Structure–property–function relationships of natural and engineered wood

Chaoji Chen[1], Yudi Kuang[1], Shuze Zhu[2], Ingo Burgert[3,4], Tobias Keplinger[3,4], Amy Gong[5], Teng Li[2], Lars Berglund[6], Stephen J. Eichhorn[7] and Liangbing Hu[1] ✉

Abstract | The complex structure of wood, one of the most abundant biomaterials on Earth, has been optimized over 270 million years of tree evolution. This optimization has led to the highly efficient water and nutrient transport, mechanical stability and durability of wood. The unique material structure and pronounced anisotropy of wood endows it with an array of remarkable properties, yielding opportunities for the design of functional materials. In this Review, we provide a materials and structural perspective on how wood can be redesigned via structural engineering, chemical and/or thermal modification to alter its mechanical, fluidic, ionic, optical and thermal properties. These modifications enable a diverse range of applications, including the development of high-performance structural materials, energy storage and conversion, environmental remediation, nanoionics, nanofluidics, and light and thermal management. We also highlight advanced characterization and computational-simulation approaches for understanding the structure–property–function relationships of natural and modified wood, as well as informing bio-inspired synthetic designs. In addition, we provide our perspective on the future directions of wood research and the challenges and opportunities for industrialization.

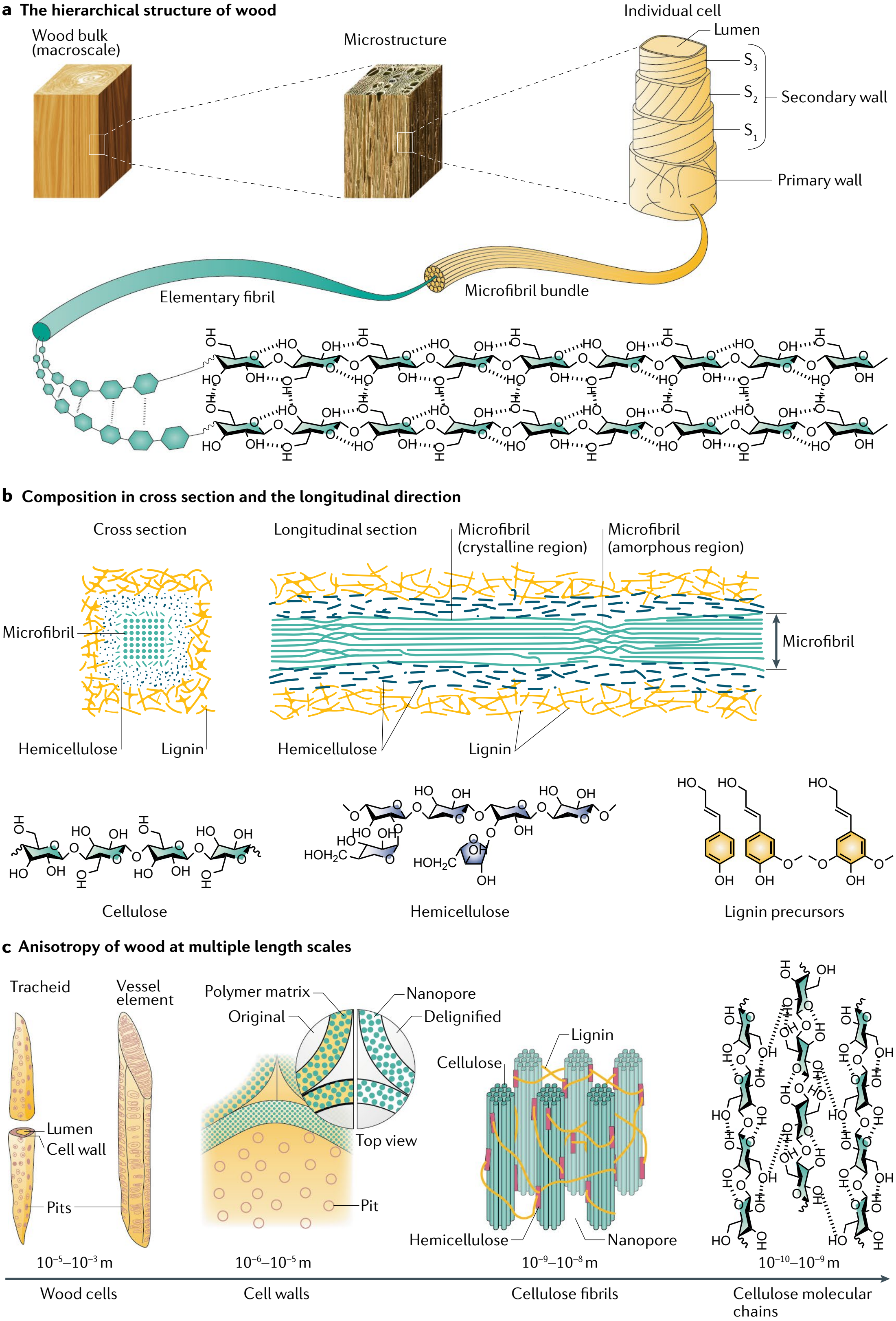
Forests cover over 30% of the land on Earth and provide a renewable and sustainable resource. Wood has been ubiquitously used for thousands of years, most commonly for construction, furniture and tools, and as a source of fuel. In 2017, the annual industrial production of wood was ~3.8 billion m^3 (REFS[1–3]). Efforts towards achieving a sustainable society create opportunities for wood to replace non-renewable, petroleum-based materials in a broad range of products and applications. Specifically, the expanding use of wood-based materials has been driven by a variety of factors, including the need to reduce carbon footprints, increasing energy and water security concerns, and the desire for sustainable industrial growth. As a consequence of the abundance of wood, wood-based materials are well placed to address societal needs of low-cost and high-performance composites with minimal environmental impact. These wood-based materials include bio-based composites that comprise only wood components and hybrid materials that comprise wood as well as other non-wood components, such as polymers and organic or inorganic compounds.

Wood possesses a hierarchical cellular structure with pronounced anisotropy and lignocellulosic compositions (mainly cellulose, hemicelluloses and lignin) synthesized by the tree[4–6]. This hierarchical structure provides wood with efficient mass transport (for water and nutrients) and load-bearing functions in the living tree[7–11]. Beyond these basic functions, the structure of harvested wood offers opportunities for the regulation of fluidic and ionic transport at the microscale and nanoscale, and the management of light and thermal properties. In the past decade, the function of wood has extended to applications beyond construction through the optimization of its structure and composition by physical, chemical and/or combined modification approaches[6,11].

The hierarchical and porous structure of wood enables the material to be structurally and/or compositionally designed and modified. Early modification strategies focused on improving stability (for example, dimensional and mechanical stability), rather than adding functionalities[12–17]. Although performance was improved, the control of such modifications was imprecise, owing to the limitations in material-synthesis and material-characterization techniques. In the past decades, advances in commercial methods for wood modification, including thermal treatments[15,18], organic and/or inorganic salt impregnation[14], chemical modification (for example, furfurylation or acetylation)[12,19–21] and coatings[17], have been realized. For example,

✉e-mail: binghu@umd.edu

https://doi.org/10.1038/s41578-020-0195-z



a The hierarchical structure of wood

b Composition in cross section and the longitudinal direction

c Anisotropy of wood at multiple length scales

copper-carbonate microparticles and nanoparticles have been widely used as wood preservatives, making wood protection one of the largest global end uses of nanoparticles[14]. Recent advances in nanotechnology and modification strategies enable the addition of properties and functions to wood-based materials from the macroscale to the molecular scale[22–26].

There has also been growth in characterization and computational-simulation methodologies[27]. Important insights into the morphology, chemical composition

◀ Fig. 1 | **The hierarchical and porous structure of wood at multiple length scales.** **a** | Wood has a hierarchical porous structure with hollow channels aligned along the longitudinal direction. The secondary walls of individual wood cells feature three layers (S_1, S_2 and S_3) that surround the interior lumen (that is, the void space in the centre of the cell). Cellulose, hemicelluloses and lignin are the three major components that form the rigid cell wall of wood. **b** | The cross section and longitudinal views of the structure of the wood cell wall reveal that the cellulose microfibrils embedded in the lignin and hemicellulose matrix have both crystalline and amorphous microfibril regions. **c** | Anisotropy of wood structure, including the orientated macroscale and microscale wood cells, microscale cell walls, nanoscale cellulose fibrils and molecular-scale cellulose chains. Panel **a** (individual cell) is adapted from REF.[212], Springer Nature Limited.

and structure of wood can be gained using electron microscopy[24,28], X-ray diffraction (XRD)[24], Raman spectroscopy[29,30], atomic force microscopy (AFM)[31], time-of-flight secondary ion mass spectrometry (TOF-SIMS)[32], neutron diffraction[24,33] and NMR spectroscopy[34]. These analyses can improve our understanding of the process–structure–property relationships of wood, particularly when combined with powerful computational-modelling methods, such as molecular dynamics (MD)[35] and finite-element simulations[36]. This collective information enables more precise control and tuning of the wood composition, porosity, surface properties, fibril orientation and molecular structure, all of which can accelerate the discovery of modification and functionalization approaches.

In this Review, we overview the structure and composition of wood, as well as modification strategies. Then, we explore the intrinsic properties of wood that originate from its hierarchically porous, anisotropic structure and lignocellulosic compositions. We discuss achievements in wood structural design, engineering and applications, with a focus on understanding the mechanical, ionic, fluidic, optical and thermal properties of wood bestowed via diverse structural modifications. Characterization techniques and modelling approaches that capture the relationship between wood structure and performance are discussed. Finally, we offer our perspectives on future research directions for addressing global challenges in a sustainable manner using wood-based materials.

Wood structure and composition

Wood has a porous hierarchical structure extending from the nanoscale of the cell walls to the macroscale of the wood stem[4–9] (FIG. 1a,b). The rigid cell walls of wood consist of three biopolymers — cellulose, hemicelluloses and lignin — that form a natural fibril-based composite, the properties of which are determined by the orientation of the aligned cellulose fibrils embedded in the lignin and hemicellulose matrix[10,11,37]. The bundles of cellulose microfibrils contain crystalline and amorphous regions, and are comprised of elementary fibrils with diameters of approximately 3 nm. Repeating units of D-glucose assemble through covalent bonding, as well as intrachain and interchain hydrogen bonding at the molecular level, forming linear and stiff cellulose chains.

At the cell and tissue level, wood is composed of different cell types with different volume fractions, depending on the species of tree (BOX 1). Softwoods are comprised >90% of one cell type (the tracheid), which varies in cell diameter and cell-wall thickness, depending on its function. Tracheids with a large cell diameter and thin cell walls provide water transport (so-called 'earlywood'), whereas tracheids with a small cell diameter and thick cell walls provide mechanical strength (so-called 'latewood')[4]. Evolutionarily, hardwoods developed later and use specific cell types for these functions, namely, vessels for water transport and fibres for mechanical strength, which has led to a competitive advantage over softwoods in most climate zones. The lumina (that is, the open interiors of the cell) of the tracheids, the vessels and fibres (with diameters varying from a few micrometres to around half a millimetre), along with the micrometre-sized pits traversing the cell walls and the nano-sized pores between the cellulose fibrils within the cell walls, form the hierarchical porous structure of wood (FIG. 1).

The structural anisotropy of wood is caused by the pronounced directionality of channels and constituent cellulose fibrils at different scales[4–6] (FIG. 1c). At the microscale, most of the lumina of the vessels, tracheids and fibres are aligned along the longitudinal direction. At the nanoscale, cellulose nanofibrils in the cell walls are orientated in parallel with a certain angle (generally between 0–60°) to the cell axis, depending on the tissue type and layer. Furthermore, the gaps between the cellulose nanofibrils, which are nanoscale or sub-nanoscale in size, form nanopores with similar alignments to the cellulose nanofibrils after the polymer matrix has been partially or completely removed. At the molecular scale, the cellulose chains are linearly aligned. The hierarchical anisotropy structure with abundant multiscale pores offers favourable pathways for multiphase transport (of ions, molecules, gas, solid particles and liquids) and multispectral energy transfer (for example, photons, phonons, microwaves and acoustic waves), contributing to an array of intriguing properties[23–26].

