale are difficult to apply to the manufacturing of large wood samples: the larger the size, the lower the uniformity achieved [81]. Therefore, it becomes crucial to develop cost-effective, sustainable, and scalable manufacturing processes, aiming to achieve a widespread use of transparent wood materials.

All these findings suggest that TW and its analogs may have a great development ahead of them both in terms of ongoing research, development of more practical solutions, and possible applications, even in advanced sectors.

Table 3
The transparent wood materials' properties and performance indicators discussed in the present paragraph.

Type of wood	Infiltrated materials	Performance indicators	Ref.
Balsa wood	poly(methyl methacrylate)	• solar modulation ability • optical transmittance: 78% • enhanced tensile and flexural strength (ca. 71 and 93 MPa, respectively)	[63]
Balsa wood	waterborne wood carbon ink	• tensile strength of ca. 230 MPa • optical transmittance > 40% • haze at 800 nm: 93%	[64]
Balsa wood	organic dye molecules	• high room temperature phosphorescence emission	[65]
Balsa wood	poly(vinyl alcohol) and aryl boronic acids	• high room temperature phosphorescence emission • good optical transmittance (≈90%) • high strength (≈150 MPa)	[66]
Basswood and dye	UV-curable mixture of polyurethane acrylate, polyester acrylate, epoxy acrylate, and acrylamide morpholine	• tensile strength of dyed transparent wood: ca. 120 MPa • elongation at break: ca. 6% • improved toughness • optical transmittance: ca. 80% • no changes in TW transmittance induced by the dye	[68]
Balsa wood	epoxy resin, poly(ethylene glycol), triethyl phosphate	• optical transparency: 95% • tensile strength of ca. 2 MPa • impact resistance: 8 kJ/m^2	[72]
Balsa wood	polyethylene glycol based composite material embedding graphene quantum dot-grafted boron nitride	• thermal conductivity: 0.392 W/(mK) • high latent heat value • high optical transparency	[73]
Balsa wood	epoxy resin and carbon quantum dots	• tensile strength: ca. 19 MPa • elongation at break: ca. 5% • high UV-light blocking rate • optical transmission: 70% • outstanding water resistance • good thermal insulation	[74]
Canadian white maple	carbon quantum dot and epoxy resin	• excellent optical transmittance: ca. 90% • high water absorption stability • longitudinal tensile strength: ca. 140 MPa • UV-shielding properties • uniform luminescence under ultraviolet lamps	[75]
Balsa wood	epoxy resin and spiropyran	• reversible photoresponse upon UV exposure	[77]
Balsa wood	gelatine	• high strength: ca. 155 MPa • light transmittance: 86.2% at 600 nm • low haze: ca. 17% • high water stability (wet strength: ca. 130 MPa) • ultraviolet blocking efficiency.	[78]
Balsa wood	epoxy resin	• optical transmittance: 70% • haze: 95% • tunable stiffness • shape recovery ability	[79]
Balsa wood	polyacrylamide embedding different nanofillers	• low thermal conductivity: 0.45 W/(mK) • high electromagnetic absorption • optical transmittance >83%	[80]

CRediT authorship contribution statement

Alberto Mariani: Conceptualization, Writing- Reviewing and Editing. **Giulio Malucelli**: Conceptualization, Writing- Original draft preparation, Writing- Reviewing and Editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors thank the HORIZON AI-TRANSPWOOD (AI-Driven Multiscale Methodology to Develop Transparent Wood as Sustainable Functional Material) project, Grant no. 101138191. Views and opinions expressed are however those of the authors only and do not necessarily reflect those of the European Union. Neither the European Union nor the granting authority can be held responsible for them.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.nxmate.2024.100255.

References

[1] C. Chen, Y. Kuang, S. Zhu, I. Burgert, T. Keplinger, A. Gong, T. Li, L. Berglund, S. J. Eichhorn, L. Hu, Structure–property–function relationships of natural and engineered wood, Nat. Rev. Mater. 5 (9) (2020) 642–666, https://doi.org/10.1038/s41578-020-0195-z.
