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Engineered Wood: Sustainable Technologies and Applications

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Abstract

Natural wood has been used for construction, fuel, and furniture for thousands of years because of its versatility, renewability, and aesthetic appeal. However, new opportunities for wood are arising as researchers have developed ways to tune the material's optical, thermal, mechanical, and ionic transport properties by chemically and physically modifying wood's naturally porous structure and chemical composition. Such modifications can be used to produce sustainable, functional materials for various emerging applications such as automobiles, construction, energy storage, and environmental remediation. In this review, we highlight recent advancements in engineered wood for sustainable technologies, including thermal and light management, environmental remediation, nanofluidics, batteries, and structural materials with high strength-to-weight ratios. Additionally, the current challenges, opportunities, and future of wood research are discussed, providing a guideline for the further development of next-generation, sustainable wood-based materials.

1. INTRODUCTION

With the emergence of climate change and increasing resource scarcity, sustainable natural materials have gained increased interest in recent years. For example, wood is abundant, biodegradable, and renewable and has traditionally been used for construction, tools, furniture, and fuel. It is also a carbon-negative material, storing a large amount of atmospheric carbon dioxide (CO_2) through photosynthesis (~1.6 kg of CO_2 per kg of wood) (1), which makes it attractive as a sustainable alternative to materials with high carbon footprints. In recent decades, the wood industry has developed several modification strategies, such as thermal and chemical modification (2, 3), salt impregnation (4), and surface coating (5), to improve wood's moisture sensitivity, low hardness, low stability, and poor resistance to biodeterioration from fungi, marine borers, and termites (6). However, despite these advances, the use of natural wood has largely remained limited due to its opaque appearance, low mechanical strength (<400 MPa) relative to metals (e.g., aluminum and steel), and high thermal conductivity [>0.1 W/(m·K)] compared with foams and wools. To make wood a viable alternative to such high-carbon-footprint materials, its properties and performance must be further improved.

Toward this aim, in recent years researchers have developed emerging wood modification strategies that equip wood with new capabilities that could enable the replacement of traditional nonrenewable, petroleum-derived materials in various applications, such as automobiles, energy storage, construction, and environmental remediation (7–11), taking wood out of the traditional construction and paper industries. Researchers have shown that the natural structure and composition of wood support emerging modifications that can control and regulate the surface properties, molecular structure, porosity, and composition of wood, all of which could significantly expand the material's potential. For example, wood consists primarily of three major components, hemicellulose, cellulose, and lignin, and features a hierarchically aligned porous structure that enables efficient ion and water transport in addition to load-bearing capacity (7, 12–15). Utilizing these natural features and improving upon them through physical or chemical modification (e.g., in situ delignification, polymer/nanoparticle infiltration, densification, functional group grafting, chelation, and carbonization) allows the synthesis of novel engineered wood materials that retain many of the inherent advantages of wood (e.g., renewability, biodegradability, and porous structure) while also engendering new properties (e.g., high strength, thermal insulation, optical transparency, and high ionic conductivity). For example, the Hu and Berglund groups (16–18) have reported transparent wood biocomposites that exhibit an excellent optical transmittance of 90% with a high mechanical performance and could potentially replace glass. In another example, by taking advantage of the chelation of copper ions with the nanocellulose in wood, the Hu group (19) demonstrated novel solid polymer ion conductors, with a high Li^+ conductivity of $\sim 1 \times 10^{-3}$ S/cm and a high transference number of 0.78, that could be used for high-energy-density solid-state batteries.

In this review, we survey recent developments in engineered wood for thermal energy storage, thermal and light management, environmental remediation, nanofluidics, batteries, and lightweight structural materials. Note that this review focuses on the process and structural perspectives of how wood can be modified through physical or chemical methods (e.g., polymer/nanoparticle infiltration, densification, in situ delignification, functional group grafting, chelation, and carbonization) to engender new properties (e.g., high strength, thermal insulation, optical transparency, and high ionic conductivity). More specific discussions on the wood/bamboo delignification methods and delignified biomass-based materials are described elsewhere (20). We begin with an introduction to wood-based energy-efficient materials for the construction industry, focusing on thermal and light management. We then explore emerging wood-derived materials used

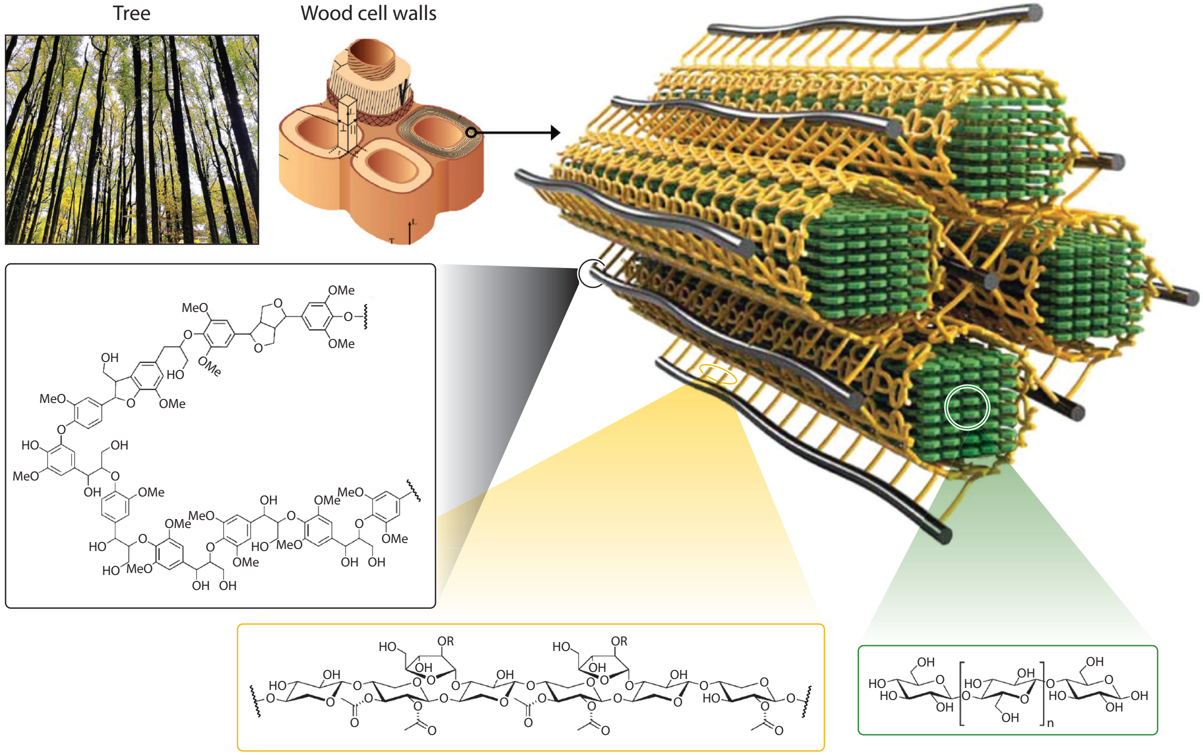

Figure 1

The structure of wood from the macroscopic to molecular scale. The wood cell wall is made of 40–50 wt% cellulose microfibril bundles, 20–30 wt% lignin, and 10–30 wt% hemicellulose. The cell wall structure image is adapted from Reference 24 with permission from the Royal Society of Chemistry. The images of the main components and structure of wood cell walls are adapted from Reference 25 (CC BY 4.0)

for environmental remediation, nanofluids, and batteries. Additionally, we discuss densified wood: a sustainable, lightweight structural material that can be used to replace traditional metals and alloys. To close, we provide perspectives on the opportunities, challenges, and future directions of wood research, which may have far-reaching impacts for a more sustainable world.

2. STRUCTURE AND CHEMICAL COMPOSITION OF WOOD

Wood, a structural tissue found mainly in tree stems, is a biopolymer composite made up of wood cells. The hierarchically porous structure of wood cell walls is shown in **Figure 1**. Most wood cells are longitudinal, meaning that the long axis of wood cells runs parallel to the tree growth direction (21). The wood cell wall is made of 40–50 wt% cellulose microfibril bundles, 20–30 wt% lignin, and 10–30 wt% hemicellulose (7). The cell wall functions as a load-bearer for the cell while the lumen cells (i.e., the central cell of the pore space), together with the pits traversing the cell wall, form an interconnected network in the wood (**Figure 1**) (7). In the primary and secondary cell walls, cellulose nanofibers (CNFs) are embedded inside a matrix consisting of pectins and hemicellulose. The CNFs are composed of elementary fibrils that have diameters of about 2–4 nm and consist of crystalline and amorphous domains (14). Each D-glucose unit in the cellulose molecular chain is connected to the adjacent unit via a carbon–oxygen–carbon bond, forming a linear and rigid cellulose chain. The rigidity of secondary walls is further enhanced by lignin, a complex phenolic polymer that plays a large role in improving the mechanical properties of wood. Benefiting from its unique structural and chemical properties, wood can efficiently transport nutrients, minerals, and water up from the roots to the leaves.

The biological diversity of trees leads to variation between the properties of different wood species (22). Generally, coniferous species (softwoods) and deciduous species (hardwoods) have different chemical compositions and physical structures (22). Softwoods usually have a higher lignin content (26–34%), higher cellulose content (40–45%), and lower hemicellulose content (7–14%) when compared with hardwoods, which have a lignin content of 23–30%, a cellulose content of 38–49%, and a hemicellulose content of 19–26% (22). At the macrobiological scale, wood structures across hardwood and softwood species differ in shape and size, frequency and branching pattern, and wood properties such as strength, density, thermal conductivity, and elasticity. Additionally, there are significant differences in the microstructures of softwood and hardwood species. Softwood species generally contain longitudinal tracheid cells, commonly referred to as fiber cells in the pulping industry. These cells are approximately 3–5 mm in length. Meanwhile, tubular cells of hardwoods are usually smaller, closer to 0.75–1.5 mm in length (23). The hardwood xylem contains numerous vessel channels, which are longitudinally arranged cells that are significantly larger in diameter than the longitudinal tracheid cells of conifers (softwood). Softwood and hardwood cells have numerous pits connecting their neighboring cells. Variations in the microstructures of different wood species are typically responsible for the thermal and mechanical properties of the wood. The unique structural and chemical components of different wood species provide opportunities for structural modification and application of wood for sustainable purposes.

3. ENGINEERED WOOD FOR THERMAL MANAGEMENT

In 2021, the US building sector consumed approximately 21 quadrillion British thermal units (Btu) of energy. This represents about 28% of the energy consumption in the United States (26). It is predicted that building energy consumption will continue to climb (27). Therefore, taking effective measures to improve building energy efficiency is crucial to reduce energy consumption.

3.1. Engineered Wood for Thermal Energy Storage

Cost-effective, form-stable, high-thermal-conductivity, and sustainable composite phase-change materials (PCMs) are desirable for thermal energy storage (28–30). Recently, Yang et al. (31) reported a low-cost, stable, wood-derived PCM with a high latent heat of fusion (165.8 J/g) and a high thermal conductivity [0.669 W/(m·K)], prepared via impregnation of 1-tetradecanol (TD) into porous carbonized wood (CW) to form TDCW (**Figure 2*a***). Compared with common carbon materials (e.g., graphene and carbon nanotubes) with low loading content of PCMs (30–60 wt%), CW has a higher loading content (73.4 wt%) and is lower in cost. The infrared thermal images in **Figure 2*b*,*c*** compare the spatial variation of temperature over time during the heating and cooling of CW, TDCW, pristine wood (PW), and TDPW. A temperature plateau between 37 and 44°C, corresponding to the solid–liquid phase transition, is observed for TDCW and TDPW during both heating and cooling (**Figure 2*c*,*d***).

The same group also prepared a self-luminous wood with a high latent heat of fusion of 146.7 J/g and a high thermal conductivity of 0.469 W/(m·K) by impregnating a mixture of PCMs (TD) and long-afterglow luminescence materials ($SrO{\cdot}Al_2O_3{\cdot}SiO_2{:}Eu^{2+}$) into delignified wood (32). Small house models made of self-luminous wood were constructed as a demonstration (32). A xenon lamp causes the water temperature in the self-luminous wood boxes to rise in the first

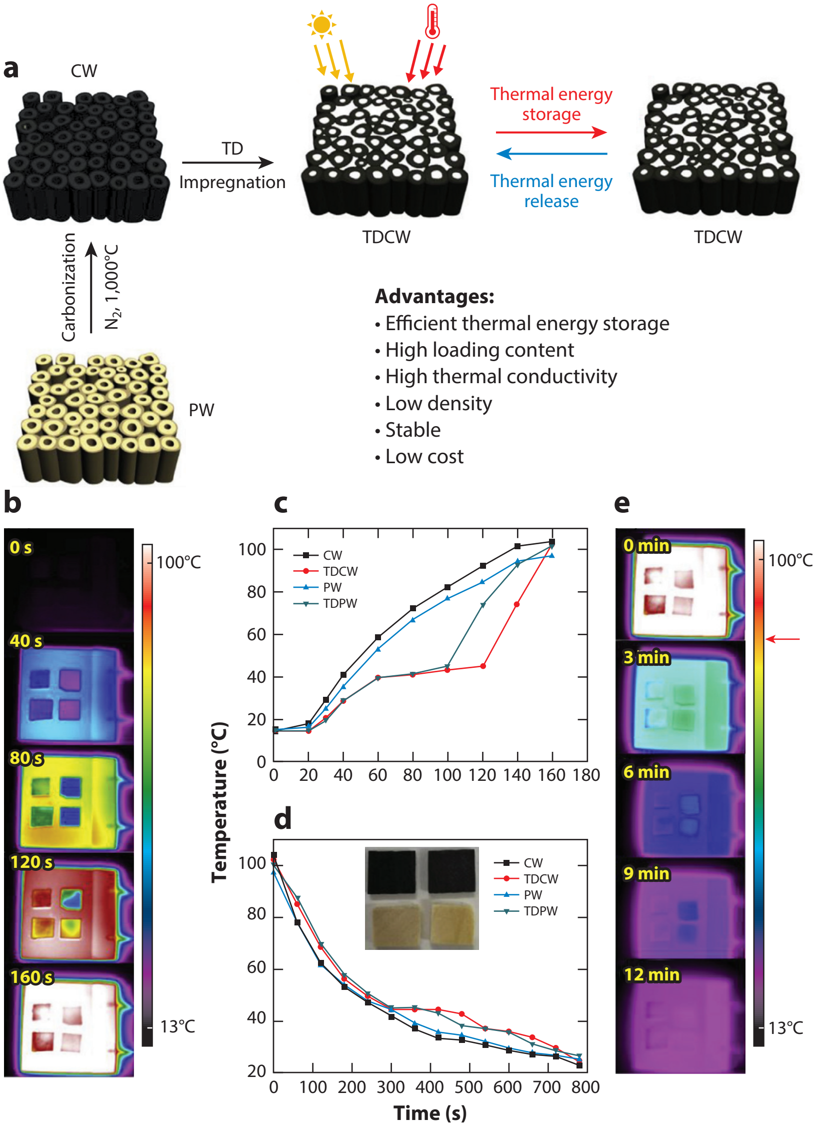

Figure 2

Wood-based PCMs for building thermal energy storage. (*a*) The sunlight- or heat-driven thermal energy storage and release process of TDCW. The TDCW was prepared via impregnation of TD into porous CW. (*b*) Infrared thermal images and (*c*) surface temperature changes of CW, TDCW, PW, and TDPW during the thermal energy storage process. (*d*) Surface temperature changes and (*e*) infrared thermal images of CW, TDCW, PW, and TDPW during the thermal energy release process. A temperature plateau between 37 and 44°C, corresponding to the solid–liquid phase transition, is observed for TDCW and TDPW during both heating and cooling. Abbreviations: CW, carbonized wood; PCMs, phase-change materials; TD, 1-tetradecanol; PW, pristine wood. Figure adapted with permission from Reference 31; copyright 2018 Elsevier.