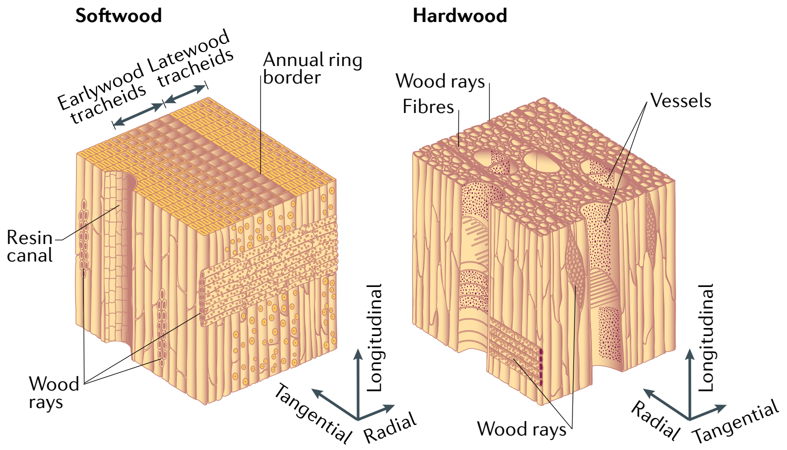
Beyond these general principles of wood's structure, there is variability in the cell type, size, shape and wall-to-lumen ratio, leading to a large diversity in wood anatomy among tree species[4,11]. Furthermore, variability in chemical composition, in particular, of wood extractives (for example, resins, stilbenes and flavonoids), which are responsible for the colour, odour and durability of wood, also contribute to the diversity of wood. Structural diversity mainly manifests at the cell and tissue levels, resulting in different wood densities across species. For example, the density of wood ranges from ~150 kg m^{-3} (for balsa) to ~1,200 kg m^{-3} (for pockwood)[11]. Although there are slight differences in the

Author addresses

[1]Department of Materials Science and Engineering, University of Maryland, College Park, MD, USA.
[2]Department of Mechanical Engineering, University of Maryland, College Park, MD, USA.
[3]Wood Materials Science, Institute for Building Materials, ETH Zurich, Zurich, Switzerland.
[4]Empa, Laboratory for Cellulose & Wood Materials, Dübendorf, Switzerland.
[5]InventWood LLC, College Park, MD, USA.
[6]Wallenberg Wood Science Center, Department of Fiber and Polymer Technology, KTH Royal Institute of Technology, Stockholm, Sweden.
[7]The Bristol Composites Institute, School of Civil, Aerospace and Mechanical Engineering, University of Bristol, Bristol, UK.

Box 1 | **The microstructure of wood**

Wood is the load-bearing, water-conducting and nutrient-conducting tissue of trees, and can be divided into two categories — softwood and hardwood[4] (see the figure). Softwood is composed of tracheids and parenchyma, whereas hardwood features a more complex microstructure containing vessels, fibres and parenchyma (note that tracheids are found in some species of hardwood). Radial planar cellular structures that are perpendicular to the growth rings are called ray cells, which function as pathways for the radial conduction of water, nutrients and other organic substances in the tree. Radial parenchyma cells constitute the rays entirely in hardwoods; however, in softwoods, ray tracheids or resin canals might serve as ray constitution in addition to ray parenchyma. In general, wood cells have a hollow-tube-like structure with varied wall thicknesses, depending on their functions. The void space in the centre of the cell is called the lumen (plural lumina), whereas pores connecting adjacent cells are known as pits.



volume fraction and the chemical composition of the cell-wall biomacromolecules (in particular, the hemicelluloses, lignin and extractive content), unlike the wood density, the cell walls are very similar between species in terms of structure, which is reflected in the similar cell-wall density (~1,550 kg m^{-3})[11]. However, structural and chemical adaptation may occur at all length scales when the tree uses its structural and chemical plasticity to form specific tissue types, such as reaction wood, to cope with specific loading conditions or to control and change the growth direction of stems and branches. These reaction-wood tissues, which differ considerably between softwoods and hardwoods in terms of structure and chemistry at the cell and cell-wall levels, as well as in their biomechanical functionality, are an additional source of structural diversity provided by nature for improved material functionalities[38–41]. This diversity at the different hierarchical levels of wood is highly beneficial for modification and functionalization treatments of the wood scaffold at the cell-wall level. Furthermore, independent of the wood species, the similarity of the cell walls, in particular, of 'normal wood' tissues, allows similar modification protocols to be applied, particularly when the cell-wall extractives have been removed to avoid interference with subsequent processing and chemical modification steps.

Modification strategies

Generally, modification strategies can be divided into three categories, physical, chemical and combined modifications, with chemical modification being further classified into subtractive and additive techniques (FIG. 2).

In physical modification, processes such as mechanical compression, water or steam wetting, surface patterning, surface coating or painting, or microwave treatment are involved (FIG. 2a). With such techniques, the macrostructure and microstructure, and surface properties of wood can be tuned to impart improved or new properties and functions. Compression, for example, has been widely used to densify wood boards accompanied with pretreatments, such as steam, heat, ammonia or cold rolling[42–44]. These processes cause the wood cells to collapse, leading to the compression or elimination of large pores and enhanced density and mechanical strength.

In contrast to physical modification, chemical modification, which can either subtract or add components to the natural wood structure, offers more diversity at multiple length scales[45–48] (FIG. 2b). In subtractive chemical modification, certain components of wood (for example, cellulose, hemicellulose, lignin, extractives and other functional groups) are either partially or completely removed, resulting in a new chemical and/or pore structure[49–54]. Generally, the removal of wood components introduces more nanopores to the cell walls but without destroying the cellular structure of the original wood[49,50]. More drastic chemical treatments can convert the porous cellular structure into a substantially different structure (for example, collapsing into a lamellar sponge)[25,51]. Delignification — the process of removing lignin from natural wood via chemical treatment (for example, using NaOH/Na$_2$SO$_3$ or H$_2$O$_2$)[24,49,50] — is a common subtractive chemical modification strategy and can be used to produce 'white wood' (also called 'nanowood'). Delignified wood inherits the aligned pore structure of the natural wood and the cellulose nanofibrils of the cell walls, but without the lignin component, which functions as a binder to hold the cellulose fibrils in the cell walls. This delignified structure alters the mechanical, thermal, optical, fluidic and ionic properties and functions of the natural wood. For example, delignified wood reflects most incident light and appears white in colour, as well as possessing a lower thermal conductivity than natural wood[51]. Carbonization is another common subtractive chemical modification strategy that can remove wood components (for example, cellulose, hemicelluloses, lignin and extractives) and convert the residual material into amorphous carbon[48]. The resultant carbonized wood inherits the cellular structure of the natural wood while providing improved electrical and thermal conductivity and light absorption.

Additive chemical modifications enable a variety of components (for example, inorganic particles, polymers, metals and metal–organic frameworks) or functional groups to be added to the wood, resulting in diverse structures and materials with additional properties and/or functions[45–48,55–59]. In situ polymerization[58,60] and mineralization[61,62] have been widely explored to alter the wood structure at the cell-wall level by coating, impregnating or filling polymer or inorganic components either on the surface or inside the cell walls and/or lumina. In addition to the properties of these new components, the location and interface between the original and added materials have crucial roles in altering the properties and functions of chemically modified wood[16]. For example, filling polymers or inorganic particles inside the nanopores of the cell walls or the interior of the lumina can result in distinct mechanical, gas-permeability and fire-retardant properties. Additionally, chemical bonding between the original and added components is expected to improve the structural stability of the modified wood compared with if there was only physical contact between these components.

Physical and chemical modifications can be combined to tailor the structure of wood and to add intriguing functionality[26,63–67] (FIG. 2c). For example, combining delignification and polymer filling results in transparent wood with excellent optical and mechanical properties[26]. In another example, densified wood (or 'super wood') can be produced via partial delignification, followed by mechanical compression[63]. These combined processes lead to a higher degree of compression (up to 80% reduction in volume) and pronounced enhancement of tensile strength compared with densified wood produced solely via mechanical compression. Furthermore, wood-derived electrodes can be constructed via carbonization and subsequent coating or filling with electrode materials[67]. Modification strategies involving this combined approach of physical and chemical processes offer more opportunities for tuning the structure of wood to achieve optimized material functionality and performance.

Intrinsic properties of wood

Before designing and fabricating wood-based materials for applications, the relationship between the structure and properties of wood must be understood. The

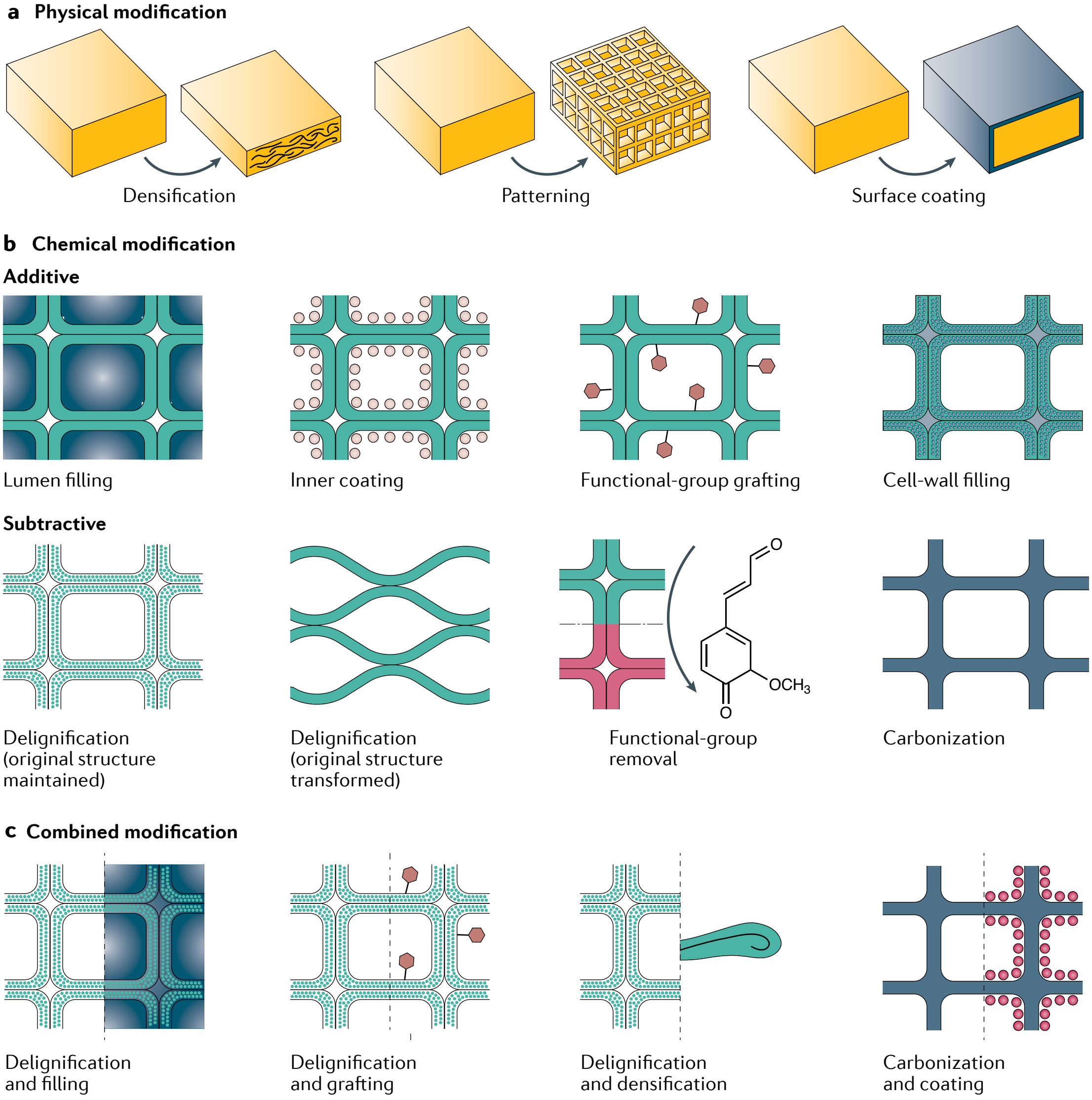


Fig. 2 | **A selection of structural modification strategies for wood. a** | Physical modification strategies, including densification, patterning and surface coating. **b** | Chemical modification strategies, including additive modifications (for example, lumen filling, inner coating, functional-group grafting and cell-wall filling) and subtractive modifications (for example, delignification, functional-group removal and carbonization). **c** | Combined (physical and chemical) modification strategies, such as delignification and filling, delignification and grafting, delignification and densification, as well as carbonization and coating.

intrinsic mechanical, ionic, fluidic, optical and thermal properties of wood originate from its hierarchical cellular structure that features aligned cellulose fibrils embedded in the lignin and hemicellulose matrix of the cell walls. Pores and channels of various sizes are present in the hierarchical structure; more specifically, wood cells are organized to form abundant pores and channels within the cells (that is, lumina of the cells), and, at smaller scales, pores are present in the form of pits traversing the cell wall.