[2] S.K. Cousins, R.M. Brown, Cellulose I microfibril assembly: computational molecular mechanics energy analysis favours bonding by van der Waals forces as the initial step in crystallization, Polymer 36 (1995) 3885–3888, https://doi.org/10.1016/0032-3861(95)99782-P.
[3] S. Zhu, S.K. Biswas, Z. Qiu, Y. Yue, Q. Fu, F. Jiang, J. Han, Transparent wood-based functional materials via a top-down approach, Prog. Mater. Sci. 132 (2023) 101025, https://doi.org/10.1016/j.pmatsci.2022.101025.

[4] M.W. Zhu, J.W. Song, T. Li, A. Gong, Y.B. Wang, J.Q. Dai, Y. Yao, W. Luo, D. Henderson, L. Hu, Highly anisotropic, highly transparent wood composites, Adv. Mater. 28 (26) (2016) 5181–5187, https://doi.org/10.1002/adma.201600427.
[5] A. Mariani, G. Malucelli, Transparent wood-based materials: current state-of-the-art and future perspectives, Materials 15 (2022) 9069, https://doi.org/10.3390/ma15249069.
[6] Y. Li, E. Vasileva, I. Sychugov, S. Popov, L. Berglund, Optically transparent wood: recent progress, opportunities, and challenges, Adv. Opt. Mater. 6 (14) (2018) 1800059, https://doi.org/10.1002/adom.201800059.
[7] N.P. Simelane, O.S. Olatunji, M.J. John, J. Andrew, Engineered transparent wood with cellulose matrix for glass applications: a review, Carbohydr. Polym. Technol. Appl. 7 (2024) 100487, https://doi.org/10.1016/j.carpta.2024.100487.
[8] S. Fink, Transparent wood — a new approach in the functional study of wood structure, Holzforschung 46 (1992) 403–408, https://doi.org/10.1515/hfsg.1992.46.5.403.
[9] M.W. Zhu, J.W. Song, T. Li, A. Gong, Y.B. Wang, J.Q. Dai, Y.G. Yao, W. Luo, D. Henderson, L.B. Hu, Highly anisotropic, highly transparent wood composites, Adv. Mater. 28 (2016) 5181–5187, https://doi.org/10.1002/adma.201600427.
[10] Y.Y. Li, Q. Fu, S. Yu, M. Yan, L. Berglund, Optically transparent wood from a nanoporous cellulosic template: combining functional and structural performance, Biomacromolecules 17 (2016) 1358–1364, https://doi.org/10.1021/acs.biomac.6b00145.
[11] H. Chen, C. Montanari, M. Yan, S. Popov, Y. Li, I. Sychugov, L. Berglund, Refractive index of delignified wood for transparent biocomposites, RSC Adv. 10 (67) (2020) 40719–40724, https://doi.org/10.1039/D0RA07409H.
[12] I. Haq, Payal Mazumder, A.S. Kalamdhad, Recent advances in removal of lignin from paper industry wastewater and its industrial applications – a review, Bioresour. Technol. 312 (2020) 123636, https://doi.org/10.1016/j.biortech.2020.123636.
[13] A. Kumar, T. Jyske, M. Petrič, Delignified wood from understanding the hierarchically aligned cellulosic structures to creating novel functional materials: a review, Adv. Sustain. Syst. 5 (2021) 2000251, https://doi.org/10.1002/adsu.202000251.
[14] X. Hu, R. Yu, F. Wang, Z. Liu, H. Yang, C. Chen, Y. Li, N. Noor, B. Fei, Fabrication, functionalities and applications of transparent wood: a review, Adv. Funct. Mater. 33 (2023) 2303278, https://doi.org/10.1002/adfm.202303278.
[15] M. Chutturi, S. Gillela, S.M. Yadav, E.S. Wibowo, K. Sihag, S.M. Rangppa, P. Bhuyar, S. Siengchin, P.A.L. Kristak, A. Sinha, A comprehensive review of the synthesis strategies, properties, and applications of transparent wood as a renewable and sustainable resource, Sci. Total Environ. 864 (2023) 161067, https://doi.org/10.1016/j.scitotenv.2022.161067.