20 min until reaching a plateau between 36 and 39°C due to the solid–liquid phase transition as well as the thermal energy storage of the self-luminous wood under light illumination (32). The self-luminous wood composite material emits green light for about 11 hours in a dark ambient environment, exhibiting a superior capability of light energy storage and release (32).

Note that the porous support material (e.g., delignified wood) and most PCMs (e.g., TD) are hydrophilic and hygroscopic. The adsorbed moisture is prone to develop defects at the interface between the support material and the PCMs, resulting in a decrease in the thermal energy storage performance. Yang et al. (33) developed superhydrophobic wood-based composite PCMs by infiltrating TD into delignified wood and spraycoating it with a superhydrophobic protective layer. The superhydrophobic surface not only reduces the risk of PCM leakage and enhances the thermal energy storage performance in high humidity environments but also imparts the material with self-cleaning properties. The facile and scalable fabrication process, coupled with superior energy storage and release performance, marks wood-based composite PCMs as promising candidates for building applications.

Although wood-based composite PCMs demonstrate promising potential for energy-saving building applications, there is still a long road ahead to further improve the energy storage and release performance. Efforts must be taken to eliminate the risks of PCM leakage and further improve mechanical performance and thermal conductivity while maintaining or increasing porosity and promoting large-scale production. When used as a building material, wood-based composite PCMs also require additional treatment for fire resistance and antifungal properties, which may be harmful to the environment.

3.2. Thermally Insulating Wood

Improving the thermal insulation performance of building envelopes such as walls, roofs, and floors can reduce heat loss and improve thermal comfort (34–36). Commonly used building insulation materials such as wool and polystyrene foam often have thermal conductivities of ~0.035 W/(m·K), are essentially isotropic, and are not ideal for efficient thermal management (35). Silica aerogels exhibit a lower thermal conductivity of ~0.02 W/(m·K). However, they are too brittle and expensive to be manufactured on a large scale (37). Cellulose has also been used to develop thermal insulation materials, and both bottom-up and top-down approaches have been adopted. The bottom-up method used to create nanocellulose-based foam includes three main steps: (*a*) extracting CNFs from plants through chemical, mechanical, and/or enzymatic treatments; (*b*) dispersing the extracted CNFs homogeneously into a suspension; and (*c*) removing the solvent using different drying techniques to form a porous aerogel. However, the bottom-up method involves complex physical, chemical, and biological processes and requires a well-controlled drying step to induce the assembly of the CNFs into aerogels. Li et al. (38) developed a top-down method for fabricating an anisotropic, thermally insulating nanowood via complete delignification of PW followed by freeze drying (**Figure 3*a***). The delignification process improves the structure's porosity by isolating CNFs, which is beneficial for improving the thermal insulation properties of the material but not for improving the mechanical performance of the material. With the maintenance of natural wood's microstructural characteristics, the delignified cellulose bulk material consists primarily of well-aligned CNFs, leading to anisotropic thermal conductivity (**Figure 3*b***). The nanowood exhibits a low thermal conductivity of ~0.06 W/(m·K) along the tree growth direction and ~0.03 W/(m·K) in the transverse direction (**Figure 3*c***). In addition, the compressive strength of nanowood is ~13 MPa, which is much higher than that of mainstream insulation materials such as silica aerogel, Styrofoam, and cellulose-derived foam. A balance between thermal conductivity and mechanical performance is pursued via controlled densification or polysiloxane cross-linking (39, 40).

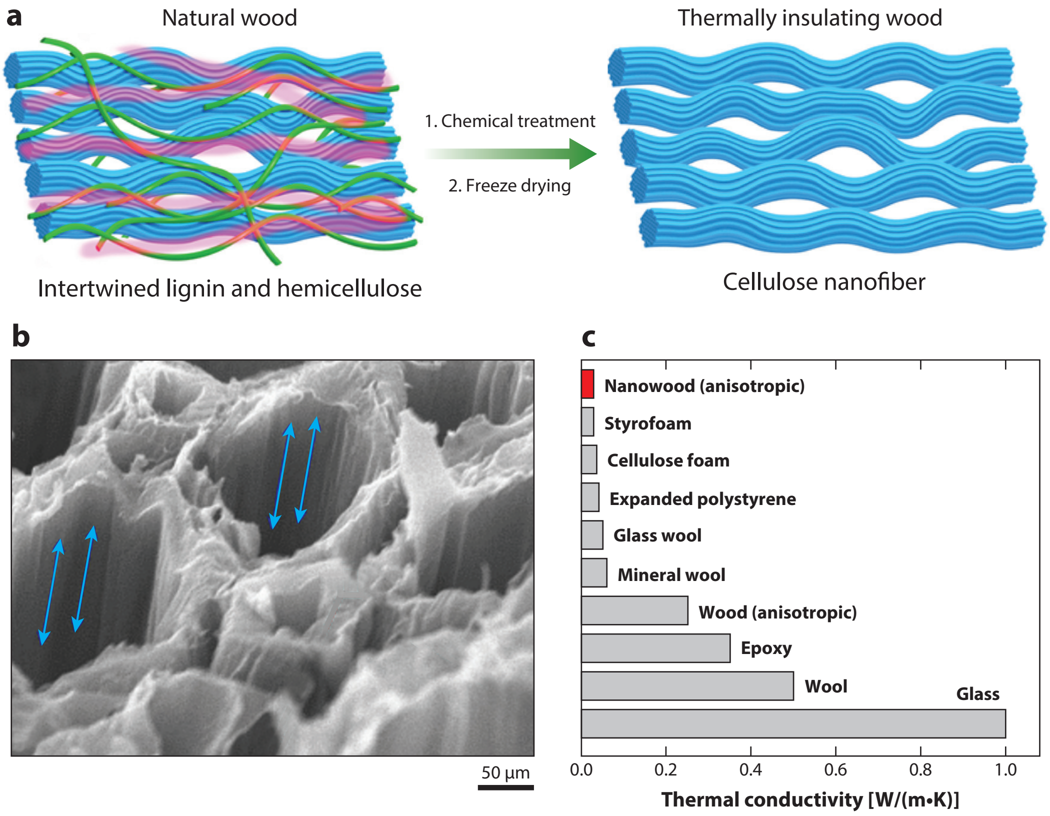

Figure 3

(*a*) The top-down preparation process (delignification combined with freeze drying) of thermally insulating, anisotropic, strong, and lightweight nanowood for building insulation applications. (*b*) Scanning electron microscopy image of nanowood. The blue arrows represent the orientation of cellulose nanofibers in line with the direction of wood growth. (*c*) Thermal conductivity of nanowood and selected commercially available building thermal insulation materials. The thermal conductivity of nanowood is ~0.03 W/(m·K) in the transverse direction, much lower than that of common building insulation materials such as Styrofoam and glass wool. Figure adapted with permission from Reference 38 (CC BY-NC 4.0).

High-performance, cellulose-based building insulation materials not only are beneficial for saving energy but also reduce the adverse impacts of global greenhouse gas emissions. The mechanical performance, moisture resistance, and durability of wood-based building insulation materials need to be further improved while simultaneously reducing their thermal conductivity. The processing also needs to be cost-effective.

3.3. Radiative Cooling Wood

Recently developed passive radiative cooling materials, such as paints and polymers with a high emissivity (>0.9) and a high solar reflectance (>0.9) within the 8–13 µm atmospheric window, can dissipate heat from the building envelope into the cold outer space via infrared thermal radiation without energy consumption (41, 42). However, these materials (i.e., films, coatings, and paints) are not structural materials and cannot be installed directly as building envelopes such as roofs or walls. Recently, Li et al. (43) reported a wood-based structural material for passive daytime radiative cooling applications via a scalable process of delignification and densification of natural wood

(**Figure 4*a*,*b***). The CNFs act as highly effective scattering elements for an intense broadband reflection in the solar spectrum, making the cooling wood emit a bright white color and possess a high solar reflectance of ∼96%. Meanwhile, the chemical bond (e.g., C–C, C–O, C–H) stretching and vibration of cellulose molecules at the atomic level generate strong emissions in mid-infrared wavelengths (**Figure 4*c***), making the cooling wood black in the far-infrared range with a high emittance of >90% in the atmospheric window (**Figure 4*d*,*e***). The high solar reflectance along with

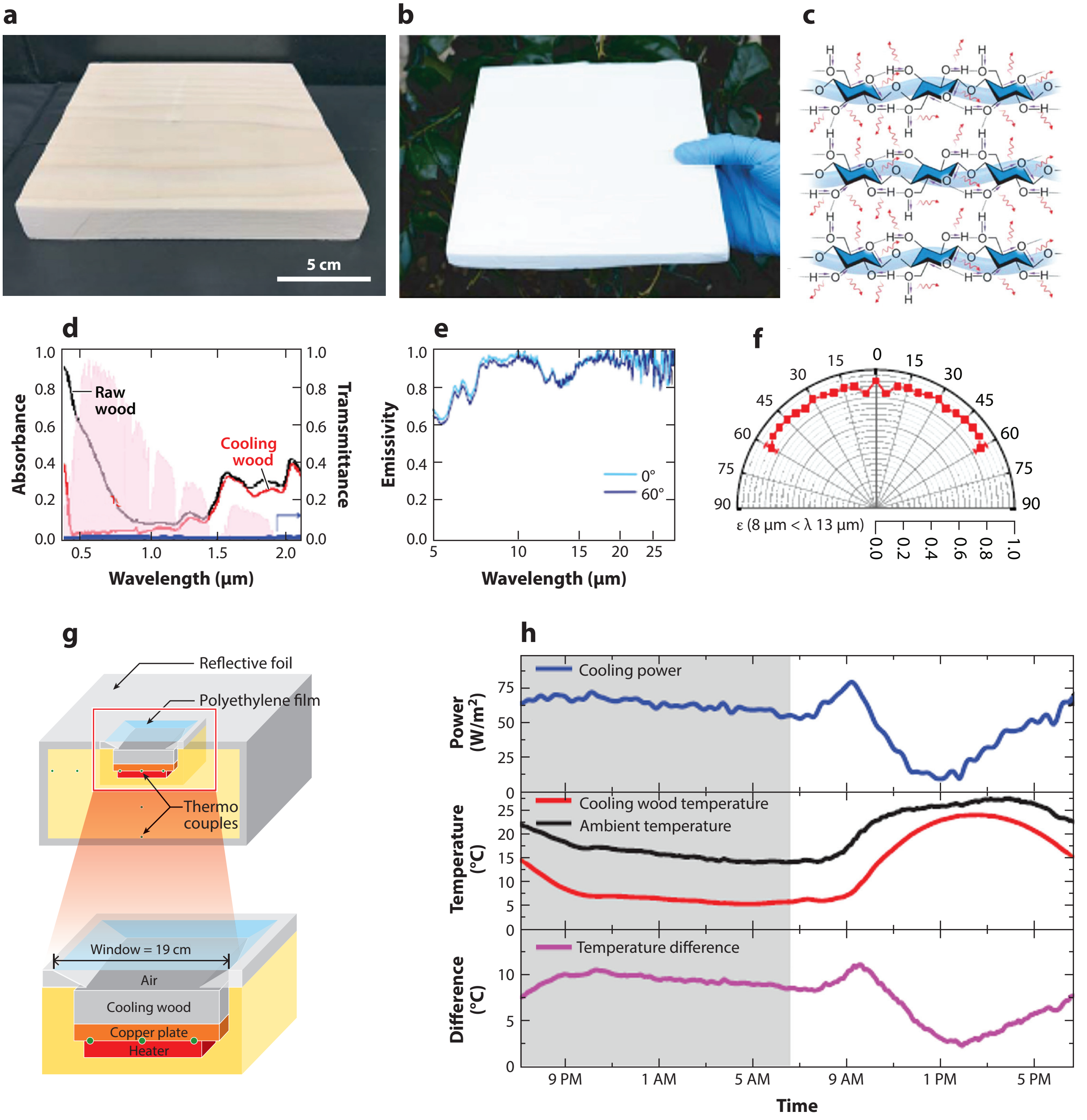

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Figure 4 (*Figure appears on preceding page*)

Radiative cooling wood. Digital images of (*a*) raw wood and (*b*) cooling wood, which effectively scatters solar irradiance, are shown. (*c*) The high-infrared emissive property of cooling wood is mainly attributed to the molecular vibration of its inherent functional groups. (*d*) Absorption and transmittance of raw wood (*black*) and cooling wood (*red*) under solar irradiance (*pink*). (*e*) Infrared (5–25 μm) emissivity spectra of cooling wood at emission angles of 0° and 60°. The chemical bond (e.g., C–C, C–O, C–H) stretching and vibration of cellulose molecules at the atomic level generate strong emissions in mid-infrared wavelengths, making the cooling wood black in the far-infrared range with a high emittance of >90% in the atmospheric window. (*f*) Polar distribution of the emissivity of cooling wood in the atmospheric window. (*g*) The device for measuring the cooling temperature and cooling power. (*h*) Cooling performance of cooling wood. (*top*, *blue*) Cooling power of cooling wood during operation. (*middle*, *red* and *black*) Cooling wood's steady-state temperature during operation. (*bottom*, *purple*) The temperature difference between cooling wood and the ambient air during operation. The cooling wood shows a mean below-ambient temperature drop of >9°C in the nighttime and of >4°C during midday. Panel *a* adapted from Reference 38 (CC BY-NC 4.0). Panels *b*–*h* adapted from Reference 43.

the high infrared emittance allows for the reflection of incoming solar radiation during daytime and the dissipation of heat from the cooling wood into the ultracold universe (**Figure 4*d*–*f***). The cooling power and the subambient radiative cooling temperature of the cooling wood with dimensions of 200 mm × 200 mm were tested using a feedback-controlled heating system (**Figure 4*g***). The cooling wood with a high radiative cooling power of 53 W/m^2 shows a mean below-ambient temperature drop of >9°C in the nighttime and of >4°C during midday (**Figure 4*h***). Meanwhile, the tensile strength of cooling wood is ~400 MPa, which is roughly eight times higher than that of raw wood. This mechanically robust, scalable, and sustainable cooling-wood material is expected to be used in future energy-efficient buildings, significantly reducing greenhouse gas emissions and energy consumption. Despite significant cooling performance and improved mechanical performance compared with natural wood, cooling wood will require additional treatment to improve fire resistance, anticorrosive, moisture resistance, and antifungal properties.