Mechanical properties

The mechanical properties of wood are determined at different length scales by the hierarchical structure. At the bulk wood and tissue level, density, as a measure of the relative volume fraction of cell-wall material, is the dominant factor governing mechanical properties. At the cell-wall level, the orientation of the cellulose nanofibrils, the density of their hydrogen bonds and the interaction between cellulose and the surrounding polymer matrix (composed of lignin and hemicellulose) are particularly important. Cellulose has appealing mechanical properties, with a higher specific modulus and specific strength than most metals[22,35]. Under mechanical stress, the deformation of wood involves various processes at the cell-wall level, including fibril sliding and cellulose–hemicellulose interactions with repeated breaking and reforming of hydrogen bonds. At the molecular scale, fibril sliding is facilitated by hydrated hemicelluloses, which form a soft interphase that interacts strongly with the cellulose fibrils via the densely distributed hydroxyl groups on the molecular chains, which enable secondary interactions, such as hydrogen bonding. Deformation-induced cascades of the breakage and reformation of these hydrogen bonds induce a repeated energy cost, which adds to the work needed to fracture the wood. This reformation of hydrogen bonds is, therefore, a contributing factor to the unique properties of wood and its local plasticity[68]. Although the mechanical properties of wood substantially benefit from the cellulose nanofibrils and interfacial hydrogen bonds, they suffer from the natural occurrence of pits in the cell walls, which, while serving essential biological functions in trees, behave as defects from a structural-material perspective. At a macroscopic scale, knots are the main defects, which limit large-scale strength properties[69].

Of note, the hydration state of lignocellulose is of fundamental importance to its mechanical properties[70], particularly when variations of moisture content in wood occur as a consequence of a change in the surrounding environment (for example, relative humidity and temperature). Such variation of moisture content in wood can influence the macroscopic physical properties of wood, such as mechanical strength. Some of the challenges of using wood as an engineering material come from this moisture-content change or abundance of moisture within wood[70].

Fluidic and ionic properties

In addition to the load-bearing function, the structure of wood is intrinsically designed for the transport of water and nutrients[11,71,72]. These are transported from the tree roots to the upper trunk, branches and leaves via open channels defined by the vessels and tracheids. The hierarchically aligned pore structure of wood (including mainly the various sized lumina of tracheids, vessels and fibres) and the hydrophilic nature of cellulose and hemicellulose are crucial for water transport, allowing passive capillary force to move water upwards along the longitudinal direction to a maximum height of more than 100 m (REF.[71]). The cell walls, with aligned cellulose nanofibrils and nanoscale pathways, also favour ion transport. In addition, the surface charge can be used to tune the behaviour of ionic transport at the nanoscale[50]. The abundant hydroxyl groups in the molecular chains of cellulose and hemicelluloses enable the facile tuning of the surface-charge properties (for example, charge density and potential), which is another structural benefit of wood for fluidic and ionic applications[50].

Optical properties

The structure and molecular composition of wood influence its optical properties. Intrinsically, natural wood demonstrates a brownish colour that varies between wood species. The brownish colour of wood is attributed to the strong light absorption of the lignin, as well as the intensive light scattering by the lumina of the cell[64,73]. By contrast, pure cellulose and hemicelluloses are optically transparent to visible light when the material thickness is small and the porosity is low.

The microstructure of wood also influences its optical properties. One interesting example of such influence is the intrinsic grain structure of wood (for example, annual-growth-ring patterns), which is derived from its alternating structures at the macroscopic and microscopic scales. The variations in grain structure and appearance of different species dramatically increase the value of specific woods for construction and furniture applications simply because of the aesthetic appearance. The abundant pore structure, at both the microscale and the nanoscale, has a key role in determining the optical properties of the material, because it creates multiple air–tissue interfaces that are unfavourable for photon transport, leading to light scattering[26]. The amount of light absorption is highly dependent on the chemical composition, whereas the amount of light scattering is related to the wood structure. By altering the composition and microstructure (for example, pore structure and interfaces) of wood, its optical properties can be readily controlled.

Thermal properties

The thermal properties of wood are similarly related to the compositional and structural characteristics. Wood naturally demonstrates low thermal conductivity and anisotropic thermal transport, owing to its high porosity, low levels of crystalline (or even amorphous) biopolymeric components and structural anisotropy at multiple length scales (for example, the orientated distribution of lumina at the macroscale and microscale, and the cellulose nanofibrils within the cell walls at the nanoscale)[49]. From a compositional point of view, the lignocellulosic components in wood have distinct thermal conductivities. Thus, it should be possible to control the thermal properties of wood by tuning its lignocellulosic composition. The crystalline structure of biopolymers in wood (for example, cellulose) and the orientation of the fibril assembly also influence the thermal transport. Tuning the crystalline structure and/or orientation of the cellulose fibrils, although challenging, should be effective in modulating the thermal properties of wood.

Another factor that influences the thermal properties of wood is the pore structure, particularly, nanopores with a size smaller than the mean free path of phonons in air[49]. Phonon transport in such confined spaces is substantially inhibited, leading to improved thermal insulation. In addition, the existence of abundant pores introduces numerous air–tissue interfaces, which may disturb the phonon transport. Structural modifications via composition and/or pore modification can, therefore, be used to manipulate the thermal properties of wood.

Of note, moisture content also influences the intrinsic thermal properties of wood. For example, the heat capacity of wood has a strong dependence on its moisture content[70]. Wet wood, soaked with a large amount of water, has a higher heat capacity and thermal conductivity than dry wood. Thus, moisture content must be considered in the measurement of thermal properties and the thermally related use of wood.

Sustainable applications of wood

The aforementioned intrinsic mechanical, ionic, fluidic, optical and thermal properties of wood are mainly determined by its composition and anisotropic, hierarchically porous structure. Understanding the structure–property relationships of natural wood (particularly, its anisotropy) is necessary to make more informed structural and chemical modifications and, hence, to control the properties of the material. This control is useful to tune the material for specific applications, including lightweight structural materials, energy storage, environmental remediation, ionic nanofluidics, light and thermal management, electronics and biomedical science. Towards this aim, in the past decade, research has focused on altering the structure and/or composition of wood to manipulate its ion, photon, phonon and fluidic transport behaviours and mechanical properties, which can lead to enhanced performance (for example, substantially higher mechanical strength) or even new functionalities (for example, cost-effective energy storage, efficient solar evaporation, fast ionic and fluidic transport, high optical transparency and thermal insulation).

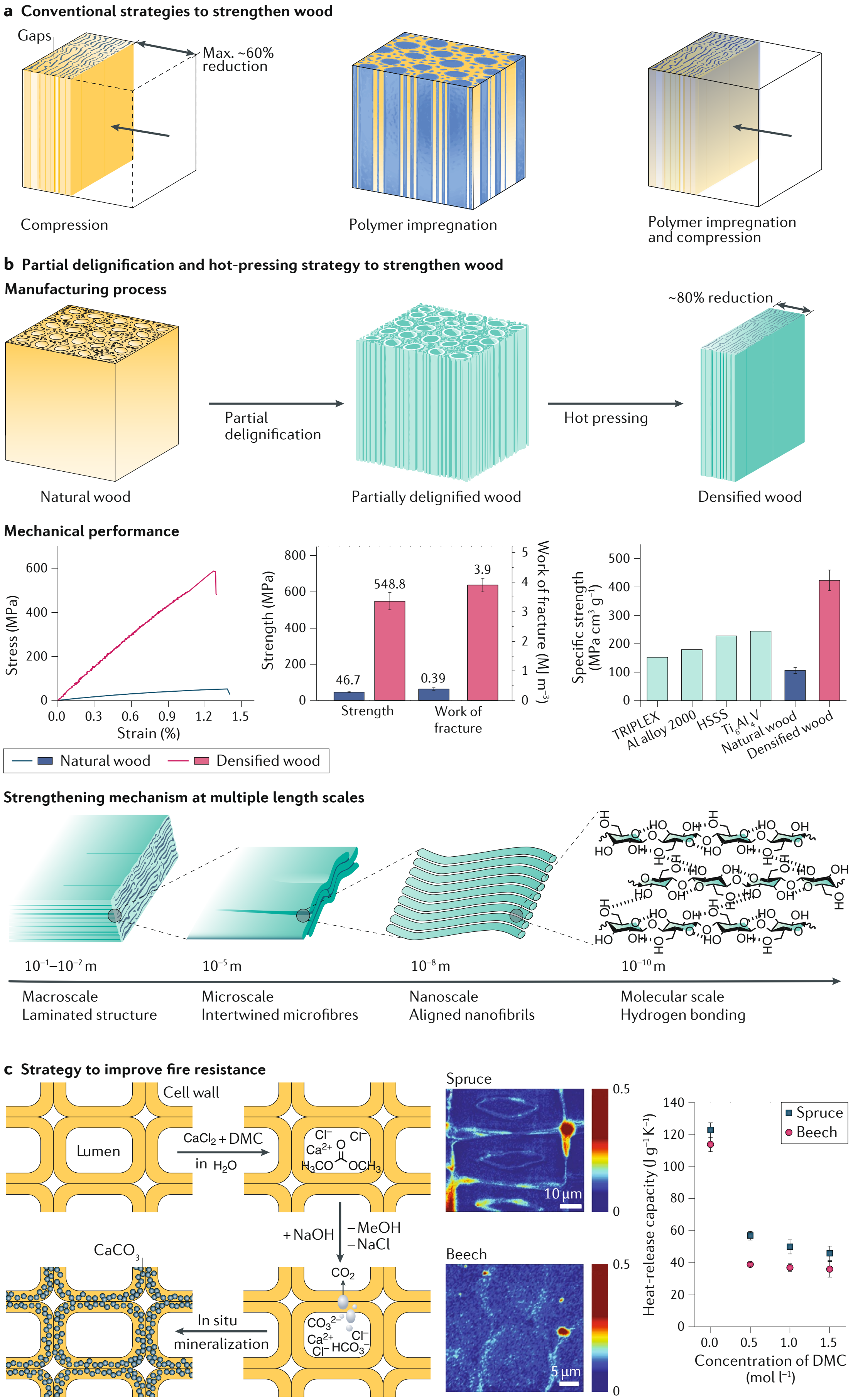
Lightweight structural materials

Natural wood has long been used as a structural material for the construction of furniture and buildings[2,74,75], owing to its high stiffness combined with its low density and low cost. However, the mechanical performance (for example, strength and toughness) of natural wood is insufficient for high-performance applications. To address this issue, a few strategies to modify the porous structure and composition of wood have been explored, with much success in strengthening and hardening natural wood. Before discussing these approaches, which are based on densification, delignification and other chemical treatments, it should be noted that there are well-established structural methods for producing engineered wood products at the veneer and bulk-wood levels that aim to decrease anisotropy and improve reliability through the optimized assembly of wood layers. Plywood, produced by the stacking of veneers with fibre orientations perpendicular to each other, is one of the oldest of these assembly concepts. In the 1990s, this idea was transferred to produce cross-laminated timber, the development of which was a cornerstone for the current trend towards high-rise wooden buildings[76].