[16] K.H. Pandit, A.D. Goswami, C.R. Holkar, D.W. Pinjari, A review on recent developments in transparent wood: sustainable alternative to glass, Biomass Conv. Bioref. (2024), https://doi.org/10.1007/s13399-024-05523-3.
[17] C. Wan, X. Liu, Q. Huang, W. Cheng, J. Su, Y. Wu, A brief review of transparent wood: synthetic strategy, functionalization and applications, Curr. Org. Synth. 18 (2021) 615–623, https://doi.org/10.2174/1570179418666210614141030.
[18] R. Mi, T. Li, D. Dalgo, C. Chen, Y. Kuang, S. He, X. Zhao, W. Xie, W. Gan, J. Zhu, A clear, strong, and thermally insulated transparent wood for energy efficient windows, Adv. Funct. Mater. 30 (2020) 1907511, https://doi.org/10.1002/adfm.201907511.
[19] S. He, C. Chen, T. Li, J. Song, X. Zhao, Y. Kuang, Y. Liu, Y. Pei, E. Hitz, W. Kong, An energy-efficient, wood-derived structural material enabled by pore structure engineering towards building efficiency, Small Methods 4 (2020) 1900747, https://doi.org/10.1002/smtd.201900747.
[20] T.B. Jele, J. Andrew, M. John, B. Sithole, Engineered transparent wood composites: a review, Cellulose 30 (2023) 5447–5471, https://doi.org/10.1007/s10570-023-05239-z.
[21] Y.Y. Li, Q. Fu, X. Yang, L. Berglund, Transparent wood for functional and structural applications, Philos. Trans. R. Soc. A. 37620170182 (2018), https://doi.org/10.1098/rsta.2017.0182.
[22] Y.Y. Li, Q. Fu, R. Rojas, M. Yan, M. Lawoko, L. Berglund, Lignin-Retaining Transparent Wood, ChemSusChem 10 (2107), 3445-3451, ⟨https://doi.org/10.1002/cssc.201701089⟩.
[23] X. Wang, T. Zhan, Y. Liu, J. Shi, B. Pan, Y. Zhang, L. Cai, S.Q. Shi, Large-Size Transparent Wood for Energy-Saving Building Applications, ChemSusChem 11 (2028), 4086-4093, ⟨https://doi.org/10.1002/cssc.201801826⟩.
[24] F. Jiang, T. Li, Y. Li, Y. Zhang, A. Gong, J. Dai, E. Hitz, W. Luo, L. Hu, Wood-based nanotechnologies toward sustainability, Adv. Mater. 30 (2018) 1703453, https://doi.org/10.1002/adma.201703453.
[25] Y.Y. Li, Q.L. Fu, R. Rojas, M. Yan, L. Berglund, Lignin-retaining transparent wood, ChemSusChem 10 (2017) 3445–3451, https://doi.org/10.1002/cssc.201701089.
[26] Y. Wang, Y. Wu, F. Yang, J. Wang, J. Zhou, J. Wang, A highly transparent compressed wood prepared by cell wall densification, Wood Sci. Technol. 56 (2022) 669–686, https://doi.org/10.1007/s00226-022-01372-3.
[27] S.M. Koch, M. Pillon, T. Keplinger, C.H. Dreimol, S. Weinkötz, I. Burgert, Intercellular matrix infiltration improves the wet strength of delignified wood composites, ACS Appl. Mater. Interfaces 14 (2022) 31216–31224, https://doi.org/10.1021/acsami.2c04014.
[28] H. Li, X. Guo, Y. He, R. Zheng, A green steam-modified delignification method to prepare low-lignin delignified wood for thick, large highly transparent wood composites, J. Mater. Res. 34 (2019) 932–940, https://doi.org/10.1557/jmr.2018.466.
[29] A. Khakalo, A. Tanaka, A. Korpela, H. Orelma, Delignification and ionic liquid treatment of wood toward multifunctional high-performance structural materials, ACS Appl. Mater. Interfaces 12 (2020) 23532–23542, https://doi.org/10.1021/acsami.0c02221.