4. ENGINEERED WOOD FOR LIGHT MANAGEMENT

Transparent glass is widely used in buildings for its optical visibility, comfort, and strength (44, 45). However, conventional glass windows may cause uncomfortable glare and undesirable shadows, often requiring additional daytime lighting or shielding such as blinds and curtains (46). Furthermore, glass production is an energy-intensive process that depends on the direct combustion of fossil fuels such as oil and natural gas (47). Therefore, there is an urgent need for more sustainable processes and materials that meet the increasing global demand for transparent structural materials while also alleviating global energy shortages.

Since 2016, the Hu and the Berglund groups have made a series of contributions to the development of transparent wood by directly engineering natural wood (18, 48–54). For example, the Hu group (17) has developed a transparent wood composite that can be used as an energy-efficient, light-harvesting building material. **Figure 5** shows the major fabrication strategies, which include two steps: (*a*) removal of lignin (the light-absorbing component) and (*b*) infiltration of a refractive index (~1.56)–matching polymer (e.g., epoxy) (17). The transparent wood composite features a high optical haze of ~80% (haze is defined as the ratio of diffusely transmitted light to total transmitted light) and a high transmittance of >85% and can transmit sunlight while avoiding glare, thus providing meaningful energy savings and comfortable indoor lighting (17). Thanks to the high haze of transparent wood, the indoor lighting can be kept uniform. Additionally, the transparent wood exhibits excellent mechanical robustness (~100 MPa), as well as high impact energy absorption capacity and ductility, which effectively eliminates the safety issues often encountered when using glass materials.

The transmittance of transparent wood is generally lower than that of polymers (~95%) and drops significantly as the thickness increases (58), which is due most often to the light-scattering

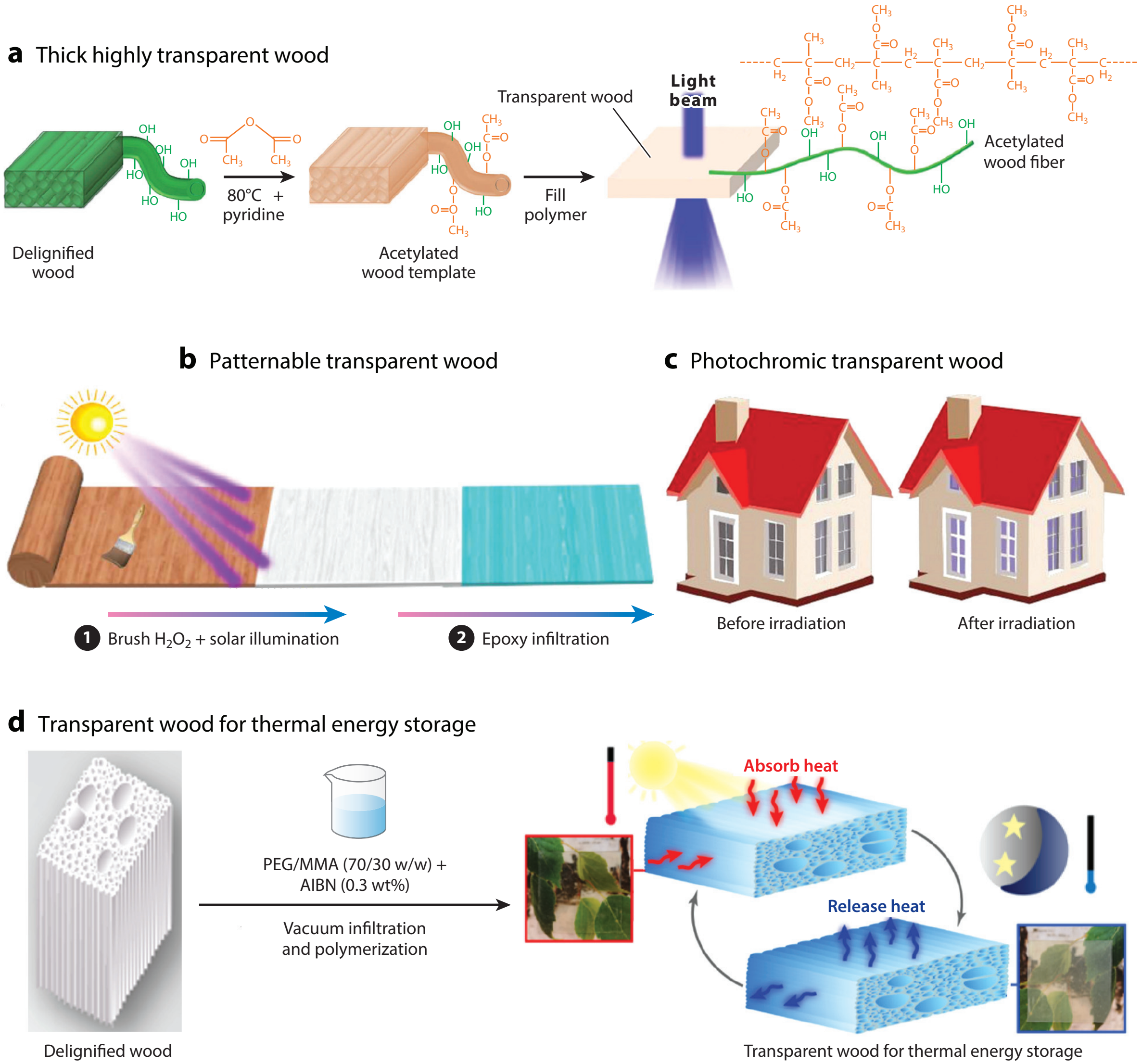

Figure 5

Engineered wood for light management. (*a*) Thick (∼1 cm) transparent wood. The compatibility between the PMMA and wood template can be greatly improved by applying surface acetylation to the delignified wood template, followed by the infiltration of PMMA. Panel adapted from Reference 50 with permission from the Royal Society of Chemistry. (*b*) Clear wood with low haze and high transmittance. The ultraviolet-assisted H_2O_2 brushing method that removed only the lignin chromophores and retained the lignin as a bio-binder provided a strong and porous template for polymer infiltration and significantly reduced chemicals, water, operation time, and electricity consumption needed in the fabrication process. Panel adapted with permission from Reference 55 (CC BY-NC 4.0). (*c*) Photochromic transparent wood. A mixture of the photochromic material DNSE and MMA was introduced into a bleached wood substrate to impart transparent wood with a photochromic function. Panel adapted from Reference 56 with permission from the Royal Society of Chemistry. (*d*) Transparent wood for thermal energy storage was developed by infiltrating the delignified wood with a mixture of PEG and MMA. Panel adapted with permission from Reference 57; copyright 2019 American Chemical Society. Abbreviations: AIBN, 2,2′-azobis(2-methylpropionitrile); DNSE, 30,30-dimethyl-6-nitro-spiro[2H-1-benzopyran-2,20-indoline]-10-ethanol; MMA, methyl methacrylate; PEG, poly(ethylene glycol); PMMA, polymethyl methacrylate.

effect caused by cracks and voids (on the order of hundreds of nanometers) at the interface between the infiltrated polymer [e.g., polymethyl methacrylate (PMMA)] and wood cell walls. These drawbacks have been overcome by employing a modified fabrication method. Li et al. (50) reported that the compatibility between the PMMA and wood template can be greatly improved by applying surface acetylation to the delignified wood template prior to the infiltration of PMMA. This method can create a defect-free wood–polymer interface, hence increasing the light transmittance of transparent wood (**Figure 5*a***) (50). The 1.5-mm-thick transparent wood exhibited a transmittance of 92%, close to that of PMMA. To reduce the haze (e.g., <20%) of transparent wood, Mi et al. (48) utilized a prolonged delignification process to eliminate lignin and hemicellulose, generating large numbers of CNFs with diameters shorter than visible light wavelengths. Polyvinyl alcohol (PVA), an environmentally friendly polymer with a good wettability for wood substrate and a well-matched optical refractive index, was introduced into highly porous delignified wood, resulting in a highly compact transparent wood. The prolonged bleaching process, combined with the infiltration of a well-matched refractive index polymer into the delignified wood, dramatically reduced scattering in the transparent wood, leading to low optical haze and high transmittance. The transparent wood shows a simultaneous low haze of ∼15% and high transmittance of ∼91%, suitable for being used as window material.

Traditional methods for preparing transparent wood usually require high chemical, water, and energy consumption. The Hu group (55) developed a transparent wood by modifying the lignin structure of wood using an ultraviolet (UV)-assisted chemical (H_2O_2) brushing strategy (**Figure 5*b***). This method removed only the lignin chromophores and retained the lignin as a bio-binder, provided a strong and porous template for polymer infiltration, and significantly reduced chemical, water, operation time, and electricity consumption. The prepared transparent wood shows a high haze (>60%) and a high light transmission (>90%). Most previous research on transparent wood has emphasized its microstructural, optical, mechanical, and thermal properties, while little research has been conducted regarding how to maintain the natural aesthetics of the wood's inherent annual growth rings. Recently, Mi et al. (59) reported a transparent wood with aesthetic features (e.g., intact annual growth rings) and outstanding optical properties (a transmittance of ∼80% and a haze of ∼93%) through a spatially selective delignification and epoxy resin infiltration process. The transparent wood's unique aesthetic is derived from the annual growth rings of softwood (e.g., Douglas fir), with early wood (spring wood) having low lignin content, low density, and large cell diameters and late wood (summer wood) the opposite.

More recently, transparent wood has been used as a scaffold for multifunctional transparent materials. For instance, luminescent transparent wood was produced by infiltrating PMMA with well-dispersed luminescent $g\text{-}Fe_2O_3@YVO_4{:}Eu^{3+}$ nanoparticles or quantum dots (60, 61). Uniform dispersion of luminescent substances in the PMMA filtration polymer is the key to obtaining excellent optical and luminescence performance. Using the same strategy, transparent wood with heat and UV shielding properties has also been developed by incorporating functional Cs_xWO_3 nanoparticles and modified antimony-doped TiO_2 nanoparticles into the infiltration polymer (62, 63). The Cs_xWO_3/transparent wood composite exhibits a transmittance of 96% in the visible light region and a superior near-infrared shielding capability (64).

Transparent wood can also be used as a template for fabricating smart windows (**Figure 5*c***). Reynolds and coworkers (36) coat a conjugated-polymer-based transparent conducting electrode layer on the surface of transparent wood. The electrochromic devices produced with this method show a magenta-to-clear color change because of the extraordinarily colorless bleached state. A color switch can be triggered by an ultralow energy input of 3 mWh/m^2 (equivalent to a power input of 2 W/m^2) owing to the low driving voltage of ∼0.8 V and the high coloration efficiency of ∼590 cm^2/C. The excellent performance highlights transparent wood's potential applications in smart windows. As another example, a transparent wood-based smart window was prepared by depositing a liquid crystal film on top of transparent wood with low haze and high transmittance (64). In this work, electric power was applied to manipulate the alignment of liquid crystals in the coating layer, switching the smart window between a transparent state when a current was applied and a hazy state (which can potentially be used for privacy protection) when not. In another study, a mixture of the photochromic material 30,30-dimethyl-6-nitro-spiro[2H-1-benzopyran-2,20-indoline]-10-ethanol and prepolymerized methyl methacrylate (MMA) was introduced into a bleached wood substrate to impart transparent wood with a photochromic function (**Figure 5*c***) (56). Multifunctional window materials can also be fabricated via surface coating. For example, smart windows with a magenta-to-clear color change function were produced by coating transparent wood with a thin layer of electrochromic material, poly(3,4-ethylenedioxythiophene):poly(styrene sulfonate), as a transparent electrode (56). These transparent wood materials show potential in strong, energy-saving, switchable, and colored smart windows. In a more recent study, the Berglund group (57) developed a new type of transparent wood, which can be used for thermal energy storage, by infiltrating the delignified wood with a mixture of polyethylene glycol and prepolymer MMA (**Figure 5*d***). The transparent wood shows an excellent latent heat capability of ∼76 J/g, tunable optical transparency, low thermal conductivity, and excellent thermal stability. These properties ensure the applications of transparent wood in heat transfer control for future energy-efficient buildings.

All in all, transparent wood-based materials, derived from earth-abundant, sustainable, and low-cost sources, demonstrate favorable light and thermal management properties, that is, visible light redirection and better thermal insulation properties. To promote applicability, more effort should be devoted to understanding the roles of various light–cellulose–polymer interaction mechanisms so that the refractive index mismatch between the infiltrated materials and wood cells can be further minimized. From a manufacturing viewpoint, scaling up and reducing the amount of the infiltration material toward producing all-wood transparent wood are sought after by the industrial community. In addition, efforts need to be made to improve the weatherability (particularly the durability under extreme weather) and light stability to meet the criteria of practical applications. It is anticipated that functionalized transparent wood can be developed to meet the requirements of versatile energy-efficient building applications that traditional glass is not able to achieve.