A large portion of the volume of wood is made up of open, air-filled cells. The cellulose component of the cell walls is essential for the mechanical strength and toughness of wood, whereas the lignin component functions as a matrix to transfer stress to the stiffer cellulose and serves to hold the individual cells together. Manipulating these open cells and the cell walls is, therefore, crucial for optimizing the mechanical properties of wood[77]. For example, filling the open cells with a monomer formulation and subsequent in situ polymerization produces a wood–polymer composite[78–80] (FIG. 3a). The resultant composite combines the properties of the wood and polymer, leading to improved compressive and bending strength.

An alternative strategy for improving the mechanical properties of wood involves reducing the open volume of the wood cells. Hypothetically, if the open cells are completely closed, then hydrogen bonding is maximized. The open volume of the cells can be reduced by mechanical compression, which increases the volume fraction of the load-bearing wood tissue and, hence, the mechanical properties are greatly improved[43,44,81,82] (FIG. 3a). Pretreatment with either steam, heat, ammonia or cold rolling is often necessary to soften the cell walls to enable densification. Furthermore, the combination of such densification and polymer-infiltration techniques can be particularly effective (FIG. 3a). For example, studies[37,83] show that combining polymer filling and mechanical compression can markedly enhance mechanical properties in wood, including the Young's modulus and bending strength. In another study, the mechanical properties of resin-impregnated wood were optimized by pretreatment with sodium chlorite ($NaClO_2$) prior to polymer impregnation and compression[84]. However, pretreatment methods that soften the wood structure without changing its chemical composition result in only a limited reduction in thickness during densification (60% reduction at maximum)[63]. Moreover, partial recovery of the wood's thickness after densification (namely, spring-back) often occurs when the material is subjected to moist conditions, which further compromises the enhancement of mechanical strength from densification[81].

The latest development of densification strategies involves the partial removal of lignin and hemicelluloses from natural wood followed by hot pressing[63] (FIG. 3b). The partial removal of lignin and hemicelluloses from the cell walls increases the porosity and decreases the rigidity of the delignified wood, given that some of the


a Conventional strategies to strengthen wood
Gaps
Max. ~60% reduction
Compression
Polymer impregnation
Polymer impregnation and compression
b Partial delignification and hot-pressing strategy to strengthen wood
Manufacturing process
~80% reduction
Partial delignification
Hot pressing
Natural wood
Partially delignified wood
Densified wood
Mechanical performance
Stress (MPa)
0
200
400
600
0.0
0.3
0.6
0.9
1.2
1.5
Strain (%)
Strength (MPa)
0
200
400
600
800
46.7
548.8
0.39
3.9
Strength
Work of fracture
Work of fracture (MJ m⁻³)
0
1
2
3
4
5
Specific strength (MPa cm³ g⁻¹)
0
100
200
300
400
500
TRIPLEX
Al alloy 2000
HSSS
Ti₆Al₄V
Natural wood
Densified wood
Natural wood
Densified wood
Strengthening mechanism at multiple length scales
10⁻¹–10⁻² m
10⁻⁵ m
10⁻⁸ m
10⁻¹⁰ m
Macroscale
Laminated structure
Microscale
Intertwined microfibres
Nanoscale
Aligned nanofibrils
Molecular scale
Hydrogen bonding
HO
OH
c Strategy to improve fire resistance
Cell wall
Lumen
CaCl₂ + DMC
in H₂O
Cl⁻
Cl⁻
Ca²⁺
H₃CO
OCH₃
O
+ NaOH
− MeOH
− NaCl
CO₂
CO₃²⁻
Ca²⁺
Cl⁻
Cl⁻
HCO₃⁻
In situ mineralization
CaCO₃
Spruce
0.5
0
10 μm
Beech
0.5
0
5 μm
Heat-release capacity (J g⁻¹ K⁻¹)
0
20
40
60
80
100
120
140
0.0
0.5
1.0
1.5
Concentration of DMC (mol l⁻¹)
Spruce
Beech

◀ Fig. 3 | **Strategies to enhance the mechanical strength and fire resistance of wood.** **a** | Conventional strategies to strengthen wood include compression, polymer impregnation and combined polymer impregnation and compression. In the third approach, wood was first impregnated with polymer and then compressed to enhance the mechanical strength. **b** | A two-step manufacturing process to strengthen wood, involving partial delignification and densification. First, the wood was chemically treated to remove part of lignin and hemicelluloses and soften the cell walls. Then, the material was hot pressed under ~5 MPa at 100 °C to densify the wood structure (~80% reduction in thickness). The mechanical properties of densified wood are greater than those of natural wood, as illustrated in the tensile stress–strain curves and the graphical comparison of the tensile strength and work of fracture. In addition, the specific tensile strength of densified wood is higher than those of typical metals, including Fe-Al-Mn-C alloy (TRIPLEX) and high-specific-strength steel (HSSS), and even lightweight titanium alloy (Ti_6Al_4V). The schematics show multiscale strengthening of the densified wood, including the macroscale laminated, dense bulk structure, intertwined microfibres, aligned cellulose nanofibrils and molecular-scale hydrogen bonds between cellulose fibrils and molecular chains. **c** | Improving the fire resistance of wood by in situ mineralization of the cell walls. A schematic shows the mineralization process (left). The Raman-mapping images show calcium carbonate ($CaCO_3$; 1,080–1,090 cm^{-1}) prevailing in the middle lamella and cell corners (middle). The heat-release capacity of spruce and beech as a function of the precursor concentration (right). The maximum rate of heat release divided by the heating rate in the combustion test is a derived property called the heat-release capacity. The in situ mineralization of the cell walls leads to the generation of calcium carbonate within the cell walls, which improves the fire resistance of spruce and beech. DMC, dimethyl carbonate. Panel **b** adapted from REF.[63], Springer Nature Limited. Panel **c** adapted from REF.[97], CC BY 3.0.

matrix that bonds cellulose fibrils together is removed. During densification, the wood lumina, as well as the porous wood cell walls, collapse, resulting in a densified piece of wood with a ~80% reduction in thickness and a >10-fold increase in strength and toughness[63] (FIG. 3b). As a result, the densified wood features specific strengths higher than almost all structural metals and alloys. The high strength and toughness of the densified wood is derived from the retained alignment of the cellulose nanofibrils, similar to natural wood but much more densely packed (FIG. 3b). The densely packed microstructure also drastically reduces the quantity and size of the pore 'defects' (more specifically, the vessels, fibres and pits) in the densified wood structure, leading to a much higher strength than natural wood. The remaining lignin within the structure has a crucial role in achieving the substantially enhanced strength and toughness by functioning as a phenolic binder of the cellulose fibrils. Studies have demonstrated that densifying fully delignified wood without adding an additional matrix phase leads to a less pronounced enhancement of the mechanical strength[85–87], although it does improve the formability of the wet cellulose scaffolds for achieving complex geometries[85,88].

For diverse civil-engineering applications, the material index, as well as performance index, serve as parameters in material selection to achieve an optimal combination of mechanical properties and weight (or cost)[7,89,90]. Such indexes are structure and function dependent. For example, the material index is $\sqrt{\rho^3/E}$ (where ρ is density and E is stiffness) in selecting a material for a plate deflecting out of its plane owing to self-weight, $\sqrt{\rho^2/E}$ in selecting a material for a beam deflecting under self-weight and ρ/E in selecting a material for a tension element[89,90]. Generally, the lower the material index of a material, the better the mechanical performance of the material. Engineering design is often imposed by limits of design variables (for example, to prevent failure). To this end, a performance index is introduced to quantify how desirable a material will be in a specific structure as a functional component. For example, for a tensile structural element, the performance index is defined as σ/ρ (where σ is tensile strength). In general, the higher the performance index of a material, the better its mechanical performance. In the case of wood densification, the increases in mechanical properties (for example, in stiffness and tensile strength) outweigh the increase in density, further lowering the material index and enhancing the performance index.

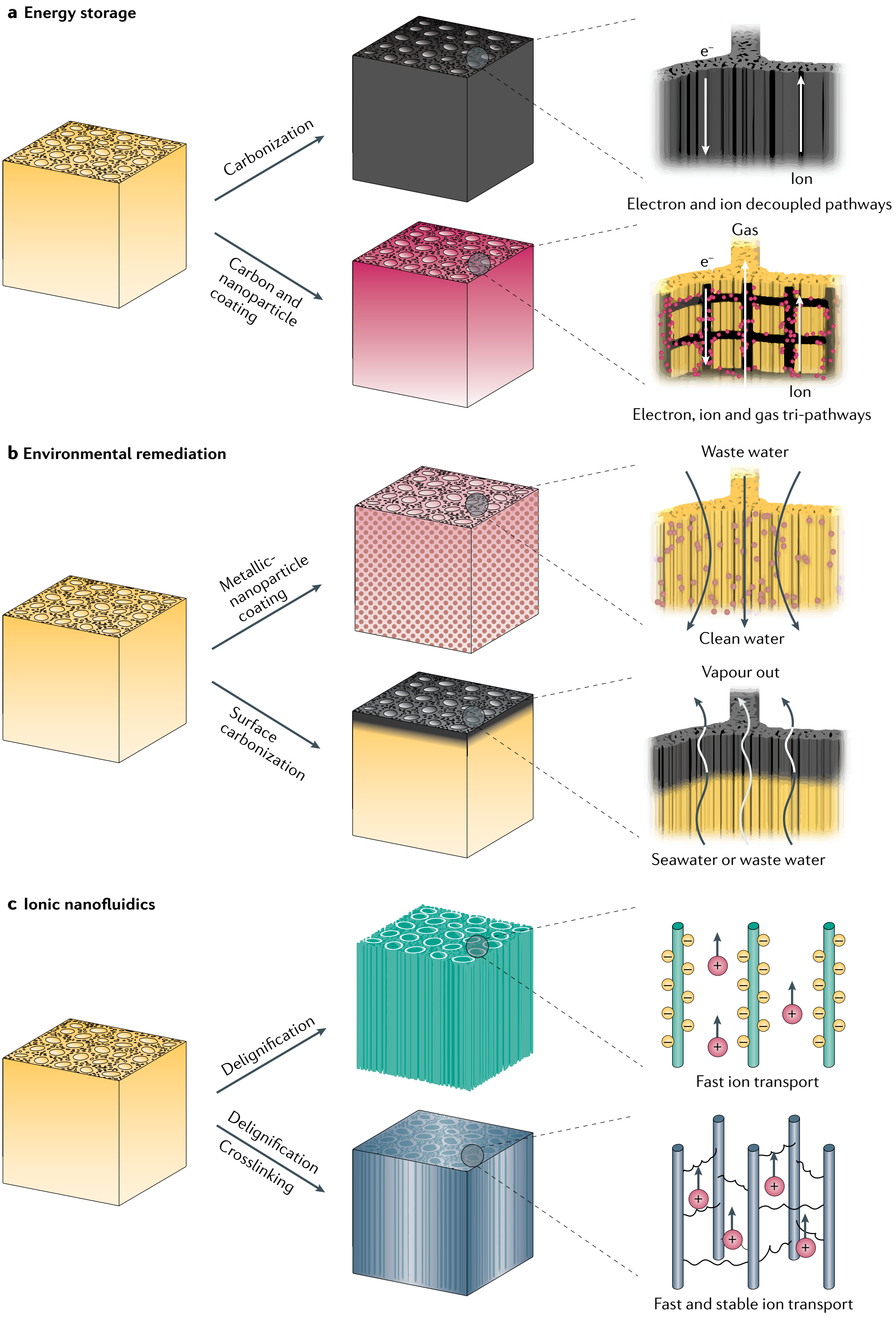
In addition to achieving good mechanical properties, fire retardancy and weather resistance are two key properties that are desirable for construction applications of wood[91–95]. In densified wood, the packed structure (with almost all of the open cells collapsed) enhances the fire retardancy by forming a dense char layer on exposure to flames[96]. This char layer can block the transportation of air and heat to the inner part of the wood, which helps to prevent the material from fully combusting. The fire resistance of wood (for example, spruce and beech) can also be improved by removing the open cell voids via in situ mineralization of calcium carbonate ($CaCO_3$) inside the nanoporous cell-wall structure[97] (FIG. 3c). Compositional analysis by confocal Raman microscopy showed a strong ν1 ($CaCO_3$) vibration at 1,086 cm^{-1}, along with cell-wall-sensitive spectral bands, confirming the presence of $CaCO_3$ within the spruce tracheids and beech fibres. The formation of minerals inside the cell wall protects the wood components (such as cellulose) from thermal decomposition by reducing the generation of volatiles, thereby, improving the fire retardancy by reducing the heat-release capacity of the hybrid wood–mineral material. Other strategies, such as the formation of the mineral struvite in the wood structure[92], the impregnation of clay into the cell walls[98], in situ polymerization inside the cell lumina[60] and boron-nitride coatings[93], have also been proved to enhance the fire retardancy of wood.