[30] J. Li, C. Chen, J.Y. Zhu, A.J. Ragauskas, L. Hu, In situ wood delignification toward sustainable applications, Acc. Mater. Res. 2 (2021) 606–620, https://doi.org/10.1021/accountsmr.1c00075.
[31] Y. Wu, J. Zhou, Q. Huang, F. Yang, Y. Wang, J. Wang, Study on the properties of partially transparent wood under different delignification processes, Polymers 12 (2020) 661, https://doi.org/10.3390/polym12030661.
[32] J. Qin, X. Li, Y. Shao, K. Shi, X. Zhao, T. Feng, Y. Hu, Optimization of delignification process for efficient preparation of transparent wood with high strength and high transmittance, Vacuum 158 (2018) 158–165, https://doi.org/10.1016/j.vacuum.2018.09.058.
[33] K. Wang, Y. Dong, Z. Ling, X. Liu, S.Q. Shi, J. Li, Transparent wood developed by introducing epoxy vitrimers into a delignified wood template, Compos. Sci. Technol. 207 (2021) 108690, https://doi.org/10.1016/j.compscitech.2021.108690.
[34] X. Chen, S. Ge-Zhang, Y. Han, H. Yang, W. Ou-Yang, H. Zhu, J. Hao, J. Wang, Ultraviolet-assisted modified delignified wood with high transparency, Appl. Sci. 12 (2022) 7406, https://doi.org/10.3390/app12157406.
[35] Y.Y. Li, Q.L. Fu, S. Yu, M. Yan, L. Berglund, Optically transparent wood from a nanoporous cellulosic template: combining functional and structural performance, Biomacromolecules 17 (4) (2016) 1358–1364, https://doi.org/10.1021/acs.biomac.6b00145.
[36] J. Pang, A. Baitenov, C. Montanari, A. Samanta, L. Berglund, S. Popov, I. Zozoulenko, Light propagation in transparent wood: efficient ray-tracing simulation and retrieving an effective refractive index of wood scaffold, Adv. Photonics Res. 2 (2021) 2100135, https://doi.org/10.1002/adpr.202100135.
[37] H. Chen, A. Baitenov, Y.Y. Li, E. Vasileva, S. Popov, I. Sychugov, M. Yan, L. Berglund, Thickness dependence of optical transmittance of transparent wood: chemical modification effects, ACS Appl. Mater. Interfaces 11 (2019) 35451–35457, https://doi.org/10.1021/acsami.9b11816.
[38] D. Yue, G. Fu, Z. Jin, Transparent wood prepared by polymer impregnation of rubber wood (Hevea brasiliensis Muell. Arg), BioResources 16 (2021) 2491–2502.
[39] Y.Y. Li, X. Yang, Q.L. Fu, R. Rojas, M. Yan, L. Berglund, Towards centimeter thick transparent wood through interface manipulation, J. Mater. Chem. A 6 (3) (2018) 1094–1101, https://doi.org/10.1039/c7ta09973h.
[40] M. Hoglund, M. Johansson, I. Sychugov, L.A. Berglund, Transparent wood biocomposites by fast UV-curing for reduced light-scattering through wood/thiol-ene interface design, ACS Appl. Mater. Interfaces 12 (41) (2020) 46914–46922, https://doi.org/10.1021/acsami.0c12505.
[41] E. Vasileva, H. Chen, Y.Y. Li, I. Sychugov, M. Yan, L. Berglund, S. Popov, Light scattering by structurally anisotropic media: a benchmark with transparent wood, Adv. Opt. Mater. 6 (2018) 1800999, https://doi.org/10.1002/adom.201800999.
[42] Q. Tang, X. Yuan, M. Zou, L. Zhang, L. Chang, X. Chen, J. Zhang, G. Zhou, K. Gao, W. Guo, Y. Chen, Mismatched refractive index strategy for fabricating laser-driven wood diffusers from bulk wood for illumination applications, Adv. Mater. 36 (2024) 2306593, https://doi.org/10.1002/adma.202306593.