5. ENGINEERED WOOD FOR WATER TREATMENT

One of the key challenges of our time is the clean water shortage. The hierarchical porous property of raw wood makes it a promising material for water treatment. Different modification strategies such as carbonization, polymer filling, particle immobilization, and chemical treatment can tune the properties of wood materials toward different water treatment methods (65–69). Of these, filtration, solar desalination, and membrane distillation (MD) are three of the most widely used methods for producing clean water.

With appropriate engineering modifications or structural tuning, such as the introduction of functional materials (e.g., metal-organic frameworks) into the microchannels, direct carbonization, or grafting metal nanoparticles (e.g., silver or palladium) or functional groups (e.g., carboxyl) throughout the microchannels, wood can be engineered into a membrane filter that effectively removes contaminants (such as organic pollutants, bacteria, dyes, heavy metals, or inorganic particles) (65, 66, 68, 70–73). The Berglund group (74) developed a strong and mesoporous wood-based device for selective separation of water and oil by infiltrating hydrophilic delignified wood substrate with epoxy (Jeffamine D-400 polyetheramine and bisphenol A diglycidyl ether), which remedies the problem of marine oil spills and industrial oily wastewater (**Figure 6*a***).

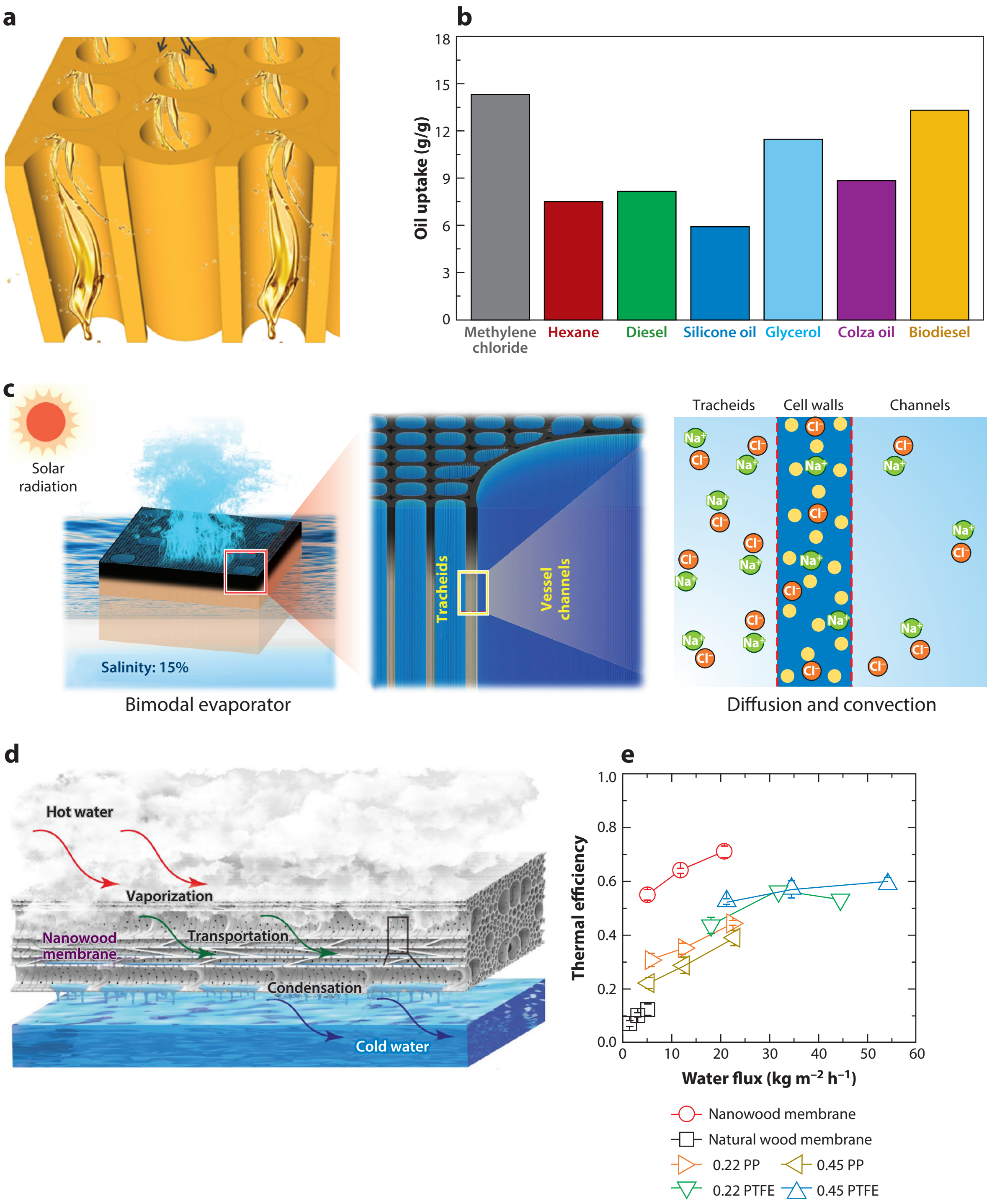

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Figure 6 (*Figure appears on preceding page*)

Engineered wood for environmental remediation. (*a*) The porous delignified wood/epoxy biocomposite for effective separation of oil–water mixtures, which was developed by infiltrating hydrophilic delignified wood substrate with epoxy. (*b*) Adsorption performance of delignified wood/epoxy biocomposites for different kinds of oil. Panels *a* and *b* adapted with permission from Reference 74; copyright 2018 American Chemical Society. (*c*) The mechanism of bimodal porous balsa as a stable evaporator for efficient desalination of high-salinity brine. The wide vessel channels ensure sufficient brine replenishment on the top surface when clean water vapor is produced, and effective lateral brine diffusion through the ray cells and pits also prevents salt buildup. Panel adapted from Reference 75 with permission from the Royal Society of Chemistry. (*d*) Membrane distillation using a porous hydrophobic wood membrane. Water vapor is transferred through the wood membrane and then condensed on the cold permeate side, achieving water vapor separation. (*e*) Thermal efficiency of wood membranes and commercial membranes as a function of water flux. Panels *d* and *e* adapted with permission from Reference 76 (CC BY-NC 4.0). Abbreviations: PP, polypropylene; PTFE, polytetrafluoroethylene.

The hydrophobic and oleophilic delignified wood/epoxy composite displays an oil absorption rate of up to 15 g/g (**Figure 6*b***). Due to the honeycomb structure of wood, the wood/epoxy biocomposites have moduli and compressive strengths of 263 MPa and 18 MPa, respectively (74). Another advantage of engineered wood filters is the high membrane flux due to the straight microchannels, in which wastewater can quickly flow through the porous wood structure and be treated. Engineered wood filters demonstrate both high efficiency and high throughput, providing a promising strategy for cost-effective and sustainable clean water production.

Solar steam generation is an ancient technology that has seen a resurgence of interest due to its efficiency, ease of operation, use of renewable solar energy, and low cost. It is well known that a living tree continuously circulates water upstream from the ground through the wood's vessel channels and tracheids by transpiration. Based on this phenomenon, a range of wood-derived solar evaporators have been developed to take advantage of the inherent microstructure and properties of natural wood (such as the well-oriented microchannels and hydrophilic property) that facilitate rapid water transport. As strong solar absorption is important for achieving high evaporation rates and efficiencies, researchers have developed various modification methods such as carbonization or the introduction of various nanostructured light-absorbing materials (such as narrow-gap semiconductors, metal nanoparticles, graphene oxide, polypyrrole, graphite, or carbon nanotubes) through dip- or spray-coating or hydrothermal synthesis to increase solar absorption across the solar spectrum from less than 30% for PW to close to 100% (77–82). Of these methods, surface carbonization is the easiest and most cost-effective. The Hu group (77) developed a wood-derived solar evaporator with a bilayer structure through surface carbonization. This bilayer structure design shows advantages for solar evaporation such as high light absorption (∼99%), fast water transport, and high evaporation rate [11 $kg/(m^2 \cdot h)$ under 10 sun illuminations]. The water vapor generated is then collected as clean water that meets World Health Organization standards (82).

In many previous wood-based solar evaporators, clean water vapor has been produced. However, salt can accumulate on the evaporator's surface during the process of solar desalination (83–85). The accumulated salts can significantly reduce the photothermal conversion efficiency and can even obstruct the water path, therefore greatly decreasing the water evaporation rate of the device. Innovative strategies have been proposed to address the problem of salt buildup on wood evaporators, such as (*a*) the use of well-designed artificial channel arrays in PW substrates, (*b*) the use of balsa with naturally large vessel channels followed by carbonization, and (*c*) surface carbonization combined with hydrophobic modification (75, 86, 87). For example, the rapid diffusion and convection of water in the bimodal porous structure of balsa, drilling macroholes (diameter of ∼1.5 mm) in basswood, and the capillary pumping of microchannels (diameters of 180–390 μm) within the wood evaporator allow for rapid replenishment of surface-evaporating brine, as well as being desirable for continuous and rapid water vapor production (**Figure 6*c***). During operation, the salt concentration in the narrow tracheids increases because of the fast vaporization of the surface brine. The tracheids are relatively narrow and cannot provide sufficient salt water replenishment in time, so the high concentration of salt water in the tracheids gradually diffuses to nearby artificial macrochannels or large vessel channels through ray cells and pits. The surrounding vessel channels or artificial macrochannels prevent the growth of salt particles on the evaporator surface and thus greatly facilitate brine convection.

In addition to wood-based evaporators, the membrane of silane-coated hydrophobic delignified wood (i.e., nanowood), which exhibits a low thermal conductivity of ~0.04 W/(m·K) and a high porosity of ~90%, was also proposed to replace traditional polymeric materials for high-performance MD. MD is a thermally driven water vapor separation process in which water vapor is transferred through a porous hydrophobic membrane and then condensed on the cold permeate side (**Figure 6*d***) (87). Since both the micropores (e.g., ray cells and pits) inherited from natural wood and nanopores generated during delignification decrease the water vapor transfer resistance and improve the temperature gradient, the membrane demonstrates an excellent thermal efficiency of 71 ± 2% and ensures a high water flux of 20.8 ± 0.8 kg/(m·h) (**Figure 6*e***). The vapor flux of the membrane can be further increased as the thickness of the wood membrane is reduced (approximately 500 μm compared with approximately 100 μm for commercial polymer membranes), and therefore, in future research, advanced manufacturing techniques are needed to make wood veneers larger, thinner, and less costly.

Despite the great potential of engineered wood in solving water scarcity problems, a great deal still needs to be done before it can be used in wastewater treatment plants. Efforts should be made to improve the stability, homogeneity, and regenerability of wood-based water treatment devices, as well as develop large-scale water treatment devices to solve real water pollution problems (sewage, seawater, industrial wastewater, etc.). The economic and environmental benefits of these wood-based water treatment devices need to be quantified and compared with commercially available water treatment devices, and pilot experiments need to be carried out.

6. ENGINEERED WOOD FOR NANOFLUIDICS

Due to their excellent performance in regulating nanoscale ion transport, nanofluidic membranes with surface-charged nanochannels have great potential for applications such as energy generation (88, 89), desalination (90), ion molecular separation (91, 92), DNA sequencing (93), and biosensors (94). Ion transport in nanofluidic channels differs significantly from that in bulk owing to the unique nanoconfinement effects (95). Fast ion transport can be realized by the nanoconfinement effect, which is of great significance for these emerging applications.

The wood cell walls comprise numerous CNFs that penetrate lignin and hemicellulose, which act as a framework for many well-aligned nanochannels for ion transport between neighboring CNFs after delignification treatment. Cellulose molecular chains contain many reactive hydroxyl groups and can easily be modified to modulate the surface charge density. The presence of numerous nanochannels and their regulatable surface charge properties sets wood apart as a promising material for the preparation of nanofluidic membranes. The nanochannel size (e.g., from 20 nm to 2 nm), surface charge properties (e.g., potential and density), and/or the molecular geometry [e.g., coordination of copper ions (Cu^{2+}) and the crystal structure transformation from cellulose I to allomorph cellulose II through the mercerization process where natural cellulose fibers are first soaked and swollen in a concentrated NaOH solution, and then rinsed using deionized water and dried] (19, 96) of wood-based materials play a crucial role in the ion transport behavior of wood-based nanofluidic membranes (19, 96). Modulating these factors through physical or chemical modifications [delignification (96), etherification (97), oxidation treatments (96), densification (96), swelling, stretching (98), hybridization (99), ion intercalation/exchange (19), and so on] is an effective way to regulate ion transport. For example, Li et al. (96) developed a nanofluidic wood membrane containing densely packed CNFs by the delignification of natural basswood. After the removal of cellulose and hemicellulose, large numbers of nanochannels were created in the vast array of 1D CNFs. The many reactive hydroxyl groups in cellulose make it possible to regulate its surface charge density via chemical modifications (e.g., oxidation treatments). Oxidation treatments (e.g., 2, 2, 6, 6-tetramethyl-1-piperidinyloxy treatment) are effective in reducing the zeta potential of cellulosic materials by converting the hydroxyl groups on the cellulose backbone into carboxyl groups (**Figure 7*a***) (96). These carboxyl groups are more inclined to dissociate into carboxylates with negative surface charge. Consequently, the zeta potential of the oxidized membrane can reach -78 mV compared with -45 mV for the unoxidized wood membrane (**Figure 7*a***), which leads to conductivity of $\sim$2 mS/cm in the surface-governed ion transport region for the oxidized wood membrane (below 10^{-3} M) compared with that of the unoxidized wood membrane (1.1 mS/cm) (**Figure 7*b***). Additionally, by modification of the reactive hydroxyl group on the cellulose chain to a cationic functional group $[(CH_3)_3N^+Cl^-]$, negatively charged wood membrane (-27.9 mV) can be converted to positively charged ($+37.7$ mV) wood membrane, enabling reversible conversion of the surface charge potential and thus modulating ion selectivity (97). Furthermore, after densification treatment, the mean diameter of the nanochannels significantly decreased from $\sim$20 nm to $\sim$2 nm, while the ionic conductivity increased by an order of magnitude in the low concentration range ($<10^{-2}$ mol/L) (96).