Thermal, acetylation, coating, inorganic and polymer-impregnation treatments have been widely applied to improve the dimensional stability and weathering resistance of wood[15,60,99]. For example, densified wood — generated via a simple coating process using an oil-based paint — demonstrated excellent dimensional and structural stability (that is, no dimensional change or mechanical strength degradation after 128 h of testing in 95% relative humidity)[63].

Despite these achievements, additional efforts are needed to simultaneously improve the mechanical properties, fire safety and weathering resistance of wood materials to meet the demands of high safety, good stability and durability, and high mechanical strength required for construction, transportation and sustainable-engineering applications.

Water and energy applications

Multiphase transport (of, for example, ions, electrons, gases and liquids) in wood is important for various applications, such as energy storage[100], solar evaporation[101], ionic nanofluidics[102], microfluidics[103,104] and filtration[105]. Although the intrinsic features of wood, including its hierarchically aligned microchannels, nanopores and cellulose nanofibrils, are beneficial for multiphase transport, structural modifications are necessary for regulating multiphase-transport behaviours, particularly for improving the transport speed to meet the performance requirements of various devices. In particular, pore structure has a vital role in multiphase transport in water-energy devices. For example, in wood-based energy-storage and nanofluidic devices, the abundant hierarchical pores with charged surfaces and



swelled polymer matrix can provide ion-transport pathways when filled with electrolyte[50,67]. In filter and solar-evaporator devices, such abundant hierarchical pores provide water-transport pathways while disturbing heat or contaminant transport with good multiphase selectivity[47,48]. Thus, the modification strategies for engineering the porosity, pore size, molecular structure and/or surface properties of wood to improve ion and fluid transport depend on the desired function (FIG. 4).

Energy storage. For energy-storage technologies, such as supercapacitors and rechargeable batteries, fast ion and electron transport is crucial for achieving high energy and power densities[106]. Wood is ionically conductive when filled with either aqueous or organic electrolyte. However, the mechanism of ion diffusion through the cell wall in natural wood has been a topic of debate[107]. A recent study has revealed that mineral-ion diffusion occurs via interconnecting nanoscale pathways of rubbery amorphous polysaccharides in natural wood, which is different from previous assertions of transport inside the cell wall being an aqueous process occurring through simple interconnecting water pathways[107]. In terms of electron transport, natural wood is electrically insulating. Thus, to make wood suitable as an electrode material for energy-storage devices, structural modification is necessary to enable efficient pathways for electron transport.

Generally, there are two strategies for constructing such electron-transport pathways[67,108,109]. The first strategy is direct carbonization of natural wood, which can transform ligneous material into amorphous carbon while maintaining the hierarchically porous structure of wood (FIG. 4a). This carbonization strategy has been widely adopted to impart wood-based materials with high electrical conductivity for energy-storage applications[54,108,110–117]. The carbonized wood structure features high porosity (~80%), high electrical conductivity (~20 S cm^{-1}), low-tortuosity hierarchical pores, good processability and low deformability, making it an ideal 3D current collector[113], in which various electrode materials, including lithium-iron phosphate, sulfur, manganese dioxide, lithium metal or sodium metal, can be infiltrated into the pores to construct high-mass-loaded, ultra-thick 3D electrodes. The decoupled low-tortuosity ionic (electrolyte-filled nanochannels in the cell walls) and electronic (carbonized cell walls) pathways facilitate the fast transport of both ions and electrons, contributing to the high energy and power density of the energy-storage device[108]. Although high ionic and electrical conductivities can be achieved via carbonization, the mechanical robustness, especially toughness, is largely sacrificed in this process, which is undesirable for wearable and portable electronic applications.

The second strategy of generating electron-transport pathways in wood involves the coating of a thin conformal layer of conductive material (for example, conductive carbon or polymer, or metallic particles) on the external and internal surface of the cellular structure (FIG. 4a). This method does not sacrifice the mechanical robustness of the cellulose-based cell walls and is an effective approach at balancing the trade-offs between the conductivity and the mechanical properties of wood[109,118]. For example, natural balsa wood can be converted into a highly conductive and flexible wood-based cathode for lithium–oxygen (Li–O_2) batteries via partial delignification (making the wood flexible), followed by a coating with carbon nanotubes and ruthenium nanoparticles, imparting the wood with electron-transport pathways and improved catalytic activity, respectively[109]. The uniform and stable coating of carbon nanotubes and ruthenium nanoparticles on the surface of the cell walls combined with the filling of electrolyte in the cell-wall nanochannels forms a robust liquid–solid–air interface, which provides three pathways for the non-competitive transport of ions (through the electrolyte-filled nanochannels), electrons (through the conductive network of the carbon-nanotube-coating layer) and gas (through the open microchannels, such as the vessel lumina). As a result of this tri-pathway design, an ultra-high areal capacity of 67.2 mAh cm^{-2} and long cycling life of 220 cycles were achieved. Moreover, the wood-based cathode and device demonstrated excellent mechanical flexibility, with the ability to be bent, rolled and even folded, holding promise for wearable and portable electronic applications. This nature-inspired, multi-pathway design could be applicable for other devices involving reactions at multiple interfaces.

Wood can accommodate a wide diversity of structural modifications at multiple length scales and, hence, has the potential for use in large-scale (for example, electric grid and electrical vehicles) and portable (for example, personal electronics) energy-storage applications. Among the intrinsic advantages of wood, its low-tortuosity, hierarchically porous structure and nanofluidic behaviour for rapid ion transport are three of its most unique features, especially when carbonization treatment is avoided to preserve the structure and compositions of the cell wall. The low-tortuosity pores enable the rapid transport of ions through the shortest distance between two ends of the electrode, which is attractive for high-performance thick-electrode designs[54,113]. Additionally, the abundant nanochannels between the fully hydrated cellulose nanofibrils in the cell walls can accelerate ion transport as a result of their charged surfaces and small diameter of less than the Debye length[109]. Despite these advantages, continuous efforts are needed to address challenges towards applications, such as

◀ Fig. 4 | **Structural modifications to enhance multiphase transport for water and energy applications. a** | The construction of wood-based energy-storage devices with decoupled pathways for fast transport of ions and electrons. These pathways can be achieved by the carbonization of the wood or by partial delignification and coating with carbon nanotubes and/or metallic nanoparticles to form triple pathways for the fast transport of ions, electrons and gas. **b** | For environmental-remediation applications, decorating metallic catalyst nanoparticles or functional groups on the surface of the cell walls can yield a wood-based filter with a high throughput of water and high efficiency. Alternatively, a surface-carbonized bilayer wood evaporator, which offers strong light absorption, fast water transport and evaporation, and good thermal insulation, can be used for solar-assisted production of clean water. **c** | Wood-based nanofluidic membranes can be constructed via delignification to produce numerous aligned nanochannels with high surface-charge density that provide highly conductive and selective ionic transport. A wood hydrogel can also be fabricated via delignification and polymer-crosslinking treatment, and functions as a highly conductive, mechanically robust and stable nanofluidic membrane.

the sacrificed volumetric energy density owing to the high porosity of the material and the relatively high cost and low efficiency and precision of the structural modification at scalable production. Future studies will need to focus on precise structural modifications, especially at the nanoscale and the molecular scale, to finely manipulate ion, electron and mass transport.

Environmental remediation. Wood also holds great promise for environmental remediation in response to the global water-scarcity and pollution issues. Water scarcity is a severe global challenge, with nearly one-fifth of the world's population living in areas with water scarcity and another 1.6 billion people living in economic water scarcity because of the technical or financial limitations of obtaining fresh water, even when it is available[101]. Efforts have been devoted to developing effective and eco-friendly technologies to produce clean and drinkable water from sources, such as sea, lake, river, underground and contaminated water[101,119,120]. Among these technologies, membrane filtration and solar evaporation are two of the most effective, cost-efficient and affordable technologies for the production of clean water, especially in remote areas where access to the grid and facilities is limited.

Wood's naturally hierarchical porous structure makes it attractive for water purification. With suitable structural modification, such as the grafting of functional groups or catalytic nanoparticles on the internal and external surface of the cell walls, wood membranes can be used as filters for water purification[46,47,121] (FIG. 4b). When the water flows through the wood channels, pollutants (such as organic contaminants, heavy metals and inorganic particles) can be absorbed by the cellulose-based cell walls grafted with functional groups (for example, carboxylic-acid groups) or even decomposed by catalytic nanoparticles (for example, silver and palladium nanoparticles), contributing to a high treatment efficiency of up to 99.5%[46,47,121]. Another benefit of wood-based filters is the high throughput imparted by the low-tortuosity porous structure, in which a large amount of water can rapidly flow through the microchannels. The trade-off between treatment efficiency and throughput has been a long-standing issue for water purification; however, as wood-based filters exhibit a high efficiency without sacrificing the throughput, they are a promising approach to the scalable, low-cost and sustainable production of clean water. Wood with modified surface properties (for example, hydrophobicity) also demonstrates capability in oil absorption and oil–water separation, representing a practical route to address severe oil pollution[23,25,122,123].

Solar evaporation, in which absorbed sunlight is used to heat and induce the fast evaporation of water as a purification method, is attracting growing interest because of its high efficiency, low cost and technical simplicity, as well as its use of renewable solar energy. The operation of a solar-evaporation device (also called a solar evaporator) involves three processes — light absorption and conversion into heat, water transport and evaporation, and thermal management[101]. It is well known that water transport in trees, from the roots to the trunk and leaves, occurs via evaporation at the leaf–air interface and is a key mechanism for tree growth and wood formation[124]. This ability inspired researchers to develop wood-based evaporators to exploit the intrinsic properties of wood, including its aligned hierarchical pores and excellent hydrophilicity, which are beneficial for fast water transport. Additionally, the low thermal conductivity of wood results in good thermal insulation and heat localization at the evaporative surface. As strong light absorption is a key factor in this process, it is necessary to structurally alter natural wood to improve this characteristic. Since 2017, intensive efforts have been dedicated to improving the solar-light absorption of wood-based evaporators, from less than 30% to nearly 100% across the full solar spectrum using structural modification strategies, such as surface carbonization[124–128] and the addition of photothermal materials via coatings of, for example, graphene oxide[129], carbon nanotubes[130], graphite[131], plasmonic metallic nanoparticles[48] and narrow-bandgap semiconductors[132].