[43] H. Chen, C. Montanari, R. Shanker, S. Marcinkevicius, L. Berglund, I. Sychugov, Photon walk in transparent wood: scattering and absorption in hierarchically structured materials, Adv. Opt. Mater. 10 (2022) 2102732, https://doi.org/10.1002/adom.202102732.
[44] E. Vasileva, A. Baitenov, H. Chen, Y. Li, I. Sychugov, M. Yan, L. Berglund, S. Popov, Effect of transparent wood on the polarization degree of light, Opt. Lett. 44 (2019) 2962–2965, https://doi.org/10.1364/OL.44.002962.
[45] Light Propagation in Transparent Wood: Efficient Ray-Tracing Simulation and Retrieving an Effective Refractive Index of Wood Scaffold 2 Adv. Photonics Res. , 2021, 2100135.
[46] C. Montanari, Y. Ogawa, P. Olsén, L.A. Berglund, High performance, fully bio-based, and optically transparent wood biocomposites, Adv. Sci. 8 (12) (2021) 2100559, https://doi.org/10.1002/advs.202100559.
[47] C. Montanari, P. Olsén, L.A. Berglund, Interface tailoring by a versatile functionalization platform for nanostructured wood biocomposites, Green. Chem. 22 (22) (2020) 8012–8023, https://doi.org/10.1039/d0gc02768e.
[48] K.E.O. Foster, R. Jones, G.M. Miyake, W.V. Srubar, Mechanics, optics, and thermodynamics of water transport in chemically modified transparent wood composites, Compos. Sci. Technol. 208 (2021) 108737, https://doi.org/10.1016/j.compscitech.2021.108737.
[49] E. Jungstedt, C. Montanari, S. Östlund, L. Berglund, Mechanical properties of transparent high strength biocomposites from delignified wood veneer, Compos. - A: Appl. Sci. Manuf. 133 (2020) 105853, https://doi.org/10.1016/j.compositesa.2020.105853.
[50] K.E.O. Foster, K.M. Hess, G.M. Miyake, W.V. Srubar III, Optical properties and mechanical modeling of acetylated transparent wood composite laminates, Materials 12 (2019) 2256, https://doi.org/10.3390/ma12142256.
[51] M.W. Zhu, T. Li, C.S. Davis, Y.G. Yao, J.Q. Dai, Y.B. Wang, F. AlQatari, J. W. Gilman, L. Hu, Transparent and haze wood composites for highly efficient broadband light management in solar cells, Nano Energy 26 (2016) 332–339, https://doi.org/10.1016/j.nanoen.2016.05.020.
[52] L. Chen, Z.W. Xu, F. Wang, G.G. Duan, W.H. Xu, G.Y. Zhang, H. Yang, J. Liu, S. Jiang, A flame-retardant and transparent wood/polyimide composite with excellent mechanical strength, Compos. Commun. 20 (2020) 100355, https://doi.org/10.1016/j.coco.2020.05.001.
[53] Y. Tan, K. Wang, Y. Dong, S. Gong, S.Q. Shi, J. Li, High performance, shape manipulatable transparent wood based on delignified wood framework and exchangeable dynamic covalent vitrimers, Chem. Eng. J. 448 (2022) 137487, https://doi.org/10.1016/j.cej.2022.137487.

[54] P. Samanta, A. Samanta, C. Montanari, Y. Li, L. Maddalena, F. Carosio, L. Berglund, Fire-retardant and transparent wood biocomposite based on commercial thermoset, Compos. Part A-Appl. S 156 (2022) 106863, https://doi.org/10.1016/j.compositesa.2022.106863.
[55] S. Liu, C.Y. Tso, H.H. Lee, Y.W. Du, K.M. Yu, S.-P. Feng, B. Huang, Self-densified optically transparent VO_2 thermochromic wood film for smart windows, ACS Appl. Mater. Interfaces 13 (2021) 22495–22504, https://doi.org/10.1021/acsami.1c03803.