Apart from ionic conductivity and selectivity, other factors such as material stability, mechanical strength, and scalability are also important for nanofluidic membranes. Although the delignification treatment significantly increased the ionic conductivity of wood-derived nanofluidic membranes, the removal of the hydrophobic lignin binder negatively affected the stability and mechanical strength of the material in a liquid solution. It is challenging to increase the ionic conductivity without sacrificing the stability and mechanical performance of the material. To address these challenges, cross-linking methods can be used to improve the mechanical performance and water stability of wood-derived nanofluidic membranes by infiltrating polymeric networks such as polyacrylamide or PVA/acrylic acid (AA) into the microchannels of delignified wood, resulting in a material called wood hydrogel (**Figure 7*c***) (100, 101). To form polymeric hydrogels within balsa wood microchannels, most of the hemicellulose and some of the lignin were first removed by partial delignification followed by polymerization of PVA/AA (**Figure 7*d***) (101). The polymer hydrogel network not only is tightly bound to the CNFs through hydrogen bonding but also provides additional nanochannels with increased surface charge density for rapid ion transport, leading to the enhanced ionic conductivity (1.29 mS/cm along the longitudinal direction) and tensile strength (52.7 MPa) of the membrane (**Figure 7*e***). This integration of excellent mechanical performance, water stability, and fast ion transport is also realized in a wood ionic cable through partial delignification of natural wood followed by twisting the wood (101).

Although progress has been made in the last decade, continued efforts are needed from academia and industry to address issues faced in practical applications, such as fine-tuning the surface charge and geometry of nanochannels to improve ion transport and regulation, increasing performance reliability, reducing manufacturing costs, improving antifouling properties, and exploring emerging applications such as salinity-gradient power generation, seawater desalination, thermoelectric conversion, and batteries (19, 101, 102).

7. ENGINEERED WOOD FOR BATTERIES

Engineered wood can inherit the hierarchically porous structure of natural wood (such as macrochannels, microscale pits, and nanosized pores), which provides pathways for the multiphase

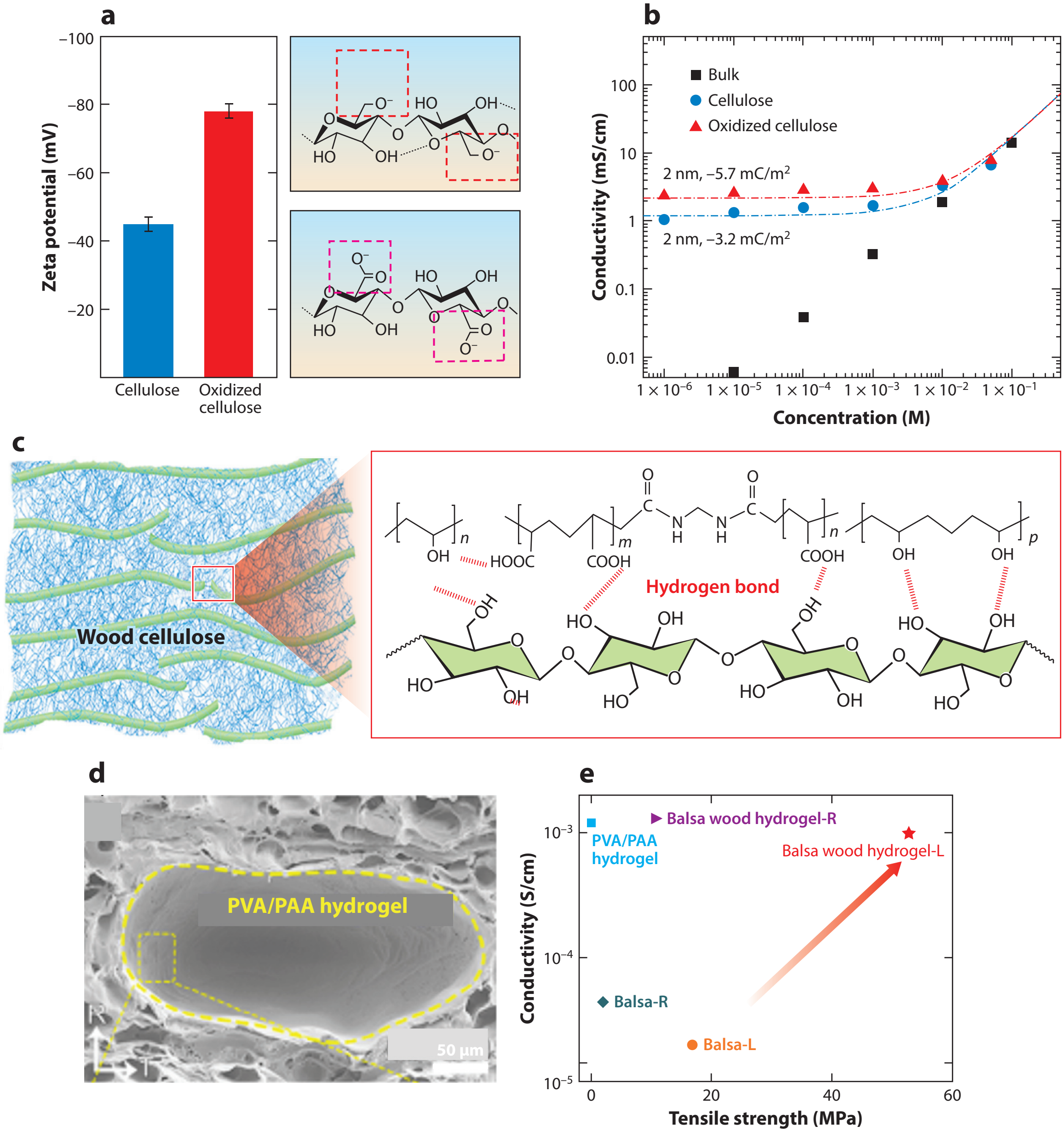

Figure 7

Engineered wood for nanofluidics. (*a*) Zeta potential of original wood and oxidized or surface-charged wood membrane at pH 6.5. (*b*) Ionic conductivity of the original wood, oxidized wood membrane, and bulk solution. The oxidized cellulose shows an enhanced ionic conductivity plateau due to its high surface charge. Panels *a* and *b* adapted from Reference 96 (CC BY-NC 4.0). (*c*) Hydrogen bonding between PVA/PAA molecular chains and cellulose nanofibers in the wood hydrogel. (*d*) Scanning electron microscopy image of the wood hydrogel shows that the PVA/PAA hydrogel network is well distributed throughout the vessel channels. (*e*) Compared with original wood and PVA/PAA hydrogels, the wood hydrogel nanofluidic membrane exhibits higher ionic conductivity and higher tensile strength. Panels *c*–*e* adapted from Reference 101; copyright 2021 American Chemical Society. Abbreviations: L, longitudinal; PAA, polyvinyl alcohol; PVA, polyvinyl alcohol; R, radial.

transport of electrons, ions, and gases. The rapid transport of electrons and ions is essential for obtaining rechargeable batteries with high energy density.

To construct electron transfer pathways in engineered wood, conductive modification strategies such as the direct carbonization of wood or the introduction of conductive materials are usually adopted (103–106). The carbonization treatment endows natural wood with high electrical conductivity while maintaining the porous structure of the wood so that it can be used as battery material when filled with catalysts (106–108). For example, the development of highly efficient and cost-effective oxygen reduction/evolution reaction bifunctional electrocatalysts is important for achieving high-performance zinc–air batteries (ZABs) (109). Recently, the Zhong group (110) reported the in situ synthesis of single-atom Fe−N−C catalysts in CW through a simple Lewis acid pretreatment and carbonization (**Figure 8*a***). Lewis acid pretreatment of wood not only produces numerous nanopores on the wood cell wall but also introduces large amounts of Fe–N active species into the mesoporous wood template. The catalyst was further used as cathode material for ZABs that exhibit a high power density of 70.2 mW/cm^2 and long-term stability (200 h, 5 mA/cm) (**Figure 8*b***).

Although higher electrical and ionic conductivity can be obtained with carbonization treatment, the strength and toughness are significantly reduced, which is not conducive to practical applications. The introduction of conductive materials into the wood microstructure can preserve the mechanical properties of the wood while simultaneously maintaining a balance between the mechanical performance and conductivity of the wood (110, 111). For instance, pristine balsa can be transformed into a flexible and conductive wood-derived cathode for high-capacity, long-life lithium–oxygen (Li–O_2) batteries via the partial removal of lignin followed by the introduction of conductive carbon nanotubes (CNTs) and ruthenium catalyst nanoparticles (107). In addition to electrons moving through the conductive networks of CNTs, oxygen and ions can transport through the electrolyte-filled nanochannels and the open microchannels in the wood-based cathode. This unique tri-pathway design enables the noncompetitive transport of Li^+ ions, oxygen molecules, and electrons in the wood-based Li−O_2 battery. Due to this unique design, a high-performance Li−O_2 battery that exhibits an overpotential as low as 0.85 V at 100 mA/g, an area capacity as high as 67.2 mAh/cm^2, and a cycling life of 220 cycles can be fabricated (107). In addition, the thick wood-based cathode demonstrates excellent flexibility, representing a promising approach for addressing the dilemma of balancing electrode thickness and flexibility.

Wood can also be used as a high-performance ionic conductor for solid electrolytes and a conductive network for Li-metal batteries. Solid polymer electrolytes (SPEs) such as poly(ethylene oxide) have great potential because of their ease of processing, strong capability to dissociate Li salts, low density, and excellent interfacial contact with electrodes (112). Although Li-metal-stable polymeric ion conductors typically display good interfacial compatibility and mechanical properties, the transport of lithium ions in SPEs is coupled with the polymer segmental motion, resulting in inferior ionic conductivity and Li^+ transfer numbers (113). To achieve a high-performance solid polymer ion conductor, a new strategy has been developed, one based on opening the angstrom-scale channels within the molecular structure of cellulose and decoupling lithium-ion transport from polymer segment relaxation by the chelation of copper ions (Cu^{2+}) with CNFs in wood (**Figure 8*c***) (19). The coordination of Cu^{2+} with CNFs altered the crystal structure of cellulose, allowing for the insertion and fast transport of Li^+ ions by enlarging the spacing between the cellulose chains into angstrom-scale channels. The Li^+-inserted Cu–CNF ionic conductor exhibits a high Li^+ transference number of 0.78 and a high ionic conductivity of 1.5×10^{-3} S/cm (**Figure 8*d***) (19). The molecular-channel engineering strategy provides a conceptual breakthrough for developing fast ion conductors that have a wide range of implications, potentially going beyond safe solid-state batteries.

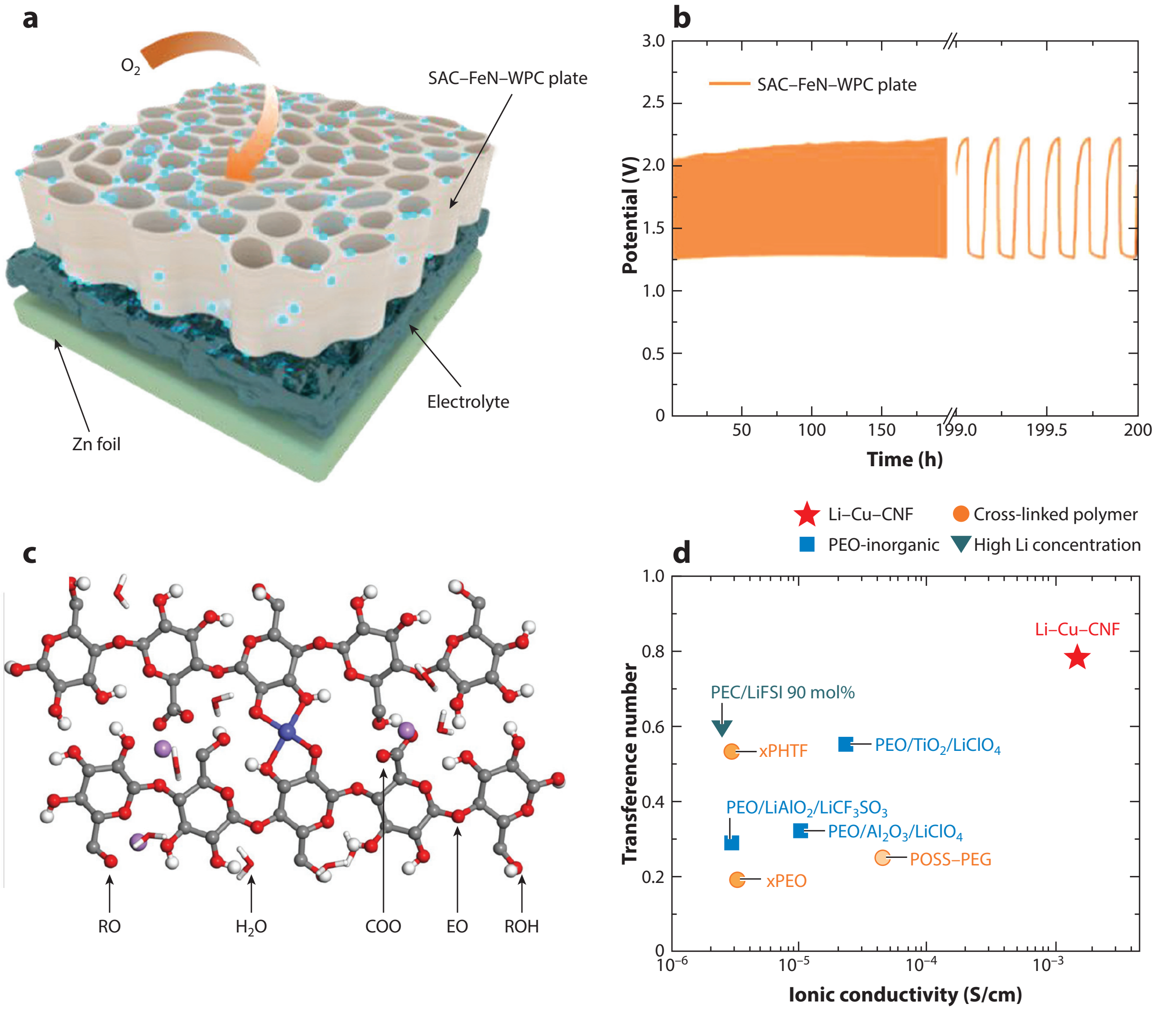

Figure 8

Engineered wood for battery applications. (*a*) The rechargeable quasi-solid-state ZAB using SAC–FeN–WPC as the cathode material. (*b*) Galvanostatic charge/discharge cycling curves of the ZAB at 5 mA/cm^2. Panels *a* and *b* adapted from Reference 110; copyright 2021 American Chemical Society. (*c*) The atomic arrangement of Li$^+$ in Li–Cu–CNF. The coordination of Cu^{2+} with CNFs altered the crystal structure of cellulose, allowing for the insertion and fast transport of Li$^+$ ions by enlarging the spacing between the cellulose chains into angstrom-scale channels. (*d*) The Li$^+$ transference number (ratio of current carried by the Li ion to the total current) versus ionic conductivity in Li–Cu–CNF compared with other previously reported SPEs. The Li$^+$-inserted Cu–CNF ionic conductor exhibits a high Li$^+$ transference number of 0.78 and a high ionic conductivity of 1.5 × 10^{-3} S/cm. Panels *c* and *d* adapted from Reference 19. Abbreviations: CNF, carbon nanofiber; PEC, poly(ethylene carbonate); POSS–PEG, polyhedral oligomeric silsesquioxane–poly(ethylene glycol); PEO, poly(ethylene oxide); PHTF, polytetrafluoroethylene; SAC, single-atom catalyst; SPE, solid polymer electrolyte; WPC, wood-based porous carbon; ZAB, zinc–air battery.