Among these approaches, surface carbonization is the most facile and cost-effective (FIG. 4b). In a typical surface-carbonized bilayer wood evaporator[124], the incident solar light is nearly completely absorbed by the black carbonized layer on top of the wood surface and converted into heat, which is largely localized at this top surface, owing to the good thermal insulation of the wood substrate[124]. Simultaneously, water is absorbed and transported from an underlying reservoir beneath the wood device, transporting up through the wood's microchannels and nanochannels to the top evaporative surface via the capillary driving force. This water is then heated by the absorbed solar light and evaporates quickly. The generated vapour is then condensed and collected as clean water that meets the World Health Organization standard for drinkable water, regardless of the water source.

The wood-based evaporator shows excellent salt-rejection capability after suitable structural modification, such as by drilling macroscale holes as replenishing channels in the structure or by carbonizing wood with naturally large vessels (for example, balsa)[133,134]. The difference in size between the drilled and natural wood channels leads to different hydraulic conductivities, which creates salt-concentration gradients between the millimetre-sized drilled channels (with a low salt concentration similar to bulk water) and the microscale natural wood channels (with a high salt concentration). Under such gradients, spontaneous interchannel salt exchange through the pits traversing the cell walls occurs, resulting in the dilution of salt in the microscale wood channels. The drilled channels with high hydraulic conductivities act as salt-rejection pathways to rapidly exchange the salt with the bulk solution, enabling the real-time self-regeneration of the evaporator. In this manner, it is simple to treat even high-concentration brines to produce potable water.

Wood-based materials, with their naturally hierarchical porous structure combined with structural modifications, have enjoyed success in environmental remediation in response to global water scarcity and the challenges of environmental pollution. Despite this success, challenges remain at the material, device and system levels, which need to be overcome before commercialization is possible. For example, the presence of water, bacteria, fungi and contaminants may lead to the poorer stability of wood than in dry conditions, which is a concern for long-term operation. Hence, strategies are required to improve stability, such as by crosslinking, the fabrication of robust surfaces via coating or impregnation, or through thermal treatment. In addition, integrating wood-based materials into a device or system for an application may be of higher cost and lower efficiency than laboratory-scale demonstrations, requiring further efforts to develop rational system designs from academia and industry.

Nanoionics and nanofluidics. Ionic nanofluidic membranes comprising a large number of nanochannels for the regulation of ion transport have been used in a range of applications, including in osmotic-energy generation[135], desalination[136], ion–molecular separation[137] and ionic circuitry[138]. Ion transport in nanoconfined, surface-charged channels substantially differs from bulk behaviour, owing to the interactions between the solvated ions and the inner channel walls. This nanofluidic effect produces high ionic conductivity and/or selectivity, which is essential for these kinds of applications. The wood cell walls are comprised of orientated, assembled cellulose nanofibrils embedded in the hemicellulose and lignin matrix, which provides a scaffold for numerous aligned nanochannels between the adjacent cellulose nanofibrils after partial or complete delignification to remove the polymer matrix. Additionally, the abundance of functional groups (such as hydroxyl groups) on the cellulose nanofibrils enables the surface-charge density to be easily tuned via chemical modification.

The existence of nanochannels combined with their tunable surface-charge density and spacing makes wood an attractive material for nanofluidic membranes. The size and surface-charge properties (for example, density and potential) of the nanochannels are two factors that can markedly influence the ion-transport behaviour of the nanofluidic membrane. Tuning these two factors via structural modification provides an effective strategy for regulating ion transport. For example, a scalable and highly ionic conductive wood-based nanofluidic membrane has been fabricated by delignifying natural basswood (*Tilia*)[50] (FIG. 4c). The removal of lignin and hemicelluloses from the wood cell walls generates more nanochannels between the aligned cellulose nanofibrils. The surfaces of the negatively charged cellulose nanofibrils can attract layers of counterions adjacent to the fibres to form an interface-dominated electrostatic field that surrounds the nanofibrils, providing surface-charge-governed ion transport along the fibre direction for desirable ionic separation. By altering the geometry and surface charge of the wood-based nanofluidic membrane, the ion transport can be easily regulated to achieve tunable ionic conductivity and selectivity. Through densification treatment, the average diameters of the nanochannels are also substantially reduced from ~20 nm to 2 nm, resulting in an order of magnitude higher ionic conductivity at a low concentration of less than 10^{-2} mol l^{-1} (REF.[50]). The surface-charge density, reflected by the material's zeta potential value, can be increased by converting the hydroxyl groups into carboxyl groups to improve the ionic conductivity of the wood-based nanofluidic membrane[50]. Moreover, the surface-charge potential can be reversibly converted (for example, from negatively charged into positively charged) to tune the ionic selectivity[139].

In addition to ionic conductivity and selectivity, material stability is crucial for nanofluidic membranes, particularly for their application. Although delignification can greatly improve the ionic conductivity of the wood-based nanofluidic membrane, the material stability in aqueous solution is sacrificed, owing to the removal of the lignin and hemicellulose binding agents. Improving the ionic conductivity without reducing the material stability is desirable, yet remains challenging. Towards this aim, a crosslinking strategy has been developed to improve the stability of a delignified wood-based nanofluidic membrane by growing a polymer network inside the lumina and cell walls in situ, resulting in a material termed a 'wood hydrogel'[66] (FIG. 4c). The polymer network not only binds the cellulose nanofibrils tightly together but provides additional nanochannels for ion transport, contributing to the membrane's improved mechanical robustness and ionic conductivity. Such a combination of high ionic conductivity, mechanical strength and stability can be achieved in a cationic wood membrane by partially removing the hemicellulose–lignin polymer matrix from natural wood, along with surface-charge modification and densification[139].

Despite the progress made, wood-based ionic nanofluidic membrane devices are still in their infancy. Continuing efforts are needed to solve the challenges for applications, such as improving the fouling issue of cellulose-based materials, finely tuning the geometry and surface charge of the wood channels to improve the precision of ion control, and exploring applications, such as heat-to-electricity conversion for low-grade heat harvesting[24].

Optical applications

Research into the manipulation of the optical properties of wood have mainly focused on making wood transparent for various optical applications[26,64,73,140–145]. In 1992, Fink[140] reported the first preparation of transparent wood for the purpose of facilitating the morphological study of wood. In 2016, the addition of functionalities to load-bearing transparent wood, such as optical transparency and thermal insulation, was realized by combining mechanical studies with the characterization of optical transmittance[26,141]. Since then, research has focused on improving the performance of transparent wood and exploring new functions[142–153].

Approaches for making wood transparent generally involve two steps — removing the light-absorbing components (mainly lignin) and infiltrating a polymer with a refractive index that matches the wood substrate[26] (FIG. 5a). The hierarchically porous structure is well maintained upon delignification and, at the same time, additional nanopores are generated from the removal of almost all the lignin and part of the hemicellulose

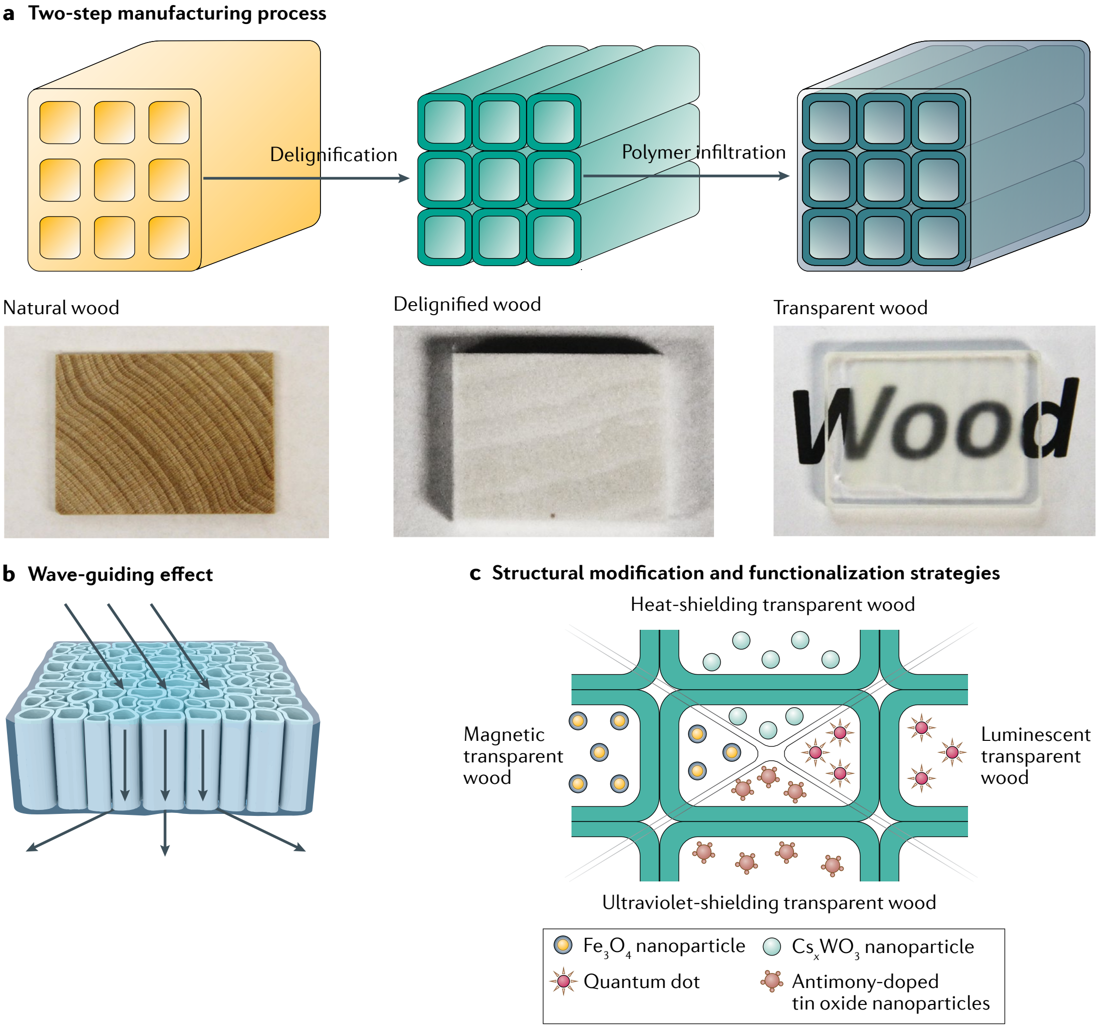


Fig. 5 | **Manipulating the optical properties of wood. a** | Wood can be made transparent via a two-step process involving delignification and polymer infiltration. First, wood is chemically treated to remove lignin from the cell walls and it is then infiltrated with a polymer of a refractive index that matches the refractive index of the wood substrate. The photographs show the colour change of wood from brown (natural wood) to white (delignified wood) to transparent. **b** | A schematic of the wave-guiding effect of transparent wood. Light can be guided along the wood fibres independent of the angle of the incident beam. **c** | Structural modification and functionalization strategies to impart additional functionality to transparent wood, including infiltrating magnetic (Fe_3O_4) nanoparticles to impart magnetic function, antimony-doped tin oxide nanoparticles to impart ultraviolet-shielding function, quantum dots to impart luminescence and caesium-doped tungsten bronze (Cs_xWO_3) nanoparticles to impart heat-shielding function. Panel **a** adapted with permission from REF.[26], *Wiley*.

content. The brown colour of natural wood becomes white after delignification, owing to the strong light scattering at the boundaries between the air in the cellular void channels and the solid cell walls, resulting in a large refractive index mismatch ($n = 1.53$ for the cell wall and $n = 1$ for air). Air can be replaced by a polymer with a refractive index of ~1.53 via infiltration, which reduces the light scattering, resulting in a highly transparent wood–polymer composite (namely, transparent wood) that features low light absorption and low reflection. Of note, although transparent wood can reach a transmittance as high as ~95%, it is difficult to reduce the haze (usually >50%), which makes the material substantially different from low-haze commercial glass[73]. The high haze is attributed to the microcurvatures and residual voids of the wood structure that can scatter light, even after polymer infiltration. The combination of high transparency and haze is desirable for light management in solar-cell applications[142] but undesirable for window applications that are currently dominated by glass, in which high transparency and low haze are required.