[56] S. Liu, C.Y. Tso, Y.W. Du, L.C. Chao, H.H. Lee, T.C. Ho, M.K.H. Leung, Bioinspired Thermochromic Transparent Hydrogel Wood with Advanced Optical Regulation Abilities and Mechanical Properties for Windows, Appl. Energy 297 (2021) 117207, https://doi.org/10.1016/j.apenergy.2021.117207.
[57] Y. Brasse, M.B. Müller, M. Karg, C. Kuttner, T.A.F. König, A. Fery, Magnetic and electric resonances in particle-to-film-coupled functional nanostructures, ACS Appl. Mater. Interfaces 10 (2018) 3133–3141, https://doi.org/10.1021/acsami.7b16941.
[58] Y.Y. Li, S. Yu, J. Linnros, L. Berglund, I. Sichugov, Luminescent transparent wood, Adv. Opt. Mater. 5 (2017) 1600834, https://doi.org/10.1002/adom.201600834.
[59] C. Jia, C. Chen, R. Mi, T. Li, J. Dai, Z. Yang, Y. Pei, S. He, H. Bian, S.-H. Jang, J. Y. Zhu, B. Yang, L. Hu, Clear wood toward high-performance building materials, ACS Nano 13 (2019) 9993–10001, https://doi.org/10.1021/acsnano.9b00089.
[60] A.N.S. Rao, G.B. Nagarajappa, S. Nair, A.M. Chathoth, K.K. Pandey, Flexible transparent wood prepared from poplar veneer and polyvinyl alcohol, Compos. Sci. Technol. 182 (2019) 107719, https://doi.org/10.1016/j.compscitech.2019.107719.
[61] J. Wu, Y. Wu, F. Yang, C. Tang, Q. Huang, J. Zhang, Impact of delignification on morphological, optical and mechanical properties of transparent wood, Compos. -A: Appl. Sci. Manuf. 117 (2019) 324–331, https://doi.org/10.1016/j.compositesa.2018.12.004.
[62] C. Fan, Y. Gao, Y. Li, L. Yan, Y. Zhuang, Y. Zhang, Z. Wang, A flame-retardant and optically transparent wood composite, J. Appl. Polym. Sci. 139 (2022) e52945, https://doi.org/10.1002/app.52945.
[63] Y. Du, S. Liu, Y. Li, X. Chen, T.C. Ho, L.C. Chao, C.Y. Tso, Perovskite-coated thermochromic transparent wood: a novel material for smart windows in energy-efficient and sustainable buildings, ACS Appl. Mater. Interfaces 15 (42) (2023) 49665–49677, https://doi.org/10.1021/acsami.3c11706.
[64] W. Zhang, B. Wang, H. Dong, Y. Li, J. Sun, Y. Pang, Z. Fan, Y. Liu, H. Guo, A strong, biodegradable, brush written all-wood-based flexible electronic device, Cellulose 31 (2024) 2571–2581, https://doi.org/10.1007/s10570-024-05770-7.
[65] G. Zhu, C. Liu, C. Zhang, J. Shi, C. Mei, M. Pan, Z. Liu, Activating the room-temperature phosphorescence of organic dyes through the confinement effect of delignified wood, ACS Sustain. Chem. Eng. 12 (2024) 3726–3735, https://doi.org/10.1021/acssuschemeng.3c07507.
[66] Z. Lu̇, Q. Gao, M. Shi, Z. Su, G. Chen, H. Qi, B. Lu̇, F. Peng, Colorful room-temperature phosphorescence including white afterglow from mechanical robust transparent wood for time delay lighting, Small Struct. (2024) 2300567, https://doi.org/10.1002/sstr.202300567.
[67] A.M. Binyaseen, O. Alaysuy, M. Alhasani, S. Sallam, F. Alkhatib, K. Alkhamis, R. Shah, N.M. El-Metwaly, Novel strategy toward color-tunable and glow-in-the-dark colorless smart natural wooden window, J. Photochem. Photobiol., A 448 (2024) 115321, https://doi.org/10.1016/j.jphotochem.2023.115321.
[68] W. Zhao, Y. Rong, R. Xu, Y. Wu, Study on transparent basswood dyed with reactive dyes and its properties, ACS Omega 9 (2024) 5378–5385, https://doi.org/10.1021/acsomega.3c06372.