While engineered wood shows several advantages for battery technologies, additional effort is needed to meet the requirements of practical applications. Advanced manufacturing technologies for precise structural modification of conductive wood at the nano- and molecular scales should be developed to finely manipulate electron and ion transport at multiple scales.

8. ENGINEERED WOOD FOR LIGHTWEIGHT STRUCTURAL MATERIALS

Due to their high mechanical strength, synthetic structural materials such as steel and concrete have been widely used in construction, particularly in commercial buildings. However, these materials usually suffer from low strength-to-weight ratios, high initial cost, and high greenhouse gas emissions (114, 115). Natural wood has been used in construction (e.g., as walls, frames, and floors) since ancient times. However, its mechanical properties can hardly meet the requirements of advanced engineering building applications. Although traditional strengthening methods such as cold rolling or pretreatment with ammonia (116), steam explosion (117), or heat (118) followed by a hot-press process can increase the mechanical properties of natural wood to some extent, they usually lead to partial or incomplete densification.

Recently, there has been increasing interest in the development of effective methods to fabricate high-strength wood-based structural materials with densely packed structure through complete densification treatment (119–122). One of the most promising strengthening strategies for wood-based materials is to create a strengthened hydrogen bonding network while generating physical entanglement of cellulose fibers. The Hu group (122) has reported an effective two-step method to fabricate high-performance bulk structural materials with significantly improved mechanical properties directly from natural wood. The method involves a partial delignification process followed by high-temperature densification that can largely eliminate the pores in the natural wood, yielding a highly compact microstructure with the inherent high alignment of CNFs being well preserved. The obtained densified wood (referred to as super wood) exhibits a tensile strength of ∼549 ± 47 MPa and a toughness of as high as 3.9 ± 0.2 MJ/m^3, which are ∼12 times and ∼10 times higher than those of natural wood, respectively (122). The simultaneously improved strength and toughness of super wood is a milestone along the path toward development of green structural materials. The specific tensile strength of the super wood is ∼420 ± 40 MPa cm^3/g, higher than some structural materials such as metals and alloys widely used in the building industry (122).

Studies have shown that densification of fully delignified wood results in a smaller strength increase than in super wood prepared by partial delignification treatment (123, 124). For example, Han et al. (123) reported a wood-based structural material with a tensile strength of 352 MPa through complete delignification combined with densification treatment. The high mechanical performances were largely attributed to the water-mediated hydrogen bonding network, which was strengthened during hot pressing (123). In another instance, the Burgert group (124) adopted a top-down strategy to produce high-performance cellulose bulk structural material. Special attention was paid to optimizing the delignification process and applying new techniques for densification. They used a bleaching agent consisting of hydrogen peroxide and acetic acid to remove lignin in natural wood blocks; this process maintains the alignment of cellulose fibers to a maximum extent (124). In addition, when applying compression during densification, the delignified wood is subjected to a transverse shear force to further increase the density and induce a unique microstructure of entangled cellulose fibers with a high degree of directional alignment (124). The mechanical properties of the cellulosic materials produced using the improved delignification and densification methods are characterized by uniaxial tensile stress–strain curves. For the highly densified 95% relative humidity samples, a tensile strength of ∼270 MPa could be obtained, which is much higher than that of natural wood. Following a similar strategy, Dong et al. (125) transformed low-value wood (including decayed, disposed, fractured, damaged, or residual wood) into new structural materials with a tensile strength of 400 ± 40 MPa through delignification, partial dissolution, and regeneration (**Figure 9*a***).

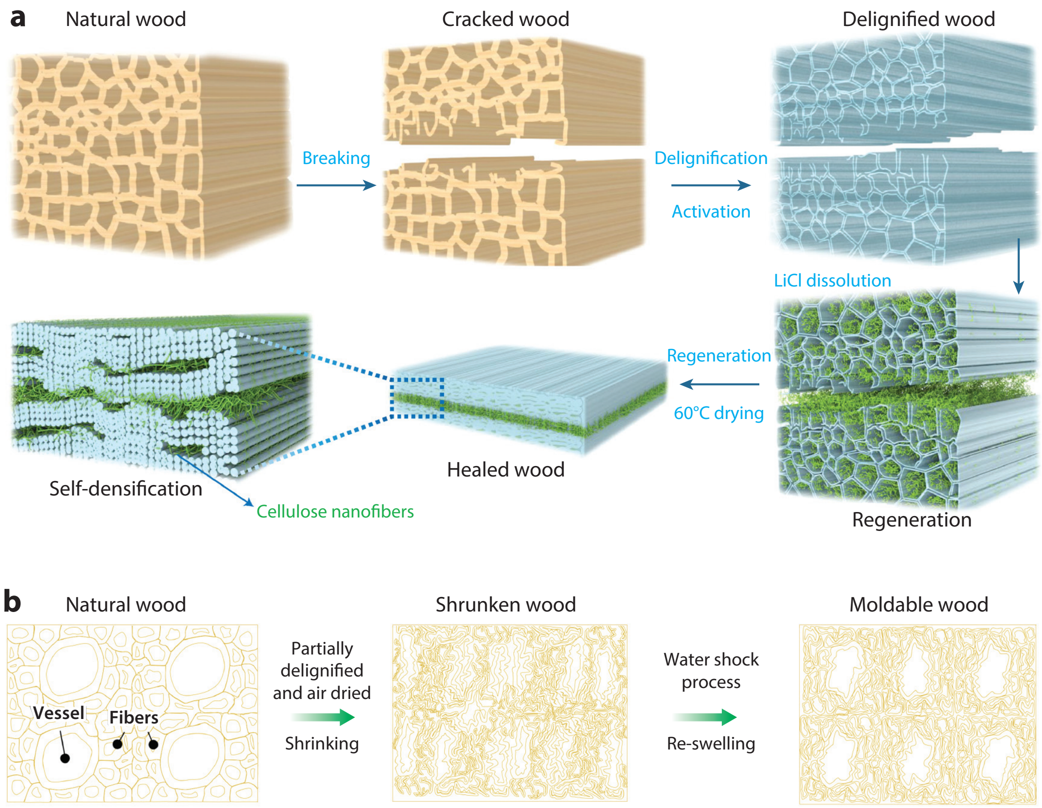

Figure 9

Wood-based structural materials. (*a*) Schematic illustrating the wood healing process. Low-value wood wastes can be transformed into new structural materials with a tensile strength of 400 MPa through delignification, partial dissolution, and regeneration. Panel adapted with permission from Reference 125. (*b*) The fabrication process of moldable wood. A cell wall–engineering strategy was used to develop moldable wood by partially removing the lignin in the wood, collapsing the microchannels through an air-drying process, and finally selectively opening the vessel channels in a fast water-shock process. Panel adapted from Reference 126.

Although wood is a green structural material, shaping it while maintaining its mechanical performance can be a challenge. Recently, Xiao et al. (126) developed a moldable wood using a cell wall–engineering strategy to shape sheets of basswood into 3D moldable wood by partially removing the lignin in the wood, collapsing the microchannels through an air-drying process, and finally selectively opening the vessel channels in a fast water-shock process (**Figure 9*b***). After these processes, the moldable wood had a wrinkled cell wall microstructure that allowed it to be molded into versatile shapes. As a result, the prepared 3D-molded wood is six times stronger than the natural wood and comparable to commercially available lightweight aluminum alloys.

Apart from the outstanding mechanical performance of engineered wood, fire retardancy is indispensable for its practical application as a structural material (127–131). Due to the densely packed microstructure of super wood, a dense charcoal layer forms on the surface of the wood once it is exposed to flame, which greatly increases the fire retardancy of the wood (132). This charcoal layer effectively prevents oxygen and heat from spreading to the interior of the super wood, contributing to the material's flame-retardant properties and gaining valuable rescue time in the event of a fire (132). The fire-retardant properties of the wood can also be enhanced by removing open pores by mineralizing calcium carbonate ($CaCO_3$) in situ within the microchannels (130, 131). Other methods, such as the infiltration of nanoclay into the wood microchannels (133), the application of a fire-resistant boron nitride– or SiO_2-based polymeric composite coating to the wood surface (134, 135), the in situ polymerization of ammonium dihydrogen phosphate with furfuryl alcohol in the wood microstructure (134, 136), or the formation of the mineral struvite within the cell walls of wood (137, 138), can also greatly improve the fire retardancy of wood materials.

Strengthening strategies based on manipulation of the well-aligned CNFs inherited from natural wood are highly promising for converting natural wood into lightweight building materials with outstanding mechanical performance. However, there is still much room for improvement. According to theoretical calculations, the strength of the highly crystalline CNFs can reach 1.6–3 GPa (139). Reaching the full potential of wood-based materials calls for an in-depth understanding of the structural roots of the mechanical properties and persistent efforts to develop new processing technologies. Note that the development of these wood-based structural materials still largely remains at a laboratory scale, and the material characterizations are carried out on small samples. Enormous challenges remain in achieving scale-up manufacturing and reducing the cost. Additional functions including water stability, corrosion resistance, and antifungal ability need to be achieved in wood-based structural materials to meet the requirements of construction materials.

9. CONCLUSION AND PERSPECTIVES

In this review, we summarize recent research progress in engineered wood toward different sustainable applications. Various strategies, such as chemical modifications, densification, polymer infiltration, carbonization, and the introduction of metal nanoparticles or organometallic frameworks, have been developed to modulate the thermal, optical, fluidic, ionic, and mechanical properties of wood for various emerging uses such as light and thermal management, nanofluidics, water treatment, batteries, and lightweight structural materials. However, challenges remain in fundamental and applied research.

The first challenge is creating high-performance materials with good product durability and service life. Currently, most modification methods have focused on enhancing the performance of wood. Little research has been conducted on the durability of wood-based materials when exposed to fire, microorganisms, water, or weathering in practical applications. This is a crucial factor to consider due to the hydrophilicity and biodegradability of the wood components. Strategies such as thermal treatment, surface coatings of polymeric or inorganic materials, and cross-linking with stable chemical bonds represent promising directions for improving engineered wood's stability without sacrificing its mechanical, thermal, and fluidic properties (140).

The second challenge is scaling up fabrication and reducing manufacturing and installation costs. Most recent nanotechnologies for wood modification have been done using small samples as the starting materials, typically <10 cm in length, width, and thickness. Scaling up production is challenging because it is difficult for the chemicals or infiltrates to diffuse into the interior of large-dimension wood samples (e.g., >15 cm). Systematic investigation of the diffusion mechanisms in wood microchannels is necessary to optimize the modification process, including studying the effects of porosity, surface chemistry, and sample size. Another approach that should be further investigated is the use of high temperature and pressure to facilitate the diffusion of chemicals in the wood microchannels, resulting in a more homogeneous modification.

A third challenge is reducing environmental pollution. Traditional chemical modification strategies require significant amounts of chemicals, electricity, and process water and generate large amounts of wastewater and toxic gasses. Production of truly green wood-based products will require the development of more efficient and environmentally friendly chemical processes. Toward this goal, researchers are investigating the use of green solvents for wood delignification such as deep eutectic solvents or organic acid, which lead to much lower environmental impacts (141). Future research should include the design of renewable, biodegradable, low-melting, and low-toxicity solvents to selectively remove lignin.

Significant efforts must be devoted to bridging the gaps between high-performance engineered wood and next-generation scalable and sustainable applications. By necessity, engineered wood must balance performance, cost, durability, and scalability to succeed in practical applications. To achieve these requirements, particularly in terms of cost and scalability, we must also consider how the proposed wood modification strategies can be integrated in the current infrastructure of the wood and paper industries. Government incentives for engineered wood to displace petroleum-based polymers and energy-intensive materials such as glass and steel will accelerate market penetration. The redesign and functionalization of wood through physical or chemical modifications will provide the basis for a range of new wood-based materials or a carbon-neutral future.

DISCLOSURE STATEMENT

The authors are not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review.