An interesting feature of transparent wood is the wave-guiding effect resulting from the anisotropic cellular structure of wood (FIG. 5b). More specifically, light is guided along the wood fibres independent of the angle of the incident beam. This ability has been used in combination with an optical dye to prepare a wood laser[148]. Additionally, when transparent wood is used as a window or roofing material for buildings, this wave-guiding effect allows the maximum utilization of solar light for illuminating the interior, holding great promise for energy-efficient buildings. In this context, transparent wood may replace some traditional window or roofing materials, such as glass.

By modification of transparent wood with various functional groups, the material may find uses in other fields, such as optics, electronics and magnetics[147–153] (FIG. 5c). For example, transparent magnetic wood with combined optical and magnetic functions was achieved by mixing ferrosoferric-oxide nanoparticles with polymers of methyl methacrylate and 2,2′-Azobis(2-methylpropionitrile) prior to polymer infiltration[151]. The uniform distribution of nanoparticles within the polymer filler without aggregation is the key to maintaining both good optical and good magnetic properties. In another study, several types of quantum dots were incorporated into the polymer filler to impart transparent wood with light-emission function (namely, luminescent transparent wood)[149]. The strong light scattering caused by the anisotropic wood structure results in diffused luminescence from the embedded quantum dots, which expands the application of transparent wood optical devices and luminescent building constructions. Other functions, such as heat shielding and ultraviolet (UV) shielding, have also been imparted to transparent wood by adding functional particles to the polymer filler[147,152].

Although progress has been made towards achieving a high optical transmittance, mechanical strength and various functions in transparent wood composites, several challenges need to be addressed. For example, a high optical transmittance is accompanied by a relatively high haze in transparent wood, which hinders its applications in areas where high transmittance and low haze are required simultaneously (for example, optically clear windows in buildings). The optical haze of transparent wood can be reduced to ~10% by removing wood components to construct a highly porous microstructure for polymer infiltration, representing a promising direction for clear wood fabrication[154]. Manufacturing of thick and large lateral-sized transparent wood is another challenge with difficulties in both fabrication (for example, the diffusion of chemicals inside large wood blocks suffers from non-uniformity) and achieving a high optical transparency (light scattering increases in severity as the thickness of transparent wood increases). In addition, the effects of weathering, for example, the UV stability of transparent wood, need to be improved to meet the requirements of outdoor application.

Thermal management

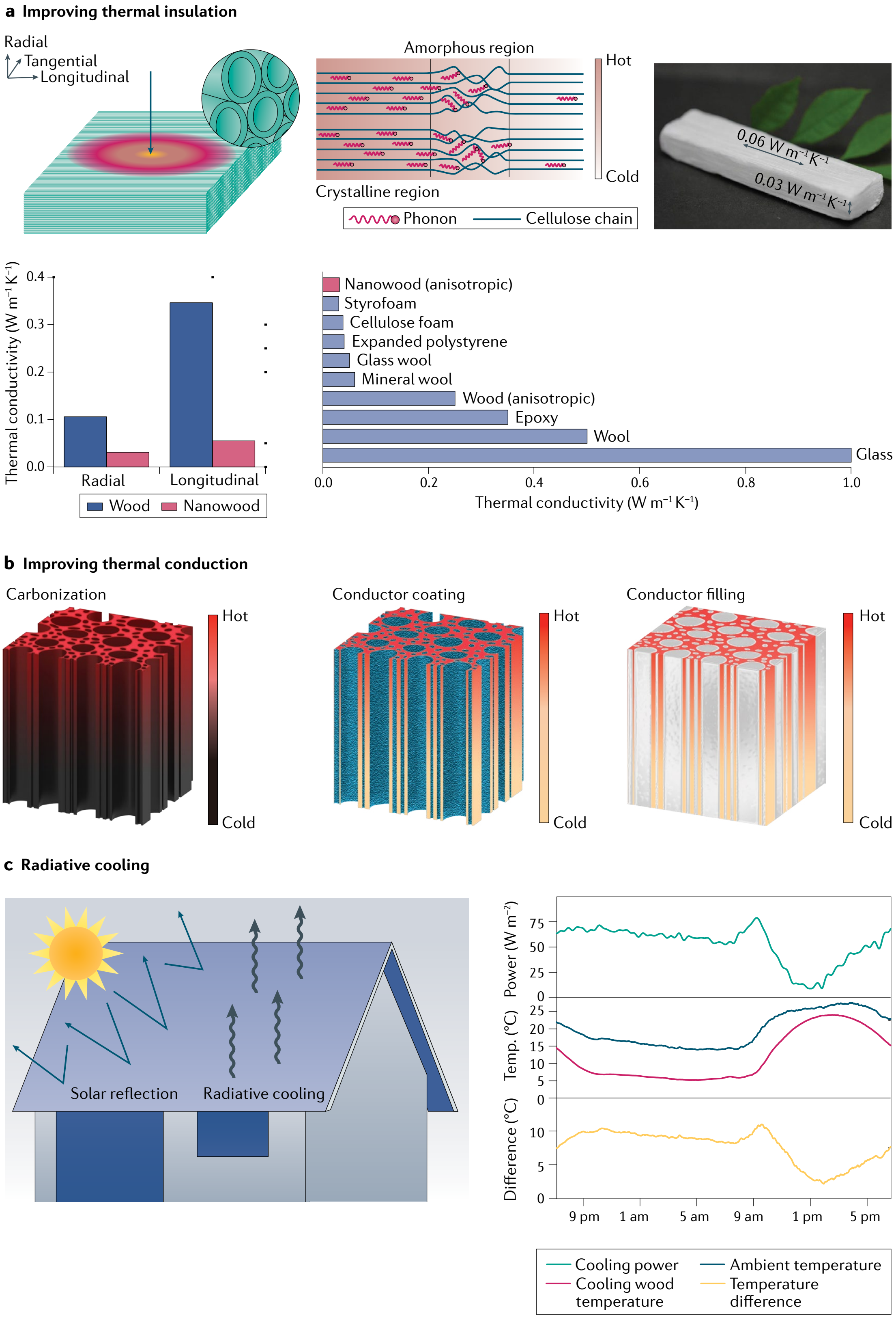
Wood has been used as a thermal insulating material in a variety of fields, including construction and solar evaporation. Wood has a good thermal-management capability, owing to its hierarchically porous structure and biopolymer-based composition[155,156]. For instance, the thermally insulating behaviour of natural wood can block most of the heat transfer from the warm outdoors to cool, air-conditioned, indoor environments during the summer (and the reverse in the winter), resulting in passive energy savings for buildings.

In the past few years, growing effort has been dedicated to improving the thermal insulation of wood[49,51,146]. Delignification is one of the most effective approaches in regulating the thermal properties of wood by removing the thermally conductive lignin component and simultaneously generating a large number of nanopores in the cell walls, which disrupt phonon transport[49] (note that the final wood product after delignification is called nanowood; FIG. 6a). In this manner, the thermal conductivity of basswood can be substantially reduced from ~0.35 to 0.06 $\mathrm{W\,m^{-1}\,K^{-1}}$ along the longitudinal direction after complete delignification[49]. Interestingly, the thermal conduction of wood is anisotropic, as a consequence of its anisotropic structure. In natural basswood, the thermal conductivities in the longitudinal and radial (normal to the growth rings) directions are 0.347 ± 0.035 and 0.107 ± 0.011 $\mathrm{W\,m^{-1}\,K^{-1}}$, respectively. After delignification, the thermal conductivities decrease substantially to 0.056 ± 0.004 $\mathrm{W\,m^{-1}\,K^{-1}}$ in the longitudinal direction and 0.032 ± 0.002 $\mathrm{W\,m^{-1}\,K^{-1}}$ in the radial direction, corresponding to an anisotropy of 2, both of which are lower than most commercially available thermally insulating materials[49] (FIG. 6a).

The low and anisotropic thermal conductivity can be attributed to the structural change in wood after the delignification process. Following this chemical treatment, the cellulose nanofibrils are partially isolated, which imparts numerous air–cellulose interfaces along the tangential direction (the direction along the tangent of the growth rings). Additionally, the resulting structure features improved nanofibril alignment, owing to the removal of non-aligned lignin and the further self-alignment of the nanofibrils when they are in the wet state. Such low and anisotropic thermal conductivities are useful in thermal-related applications, such as energy-efficient buildings, thermal insulation for space applications and insulation of electrical devices. More specifically, the use of nanowood to construct energy-efficient buildings is particularly attractive because of their substantially improved thermal insulation and high mechanical strength. In addition, nanowood has the advantage of being sustainable and green, unlike more commonly used construction materials, such as concrete, steel or brick-based systems.

However, the increase in structural porosity and the partially isolated cellulose nanofibrils that result from delignification are beneficial for thermal insulation but are detrimental to the mechanical robustness of the material. This trade-off between thermal and mechanical properties could be balanced by further densification[65] or crosslinking. Other strategies, such as hybridization with organic particles and polymers, are also promising approaches for enhancing the thermal-insulation performance of wood.

For some applications, such as battery electrodes, electronic substrates and crude-oil absorbents, a high thermal conductivity is preferred. In these cases, structural modifications that can increase the thermal conductivity of wood are needed. One widely used strategy is high-temperature carbonization, in which the thermally insulating lignocellulosic components are converted into thermally conductive carbon, increasing the thermal conductivity from ~0.1–0.3 to ~0.6 $\mathrm{W\,m^{-1}\,K^{-1}}$ (REFS[157,158]). When used as an electrode or electronic substrate, heat is conducted via the carbonized wood, preventing thermal accumulation and, therefore, device failure. Hybridizing with metal, carbonaceous materials



or thermally conductive polymers has also been proposed to improve the thermal conductivity of wood, suggesting a wide range of thermal behaviour that can be controlled via structural modification[159,160] (FIG. 6b). Nanoscale and molecular-scale structural engineering (for example, tuning the crystallinity and/or orientation of cellulose fibrils) may also enhance the thermal conductivity.