[69] Y.L. Cheng, J.G. Kim, H. Bin Kim, J.H. Choi, Y. Fai Tsang, K. Baek, Occurrence and removal of microplastics in wastewater treatment plants and drinking water purification facilities: a review, Chem. Eng. J. 410 (2021) 128381, https://doi.org/10.1016/j.cej.2020.128381.
[70] A.D. Vethaak, J. Legler, Microplastics and human health, Science 371 (2021) 672–674, https://doi.org/10.1126/science.abe5041.
[71] X. Liu, M.-C. Li, Y. Lu, Z. Li, C. Liu, Z. Liu, C. Mei, Q. Wu, Cellulose nanofiber-coated delignified wood as an efficient filter for microplastic removal, Prog. Nat. Sci.: Mater. Int. 34 (2024) 162–171, https://doi.org/10.1016/j.pnsc.2024.02.010.
[72] M. Li, X. Li, K. Xu, A. Qin, C. Yan, Y. Xu, D. Shan, J. Wang, M. Xu, X. Li, B. Li, L. Liu, Construction and mechanism analysis of flame-retardant, energy-storage and transparent bio-based composites based on natural cellulose template, Int. J. Biol. Macromol. 263 (2024) 130317, https://doi.org/10.1016/j.ijbiomac.2024.130317.
[73] Y. Li, Q. Lu, J. Yang, W. He, Delignified wood for thermal energy storage with high efficient photo-thermal conversion efficiency, J. Energy Storage 80 (2024) 110235, https://doi.org/10.1016/j.est.2023.110235.
[74] N. Zhou, S. Long, D. Song, B. Hui, X. Cui, C. An, M. Zhang, Fabrication of carbon dots-embedded luminescent transparent wood with ultraviolet blocking and thermal insulating capacities towards smart window application, Int. J. Biol. Macromol. 259 (2024) 129358, https://doi.org/10.1016/j.ijbiomac.2024.129358.
[75] R. Xu, J. Gan, J. Wang, W. Zhao, K. Tong, Y. Wu, Photoluminescent transparent wood with excellent UV-shielding function, ACS Omega 9 (2024) 8092–8102, https://doi.org/10.1021/acsomega.3c08337.
[76] P. Bisht, H.C. Barshilia, K.K. Pandey, Effect of natural weathering on optical properties of transparent wood composite, Polym. Deg. Stab. 221 (2024) 110674, https://doi.org/10.1016/j.polymdegradstab.2024.110674.
[77] L. Tian, W. Zhu, X. Chen, Y. Feng, H. Hu, H. Wang, B. Dang, H. Chai, Q. Sun, Y. Yang, Y. Li, Flexible transparent wood with reversible photoresponsive property, Polymer 294 (2024) 126725, https://doi.org/10.1016/j.polymer.2024.126725.
[78] T. Zhou, J. Zhou, Q. Feng, Q. Yang, Y. Jin, D. Li, Z. Xu, C. Chen, Mechanically strong, hydrostable, and biodegradable all-biobased transparent wood films with UV-blocking performance, Int. J. Biol. Macromol. 255 (2024) 128188, https://doi.org/10.1016/j.ijbiomac.2023.128188.
[79] Y. Liu, Y. Zhang, J. Guo, G. Guo, C. Li, Preparation and properties of soft-/hard-switchable transparent wood with 0 °C as a boundary, Forests 15 (2024) 384, https://doi.org/10.3390/f15020384.
[80] B. Zhang, J. Cui, D. He, J. Zhang, L. Yang, W. Zhu, H. Lv, Transparent electromagnetic absorption film derived from the biomass derivate, J. Mater. Sci. Technol. 185 (2024) 98–106, https://doi.org/10.1016/j.jmst.2023.10.035.
[81] J. Zhang, A. Koubaa, Y. Tao, P. Li, D. Xing, The emerging development of transparent wood: materials, characteristics, and applications, Curr. For. Rep. 8 (2022) 333–345, https://doi.org/10.1007/s40725-022-00172-z.