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LITERATURE CITED

1. Babin A, Vaneeckhaute C, Iliuta MC. 2021. Potential and challenges of bioenergy with carbon capture and storage as a carbon-negative energy source: a review. *Biomass Bioenergy* 146:105968
2. Rowell RM. 2006. Chemical modification of wood: a short review. *Wood Mater. Sci. Eng.* 1(1):29–33
3. Gérardin P. 2016. New alternatives for wood preservation based on thermal and chemical modification of wood—a review. *Ann. For. Sci.* 73(3):559–70
4. Bednarek Z, Kaliszuk-Wietecka A. 2007. Analysis of the fire-protection impregnation influence on wood strength. *J. Civ. Eng. Manag.* 13(2):79–85
5. Lozhechnikova A, Bellanger H, Michen B, Burgert I, Österberg M. 2017. Surfactant-free carnauba wax dispersion and its use for layer-by-layer assembled protective surface coatings on wood. *Appl. Surf. Sci.* 396:1273–81
6. Sandberg D, Kutnar A, Mantanis G. 2017. Wood modification technologies—a review. *iForest Biogeosci. For.* 10(6):895–908
7. Berglund LA, Burgert I. 2018. Bioinspired wood nanotechnology for functional materials. *Adv. Mater.* 30(19):1704285
8. Xu T, Du H, Liu H, Liu W, Zhang X, et al. 2021. Advanced nanocellulose-based composites for flexible functional energy storage devices (Adv. Mater. 48/2021). *Adv. Mater.* 33(48):2101368
9. Chen Y, Zhang L, Yang Y, Pang B, Xu W, et al. 2021. Recent progress on nanocellulose aerogels: preparation, modification, composite fabrication, applications. *Adv. Mater.* 33(11):2005569

10. Liu C, Luan P, Li Q, Cheng Z, Xiang P, et al. 2021. Biopolymers derived from trees as sustainable multifunctional materials: a review. *Adv. Mater.* 33(28):2001654
11. Liu C, Luan P, Li Q, Cheng Z, Sun X, et al. 2020. Biodegradable, hygienic, and compostable tableware from hybrid sugarcane and bamboo fibers as plastic alternative. *Matter* 3(6):2066–79
12. Völkel L, Beaumont M, Johansson L, Czibula C, Rusakov D, et al. 2022. Assessing fire-damage in historical papers and alleviating damage with soft cellulose nanofibers. *Small* 18(13):2105420
13. Völkel L, Rusakov D, Kontturi E, Beaumont M, Rosenau T, Potthast A. 2022. Manufacturing heat-damaged papers as model materials for evaluating conservation methods. *Cellulose* 29:6373–91
14. Beaumont M, Tardy BL, Reyes G, Koso TV, Schaubmayr E, et al. 2021. Assembling native elementary cellulose nanofibrils via a reversible and regioselective surface functionalization. *J. Am. Chem. Soc.* 143(41):17040–46
15. Sun X, Zhu Y, Zhu J, Le K, Servati P, Jiang F. 2022. Tough and ultrastretchable liquid-free ion conductor strengthened by deep eutectic solvent hydrolyzed cellulose microfibers. *Adv. Funct. Mater.* 32(29):2202533
16. Montanari C, Ogawa Y, Olsén P, Berglund LA. 2021. High performance, fully bio-based, and optically transparent wood biocomposites. *Adv. Sci.* 8(12):2100559
17. Zhu M, Song J, Li T, Gong A, Wang Y, et al. 2016. Highly anisotropic, highly transparent wood composites. *Adv. Mater.* 28(26):5181–87
18. Li T, Zhu M, Yang Z, Song J, Dai J, et al. 2016. Wood composite as an energy efficient building material: guided sunlight transmittance and effective thermal insulation. *Adv. Energy Mater.* 6(22):1601122
19. Yang C, Wu Q, Xie W, Zhang X, Brozena A, et al. 2021. Copper-coordinated cellulose ion conductors for solid-state batteries. *Nature* 598(7882):590–96
20. Li J, Chen C, Zhu JY, Ragauskas AJ, Hu L. 2021. In situ wood delignification toward sustainable applications. *Acc. Mater. Res.* 2(8):606–20
21. Keplinger T, Wittel FK, Rüggeberg M, Burgert I. 2021. Wood derived cellulose scaffolds—processing and mechanics. *Adv. Mater.* 33(28):2001375
22. Pettersen RC. 1984. The chemical composition of wood. *Chem. Solid Wood* 207:57–126
23. Zhu H, Zhu S, Jia Z, Parvinian S, Li Y, et al. 2015. Anomalous scaling law of strength and toughness of cellulose nanopaper. *PNAS* 112(29):8971–76
24. Rafsanjani A, Stiefel M, Jefimovs K, Mokso R, Derome D, Carmeliet J. 2014. Hygroscopic swelling and shrinkage of latewood cell wall micropillars reveal ultrastructural anisotropy. *J. R. Soc. Interface* 11(95):20140126
25. Brethauer S, Shahab RL, Studer MH. 2020. Impacts of biofilms on the conversion of cellulose. *Appl. Microbiol. Biotechnol.* 104(12):5201–12
26. Berardi U. 2015. Building energy consumption in US, EU, and BRIC countries. *Procedia Eng.* 118:128–36
27. Cao X, Dai X, Liu J. 2016. Building energy-consumption status worldwide and the state-of-the-art technologies for zero-energy buildings during the past decade. *Energy Build.* 128:198–213
28. Yang H, Wang Y, Yu Q, Cao G, Yang R, et al. 2018. Composite phase change materials with good reversible thermochromic ability in delignified wood substrate for thermal energy storage. *Appl. Energy* 212:455–64
29. Chang SJ, Kang Y, Wi S, Jeong S-G, Kim S. 2017. Hygrothermal performance improvement of the Korean wood frame walls using macro-packed phase change materials (MPPCM). *Appl. Therm. Eng.* 114:457–65
30. Cui Y, Xie J, Liu J, Pan S. 2015. Review of phase change materials integrated in building walls for energy saving. *Procedia Eng.* 121:763–70
31. Yang H, Wang Y, Yu Q, Cao G, Sun X, et al. 2018. Low-cost, three-dimension, high thermal conductivity, carbonized wood-based composite phase change materials for thermal energy storage. *Energy* 159:929–36
32. Yang H, Chao W, Wang S, Yu Q, Cao G, et al. 2019. Self-luminous wood composite for both thermal and light energy storage. *Energy Storage Mater.* 18:15–22
33. Yang H, Wang S, Wang X, Chao W, Wang N, et al. 2020. Wood-based composite phase change materials with self-cleaning superhydrophobic surface for thermal energy storage. *Appl. Energy* 261:114481

34. Nocentini K, Achard P, Biwole P, Stipetic M. 2018. Hygro-thermal properties of silica aerogel blankets dried using microwave heating for building thermal insulation. *Energy Build.* 158:14–22
35. Yu ZL, Yang N, Apostolopoulou-Kalkavoura V, Qin B, Ma ZY, et al. 2018. Fire-retardant and thermally insulating phenolic-silica aerogels. *Angew. Chem. Int. Ed.* 57(17):4538–42
36. Lang AW, Li Y, De Keersmaecker M, Shen DE, Österholm AM, et al. 2018. Transparent wood smart windows: polymer electrochromic devices based on poly(3,4-ethylenedioxythiophene):poly(styrene sulfonate) electrodes. *ChemSusChem* 11(5):854–63
37. Xu X, Zhang Q, Hao M, Hu Y, Lin Z, et al. 2019. Double-negative-index ceramic aerogels for thermal superinsulation. *Science* 363(6428):723–27
38. Li T, Song J, Zhao X, Yang Z, Pastel G, et al. 2018. Anisotropic, lightweight, strong, and super thermally insulating nanowood with naturally aligned nanocellulose. *Sci. Adv.* 4(3):eaar3724
39. He S, Chen C, Li T, Song J, Zhao X, et al. 2020. An energy-efficient, wood-derived structural material enabled by pore structure engineering towards building efficiency. *Small Methods* 4(1):1900747
40. Liu Q, Frazier AW, Zhao X, Joshua A, Hess AJ, et al. 2018. Flexible transparent aerogels as window retrofitting films and optical elements with tunable birefringence. *Nano Energy* 48:266–74
41. Zhai Y, Ma Y, David SN, Zhao D, Lou R, et al. 2017. Scalable-manufactured randomized glass-polymer hybrid metamaterial for daytime radiative cooling. *Science* 355(6329):1062–66
42. Yin X, Yang R, Tan G, Fan S. 2020. Terrestrial radiative cooling: using the cold universe as a renewable and sustainable energy source. *Science* 370(6518):786–91
43. Li T, Zhai Y, He S, Gan W, Wei Z, et al. 2019. A radiative cooling structural material. *Science* 364(6442):760–63
44. Kittel C. 1949. Interpretation of the thermal conductivity of glasses. *Phys. Rev.* 75(6):972–74
45. Wan C, Liu X, Huang Q, Cheng W, Su J, Wu Y. 2021. A brief review of transparent wood: synthetic strategy, functionalization and applications. *Curr. Org. Synth.* 18(7):615–23
46. Schmitz A, Kamiński J, Scalet BM, Soria A. 2011. Energy consumption and CO_2 emissions of the European glass industry. *Energy Policy* 39(1):142–55
47. Jani Y, Hogland W. 2014. Waste glass in the production of cement and concrete—a review. *J. Environ. Chem. Eng.* 2(3):1767–75
48. Mi R, Li T, Dalgo D, Chen C, Kuang Y, et al. 2020. A clear, strong, and thermally insulated transparent wood for energy efficient windows. *Adv. Funct. Mater.* 30(1):1907511
49. Jia C, Chen C, Mi R, Li T, Dai J, et al. 2019. Clear wood toward high-performance building materials. *ACS Nano* 13(9):9993–10001
50. Li Y, Yang X, Fu Q, Rojas R, Yan M, Berglund L. 2018. Towards centimeter thick transparent wood through interface manipulation. *J. Mater. Chem. A* 6(3):1094–101
51. Chen P, Li Y, Nishiyama Y, Pingali SV, O'Neill HM, et al. 2021. Small angle neutron scattering shows nanoscale PMMA distribution in transparent wood biocomposites. *Nano Lett.* 21(7):2883–90
52. Montanari C, Li Y, Chen H, Yan M, Berglund LA. 2019. Transparent wood for thermal energy storage and reversible optical transmittance. *ACS Appl. Mater. Interfaces* 11(22):20465–72
53. Li Y, Vasileva E, Sychugov I, Popov S, Berglund L. 2018. Optically transparent wood: recent progress, opportunities, and challenges. *Adv. Opt. Mater.* 6(14):1800059
54. Li Y, Fu Q, Yang X, Berglund L. 2018. Transparent wood for functional and structural applications. *Philos. Trans. R. Soc. A* 376(2112):20170182
55. Xia Q, Chen C, Li T, He S, Gao J, et al. 2021. Solar-assisted fabrication of large-scale, patternable transparent wood. *Sci. Adv.* 7(5):eabd7342
56. Wang L, Liu Y, Zhan X, Luo D, Sun X. 2019. Photochromic transparent wood for photo-switchable smart window applications. *J. Mater. Chem. C* 7(28):8649–54
57. Montanari C, Li Y, Chen H, Yan M, Berglund LA. 2019. Transparent wood for thermal energy storage and reversible optical transmittance. *ACS Appl. Mater. Interfaces* 11(22):20465–72
58. Li Y, Fu Q, Yu S, Yan M, Berglund L. 2016. Optically transparent wood from a nanoporous cellulosic template: combining functional and structural performance. *Biomacromolecules* 17(4):1358–64
59. Mi R, Chen C, Keplinger T, Pei Y, He S, et al. 2020. Scalable aesthetic transparent wood for energy efficient buildings. *Nat. Commun.* 11(1):3836

60. Gan W, Xiao S, Gao L, Gao R, Li J, Zhan X. 2017. Luminescent and transparent wood composites fabricated by poly(methyl methacrylate) and γ-Fe_2O_3@YVO_4:Eu^{3+} nanoparticle impregnation. *ACS Sustain Chem. Eng.* 5(5):3855–62

61. Li Y, Yu S, Veinot JGC, Linnros J, Berglund L, Sychugov I. 2017. Luminescent transparent wood. *Adv. Opt. Mater.* 5(1):1600834

62. Yu Z, Yao Y, Yao J, Zhang L, Chen Z, et al. 2017. Transparent wood containing Cs_xWO_3 nanoparticles for heat-shielding window applications. *J. Mater. Chem. A* 5(13):6019–24

63. Qiu Z, Xiao Z, Gao L, Li J, Wang H, et al. 2019. Transparent wood bearing a shielding effect to infrared heat and ultraviolet via incorporation of modified antimony-doped tin oxide nanoparticles. *Compos. Sci. Technol.* 172:43–48

64. Casini M. 2018. Active dynamic windows for buildings: a review. *Renew. Energy* 119:923–34

65. Cheng Z, Guan H, Meng J, Wang X. 2020. Dual-functional porous wood filter for simultaneous oil/water separation and organic pollutant removal. *ACS Omega* 5(23):14096–103

66. Kim S, Kim K, Jun G, Hwang W. 2020. Wood-nanotechnology-based membrane for the efficient purification of oil-in-water emulsions. *ACS Nano* 14(12):17233–40

67. Wang Y, Wang J, Ling S, Liang H, Dai M, et al. 2019. Wood-derived nanofibrillated cellulose hydrogel filters for fast and efficient separation of nanoparticles. *Adv. Sustain Syst.* 3(9):1900063

68. Jiao M, Yao Y, Chen C, Jiang B, Pastel G, et al. 2020. Highly efficient water treatment via a wood-based and reusable filter. *ACS Mater. Lett.* 2(4):430–37

69. Chen X, Zhu X, He S, Hu L, Ren ZJ. 2021. Advanced nanowood materials for the water–energy nexus. *Adv. Mater.* 33(28):2001240

70. Yang Z, Liu H, Li J, Yang K, Zhang Z, et al. 2020. High-throughput metal trap: sulfhydryl-functionalized wood membrane stacks for rapid and highly efficient heavy metal ion removal. *ACS Appl. Mater. Interfaces* 12(13):15002–11

71. Guo R, Cai X, Liu H, Yang Z, Meng Y, et al. 2019. In situ growth of metal–organic frameworks in three-dimensional aligned lumen arrays of wood for rapid and highly efficient organic pollutant removal. *Environ. Sci. Technol.* 53(5):2705–12

72. Yang Z, Ni H, Liu P, Liu H, Yang K, et al. 2021. Nanofibrils in 3D aligned channel arrays with synergistic effect of Ag/NPs for rapid and highly efficient electric field disinfection. *Chin. Chem. Lett.* 32(10):3143–48

73. He S, Chen C, Chen G, Chen F, Dai J, et al. 2020. High-performance, scalable wood-based filtration device with a reversed-tree design. *Chem. Mater.* 32(5):1887–95

74. Fu Q, Ansari F, Zhou Q, Berglund LA. 2018. Wood nanotechnology for strong, mesoporous, and hydrophobic biocomposites for selective separation of oil/water mixtures. *ACS Nano* 12(3):2222–30

75. He S, Chen C, Kuang Y, Mi R, Liu Y, et al. 2019. Nature-inspired salt resistant bimodal porous solar evaporator for efficient and stable water desalination. *Energy Environ. Sci.* 12(5):1558–67

76. Hou D, Li T, Chen X, He S, Dai J, et al. 2019. Hydrophobic nanostructured wood membrane for thermally efficient distillation. *Sci. Adv.* 5(8):eaaw3203

77. Zhu M, Li Y, Chen G, Jiang F, Yang Z, et al. 2017. Tree-inspired design for high-efficiency water extraction. *Adv. Mater.* 29(44):1704107

78. Li T, Liu H, Zhao X, Chen G, Dai J, et al. 2018. Scalable and highly efficient mesoporous wood-based solar steam generation device: localized heat, rapid water transport. *Adv. Funct. Mater.* 28(16):1707134

79. Yang J, Chen Y, Jia X, Li Y, Wang S, Song H. 2020. Wood-based solar interface evaporation device with self-desalting and high antibacterial activity for efficient solar steam generation. *ACS Appl. Mater. Interfaces* 12(41):47029–37

80. Huang W, Hu G, Tian C, Wang X, Tu J, et al. 2019. Nature-inspired salt resistant polypyrrole-wood for highly efficient solar steam generation. *Sustain. Energy Fuels* 3(11):3000–8

81. Zhu M, Li Y, Chen F, Zhu X, Dai J, et al. 2018. Plasmonic wood for high-efficiency solar steam generation. *Adv. Energy Mater.* 8(4):1701028

82. Guan Q-F, Han Z-M, Ling Z-C, Yang H-B, Yu S-H. 2020. Sustainable wood-based hierarchical solar steam generator: a biomimetic design with reduced vaporization enthalpy of water. *Nano Lett.* 20(8):5699–704

83. Finnerty C, Zhang L, Sedlak DL, Nelson KL, Mi B. 2017. Synthetic graphene oxide leaf for solar desalination with zero liquid discharge. *Environ. Sci. Technol.* 51(20):11701–9
84. Kashyap V, Al-Bayati A, Sajadi SM, Irajizad P, Wang SH, Ghasemi H. 2017. A flexible anti-clogging graphite film for scalable solar desalination by heat localization. *J. Mater. Chem. A* 5(29):15227–34
85. Xu W, Hu X, Zhuang S, Wang Y, Li X, et al. 2018. Flexible and salt resistant Janus absorbers by electrospinning for stable and efficient solar desalination. *Adv. Energy Mater.* 8(14):1702884
86. Kuang Y, Chen C, Chen G, Pei Y, Pastel G, et al. 2019. Bioinspired solar-heated carbon absorbent for efficient cleanup of highly viscous crude oil. *Adv. Funct. Mater.* 29(16):1900162
87. Chen X, He S, Falinski MM, Wang Y, Li T, et al. 2021. Sustainable off-grid desalination of hypersaline waters using Janus wood evaporators. *Energy Environ. Sci.* 14(10):5347–57
88. Zhang Z, Wen L, Jiang L. 2021. Nanofluidics for osmotic energy conversion. *Nat. Rev. Mater.* 6(7):622–39
89. Liu P, Zhou T, Yang L, Zhu C, Teng Y, et al. 2021. Synergy of light and acid-base reaction in energy conversion based on cellulose nanofiber intercalated titanium carbide composite nanofluidics. *Energy Environ. Sci.* 14(8):4400–9
90. Bocquet L. 2020. Nanofluidics coming of age. *Nat. Mater.* 19(3):254–56
91. Lu J, Wang H. 2021. Emerging porous framework material-based nanofluidic membranes toward ultimate ion separation. *Matter* 4(9):2810–30
92. Zhou Y, Ding H, Smith AT, Jia X, Chen S, et al. 2019. Nanofluidic energy conversion and molecular separation through highly stable clay-based membranes. *J. Mater. Chem. A* 7(23):14089–96
93. Xu Y. 2018. Nanofluidics: a new arena for materials science. *Adv. Mater.* 30(3):1702419
94. Pérez-Mitta G, Peinetti AS, Cortez ML, Toimil-Molares ME, Trautmann C, Azzaroni O. 2018. Highly sensitive biosensing with solid-state nanopores displaying enzymatically reconfigurable rectification properties. *Nano Lett.* 18(5):3303–10
95. Hou Y, Hou X. 2021. Bioinspired nanofluidic iontronics. *Science* 373(6555):628–29
96. Li T, Li SX, Kong W, Chen C, Hitz E, et al. 2019. A nanofluidic ion regulation membrane with aligned cellulose nanofibers. *Sci. Adv.* 5(2):eaau4238
97. Chen G, Li T, Chen C, Wang C, Liu Y, et al. 2019. A highly conductive cationic wood membrane. *Adv. Funct. Mater.* 29(44):1902772
98. Kong W, Chen C, Chen G, Wang C, Liu D, et al. 2021. Wood ionic cable. *Small* 17(40):2008200
99. Li T, Chen C, Brozena AH, Zhu JY, Xu L, et al. 2021. Developing fibrillated cellulose as a sustainable technological material. *Nature* 590(7844):47–56
100. Kong W, Wang C, Jia C, Kuang Y, Pastel G, et al. 2018. Muscle-inspired highly anisotropic, strong, ion-conductive hydrogels. *Adv. Mater.* 30(39):1801934
101. Chen G, Li T, Chen C, Kong W, Jiao M, et al. 2021. Scalable wood hydrogel membrane with nanoscale channels. *ACS Nano* 15(7):11244–52
102. Wu Q, Wang C, Wang R, Chen C, Gao J, et al. 2020. Salinity-gradient power generation with ionized wood membranes. *Adv. Energy Mater.* 10(1):1902590
103. Liu J, Yuan H, Tao X, Liang Y, Yang SJ, et al. 2020. Recent progress on biomass-derived ecomaterials toward advanced rechargeable lithium batteries. *EcoMat* 2(1):e12019
104. Peng X, Zhang L, Chen Z, Zhong L, Zhao D, et al. 2019. Hierarchically porous carbon plates derived from wood as bifunctional ORR/OER electrodes. *Adv. Mater.* 31(16):1900341
105. Jiao M, Liu T, Chen C, Yue M, Pastel G, et al. 2020. Holey three-dimensional wood-based electrode for vanadium flow batteries. *Energy Storage Mater*. 27:327–32
106. Huang J, Zhao B, Liu T, Mou J, Jiang Z, et al. 2019. Wood-derived materials for advanced electrochemical energy storage devices. *Adv. Funct. Mater.* 29(31):1902255
107. Chen C, Xu S, Kuang Y, Gan W, Song J, et al. 2019. Nature-inspired tri-pathway design enabling high-performance flexible Li–O_2 batteries. *Adv. Energy Mater.* 9(9):1802964
108. Chen Y, Zou K, Dai X, Bai H, Zhang S, et al. 2021. Polysulfide filter and dendrite inhibitor: highly graphitized wood framework inhibits polysulfide shuttle and lithium dendrites in Li–S batteries. *Adv. Funct. Mater.* 31(31):2102458
109. Zhao C, Liu J, Wang J, Ren D, Yu J, et al. 2021. A $\mathbf{\Delta}E = 0.63$ V bifunctional oxygen electrocatalyst enables high-rate and long-cycling zinc-air batteries. *Adv. Mater.* 33(15):2008606

110. Zhong L, Jiang C, Zheng M, Peng X, Liu T, et al. 2021. Wood carbon based single-atom catalyst for rechargeable Zn–air batteries. *ACS Energy Lett.* 6(10):3624–33
111. Zhang Y, Zuo T-T, Popovic J, Lim K, Yin Y-X, et al. 2020. Towards better Li metal anodes: challenges and strategies. *Mater. Today* 33:56–74
112. Zhu Y, Gonzalez-Rosillo JC, Balaish M, Hood ZD, Kim KJ, Rupp JLM. 2021. Lithium-film ceramics for solid-state lithionic devices. *Nat. Rev. Mater.* 6(4):313–31
113. Fan L-Z, He H, Nan C-W. 2021. Tailoring inorganic-polymer composites for the mass production of solid-state batteries. *Nat. Rev. Mater.* 6(11):1003–19
114. Pacheco-Torgal F, Jalali S. 2011. Nanotechnology: advantages and drawbacks in the field of construction and building materials. *Constr. Build. Mater.* 25(2):582–90
115. Ben Chaabene W, Flah M, Nehdi ML. 2020. Machine learning prediction of mechanical properties of concrete: critical review. *Constr. Build. Mater.* 260:119889
116. Shi J, Peng J, Huang Q, Cai L, Shi SQ. 2020. Fabrication of densified wood via synergy of chemical pretreatment, hot-pressing and post mechanical fixation. *J. Wood Sci.* 66(1):5
117. Shaw MD, Karunakaran C, Tabil LG. 2009. Physicochemical characteristics of densified untreated and steam exploded poplar wood and wheat straw grinds. *Biosyst. Eng.* 103(2):198–207
118. Taghiyari HR, Rassam G, Ahmadi-DavazdahEmam K. 2017. Effects of densification on untreated and nano-aluminum-oxide impregnated poplar wood. *J. For. Res.* 28(2):403–10
119. Luan Y, Fang C-H, Ma Y-F, Fei B-H. 2022. Wood mechanical densification: a review on processing. *Mater. Manuf. Process.* 37(4):359–71
120. Gašparík M, Gaff M. 2015. Influence of densification on bending strength of beech wood. *Wood Res.* 60(2):211–18
121. Li K, Wang S, Chen H, Yang X, Berglund LA, Zhou Q. 2020. Self-densification of highly mesoporous wood structure into a strong and transparent film. *Adv. Mater.* 32(42):2003653
122. Song J, Chen C, Zhu S, Zhu M, Dai J, et al. 2018. Processing bulk natural wood into a high-performance structural material. *Nature* 554(7691):224–28
123. Han X, Ye Y, Lam F, Pu J, Jiang F. 2019. Hydrogen-bonding-induced assembly of aligned cellulose nanofibers into ultrastrong and tough bulk materials. *J. Mater. Chem. A* 7(47):27023–31
124. Frey M, Widner D, Segmehl JS, Casdorff K, Keplinger T, Burgert I. 2018. Delignified and densified cellulose bulk materials with excellent tensile properties for sustainable engineering. *ACS Appl. Mater. Interfaces* 10(5):5030–37
125. Dong X, Gan W, Shang Y, Tang J, Wang Y, et al. 2022. Low-value wood for sustainable high-performance structural materials. *Nat. Sustain.* 5:628–35
126. Xiao S, Chen C, Xia Q, Liu Y, Yao Y, et al. 2021. Lightweight, strong, moldable wood via cell wall engineering as a sustainable structural material. *Science* 374(6566):465–71
127. LeVan SL, Winandy JE. 1990. Effects of fire retardant treatments on wood strength: a review. *Wood Fiber Sci.* 22(1):113–31
128. Samanta P, Samanta A, Montanari C, Li Y, Maddalena L, et al. 2022. Fire-retardant and transparent wood biocomposite based on commercial thermoset. *Compos. A Appl. Sci. Manuf.* 156:106863
129. Merk V, Chanana M, Keplinger T, Gaan S, Burgert I. 2015. Hybrid wood materials with improved fire retardance by bio-inspired mineralisation on the nano-and submicron level. *Green Chem.* 17(3):1423–28
130. Moya R, Gaitán-Alvarez J, Berrocal A, Araya F. 2020. Effect of $CaCO_3$ on the wood properties of tropical hardwood species from fast-growth plantation in Costa Rica. *BioResources* 15(3):4802–22
131. Merk V, Chanana M, Gaan S, Burgert I. 2016. Mineralization of wood by calcium carbonate insertion for improved flame retardancy. *Holzforschung* 70(9):867–76
132. Gan W, Chen C, Wang Z, Pei Y, Ping W, et al. 2020. Fire-resistant structural material enabled by an anisotropic thermally conductive hexagonal boron nitride coating. *Adv. Funct. Mater.* 30(10):1909196
133. Chen G, Chen C, Pei Y, He S, Liu Y, et al. 2020. A strong, flame-retardant, and thermally insulating wood laminate. *Chem. Eng. J.* 383:123109
134. Zhang L, Zhang W, Peng Y, Wang W, Cao J. 2022. Thermal behavior and flame retardancy of poplar wood impregnated with furfuryl alcohol catalyzed by boron/phosphorus compound system. *Ind. Crops Prod.* 176:114361

135. Zhang T, Xi J, Qiu S, Zhang B, Luo Z, et al. 2021. Facilely produced highly adhered, low thermal conductivity and non-combustible coatings for fire safety. *J. Colloid Interface Sci.* 604:378–89
136. Kong L, Guan H, Wang X. 2018. In situ polymerization of furfuryl alcohol with ammonium dihydrogen phosphate in poplar wood for improved dimensional stability and flame retardancy. *ACS Sustain. Chem. Eng.* 6(3):3349–57
137. Guo H, Luković M, Mendoza M, Schlepütz CM, Griffa M, et al. 2019. Bioinspired struvite mineralization for fire-resistant wood. *ACS Appl. Mater. Interfaces* 11(5):5427–34
138. Guo H, Özparpucu M, Windeisen-Holzhauser E, Schlepütz CM, Quadranti E, et al. 2020. Struvite mineralized wood as sustainable building material: mechanical and combustion behavior. *ACS Sustain. Chem. Eng.* 8(28):10402–12
139. Toivonen MS, Kurki-Suonio S, Schacher FH, Hietala S, Rojas OJ, Ikkala O. 2015. Water-resistant, transparent hybrid nanopaper by physical cross-linking with chitosan. *Biomacromolecules* 16(3):1062–71
140. Sandberg D, Kutnar A, Karlsson O, Jones D. 2021. *Wood Modification Technologies: Principles, Sustainability, and the Need for Innovation*. Boca Raton, FL: CRC Press
141. Akpan EI, Wetzel B, Friedrich K. 2021. Eco-friendly and sustainable processing of wood-based materials. *Green Chem.* 23(6):2198–232