The use of wood for the thermal management of buildings via passive radiative cooling has recently gained interest. For a material to exhibit passive radiative cooling, it must emit more heat than the amount

◀ Fig. 6 | **Manipulating the thermal properties of wood. a** | The thermal conductivity of wood can be reduced via delignification and pore engineering (generating more nanopores). After delignification, the anisotropic structure and, hence, the anisotropic thermal transport of the wood is maintained. Abundant nanopores between the cellulose nanofibrils and boundaries between crystalline and amorphous regions within a single nanofibril provide large cellulose–air and cellulose (crystalline)–cellulose (amorphous) interfaces for phonon scattering. The anisotropic wood structure leads to different thermal conductivities for both nanowood and natural wood in the longitudinal and radial directions. The enhanced phonon scattering leads to a low thermal conductivity of nanowood, which is superior to most commercially available thermally insulating materials. **b** | The thermal conduction of wood is improved by either carbonization or hybridization (for example, coating or filling) with other thermally conductive components. Carbonization converts the lignocellulosic wood components into carbon for better thermal transport. By coating or filling thermally conductive components into wood lumina, the thermal transport can also be greatly improved. **c** | Radiative cooling wood can be created via complete delignification and densification. Owing to its high solar reflectance and high infrared emissivity, as well as high mechanical strength, cooling wood can be used as an energy-efficient building material. A 24-h continuous measurement of a 200-mm × 200-mm piece of cooling wood, including the direct measurement of the radiative-cooling power (top) and the steady-state temperature (middle) of the cooling wood, and the temperature difference between the ambient and the cooling wood (bottom), indicated that an average below-ambient temperature of >9 °C during the night and >4 °C at midday (between 11 am and 2 pm) can be achieved. Panel **a** adapted (graphical illustration of thermal transport in nanowood on left) and reprinted (photographs and curves) from REF.[49], CC BY 4.0. Panel **c** (right) reprinted with permission from REF.[162], AAAS.

of solar irradiance it absorbs. This process enables the efficient regulation of interior temperatures by offering a perpetual path to dissipate heat from the structure through the atmospheric transparent window into the ultra-cold universe with zero energy consumption[161]. Wood can be made into a radiative-cooling material (namely, cooling wood) by the modification steps of complete delignification followed by mechanical compression[162]. Delignification imparts the cooling wood with brilliant whiteness, as demonstrated by its high, diffusive reflectance in the solar-radiation range, leading to a low absorbed solar irradiance. The compression increases the mechanical strength and thermal conductivity of the cooling wood. Meanwhile, the molecular vibration and stretching of cellulose in the cooling wood facilitates strong emission in the infrared range. Benefiting from these structural advantages, the cooling wood demonstrates a radiative-cooling temperature below ambient during the day and night (FIG. 6c), with an average below-ambient temperature of >9 °C during the night and >4 °C between 11 am and 2 pm (REF.[162]). Such natural cooling capability is attractive in energy-saving buildings, especially when a high mechanical strength is integrated.

As a consequence of the thermal-management requirements of wood materials and devices, manipulating thermal transfer behaviour for specific functions requires different structural modification strategies. Efforts in this direction are essential to gain a deeper understanding of the relationship between wood's structure and thermal properties.

Other applications

Wood has been explored for other functions, such as tissue engineering, thermal-energy storage, ion detection, sensing, microwave absorption, electromagnetic shielding and electrocatalysis[52,163–174]. The anisotropy of the wood structure and its abundant aligned pores provide an ideal material scaffold for the fabrication of anisotropic hydrogels and inorganic materials[60,166]. Similarly, wood can be used as a platform in tissue engineering, given the similarity between its structural features and that of animal tissue[163,172]. For example, a general and facile method employing a seeded-growth strategy enables the fabrication of self-standing zeolitic tissue that inherits the cellular structure of wood at various hierarchical levels[163]. With suitable structural modification, wood can be converted into flexible membranes, either with or without the inherent hierarchical pores, which can be used as biodegradable substrates for flexible electronics or cell culture[52,86]. Wood can be converted into a compressible aerogel by chemically removing lignin from the cell walls, with the resulting material demonstrating potential in thermal management, water–oil separation and strain sensing[25,51,167]. Additionally, if made electrically conductive via either carbonization or conductive-polymer coating, wood can absorb microwaves for electromagnetic shielding[169,170]. Highly conductive graphene can also be directly patterned on wood via ultra-fast laser pulses for use as a green electronics substrate[168]. The development of the use of wood in biofuels[175], timber construction[175] and bio-templates for bio-inspired materials[176,177] has been outlined previously.

Advanced characterization and modelling

Characterization techniques and computational-modelling approaches are critical for our understanding of the composition, structure, properties and functions of wood. Here, we overview these approaches, with a focus on how these techniques and approaches enable the regulation of composition, structure and properties of wood functional materials.

Characterization techniques

The successful development of wood-based materials requires a high degree of control over the location and distribution of the functionalization of the wood. Thus, analytical techniques that provide high-resolution 2D and/or 3D mapping with high chemical and spatial resolution of the material are needed to understand the structure at the nanoscale and sub-nanoscale[11]. As the development of these techniques has progressed, our ability to understand wood structures with increasing accuracy has improved, which should enable the optimization of the properties of the aforementioned functional devices and materials.

A range of characterization techniques based on Raman microscopy, AFM and synchrotron XRD, each of which has its unique measurement principles, can be used to identify the composition and structure of wood-based materials (FIG. 7).

Raman microscopy. Confocal Raman-spectroscopy imaging — which relies on the inelastic scattering of monochromatic light, resulting from the interactions with molecular vibrations[29] — can provide a diffraction-limited (maximum of 250–300 nm), spatially resolved visualization of the composition of the wood-based composite. In contrast to other diffraction-limited

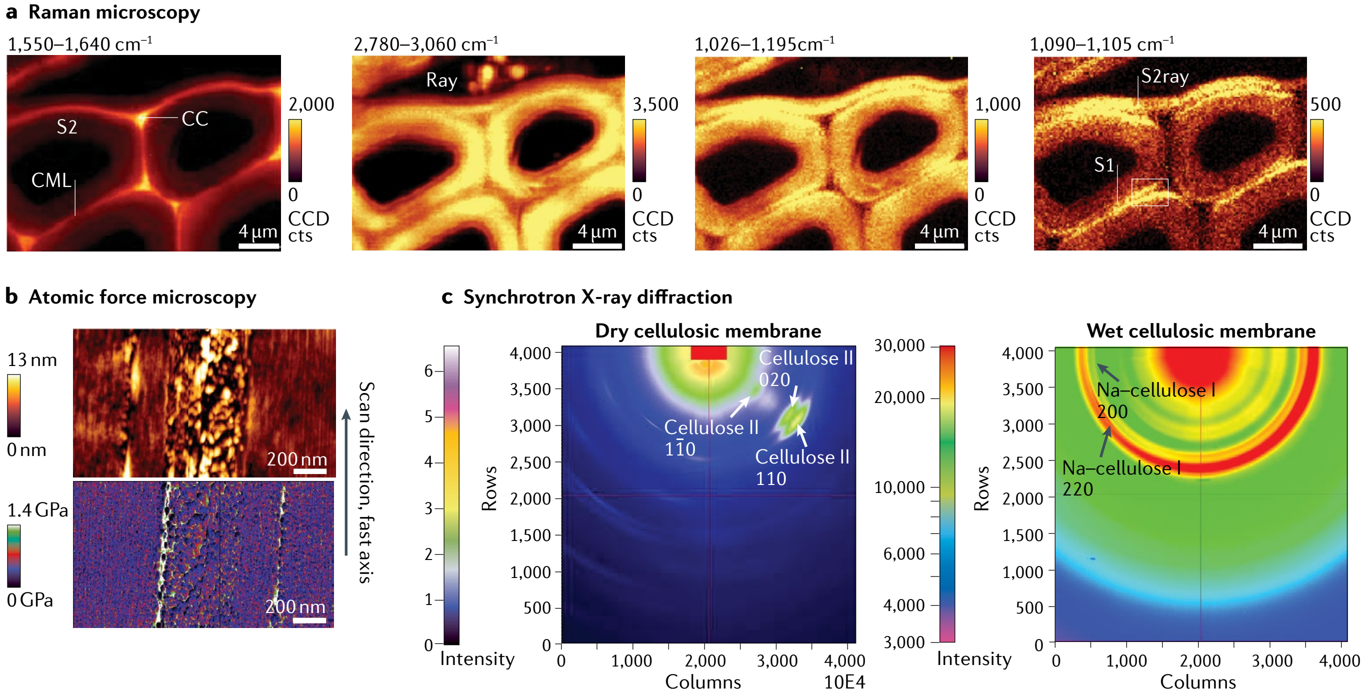


Fig. 7 | **Characterization techniques for determining the structure–property–function relationships of wood.** **a** | Raman microscopy imaging of the compositional distribution in poplar latewood by integrating over defined wavenumber areas. Note the intensity of the aromatic lignin band (1,550–1,640 cm^{-1}) and the C–H stretching region (2,780–3,060 cm^{-1}), and the intensity of the bands in the carbohydrate region at 1,026–1,195 cm^{-1} and the intensity of the 1,096-cm^{-1} band (1,090–1,105 cm^{-1}). S1 and S2 are layers of the secondary cell wall, S2ray is the S2 of the parenchyma ray cell, CC is the cell corner and CML is the compound middle lamella, which comprises two adjacent primary walls and the middle lamella. CCD is charge-coupled device and CCD cts is the digital units (or counts) contained in the CCD image. **b** | Atomic force microscopy height image (top) and Young's modulus image (bottom) of a CML. The scan direction is in line with the structures, as indicated by the arrow. The cutting direction is perpendicular to the CML. **c** | Synchrotron X-ray-diffraction-based characterization of the dry cellulosic membrane, which shows mostly cellulose II (the arrows indicate cellulose II [1$\bar{1}$0], [110] and [020], with small amounts of cellulose I crystal). The wet cellulosic membrane is infiltrated with electrolyte; a Na–cellulose I complex was observed to coexist with the cellulose II and cellulose I structures. Panel **a** reprinted with permission from REF.[180], American Society of Plant Biologists. Panel **b** reprinted from REF.[190], CC BY 4.0. Panel **c** reprinted from REF.[24], Springer Nature Limited.

optical-microscopy-imaging techniques, such as UV and fluorescence microscopy, Raman spectroscopy analysis is not limited to specific constituents. Rather, it enables the simultaneous characterization of the wood components and different types of modifying agents, including polymers, minerals and metals[45,97,178,179]. One of the first and ground-breaking studies of the composition of wood cells using this approach was by Gierlinger, Agarwal and co-workers[29,30,180]. Using Raman spectroscopy, the researchers demonstrated that spatial maps of the cells of poplar latewood could be obtained using unique spectral information emanating from the cellulose and lignin[180] (FIG. 7a). Additionally, Raman-spectroscopy imaging can provide spatially resolved chemical analysis of the delignified cellulose scaffold. Raman spectroscopy is not only capable of mapping the distribution of the individual components of wood but is highly sensitive to conformational changes of the wood constituents. For example, Raman spectroscopy has been used in situ to analyse the conformational changes in constituents of wood-hydrogel materials in response to temperature changes, which leads to transformation of the surface properties from hydrophilic to hydrophobic[181]. However, a problem with this technique for wood analysis is the presence of chromophoric structures that often remain in the sample after delignification, which can generate fluorescence during imaging and mask the Raman-scattering signal[182].

Although Raman spectroscopy is valuable in wood research, the maximum resolution of the technique is limited to half the wavelength of the incident light. However, the sizes of various substructures of the wood cells are below this limit. Thus, substantial increases in spatial resolution are needed to enable the chemical analysis of wood. In 1928, Synge[183] had the idea of breaking the diffraction limit by illuminating the sample or collecting the optical signal through a sub-wavelength aperture that is located in close vicinity (in the nanometre range) to the sample surface. The ability to bring the aperture to this position is possible with scanning-probe-microscopy feedback and, in 1984, the first near-field measurements were reported[184]. However, the low signal intensity owing to the small diameter of the aperture has necessitated the development of methods to improve the signal, such as tip-enhanced Raman spectroscopy, whereby the Raman signal is enhanced by the irradiation of a metallic probe near the sample surface. The illumination of the metallic probe results in surface plasmons, which lead to a strong electromagnetic field at the tip apex[185]. To date, such near-field optical-microscopy methods have been mainly applied for simple biological systems[186] and only a few studies have analysed the cell walls of natural wood[187]. However, these methods have immense potential for the analysis of wood-based composites.

Atomic force microscopy. Changes in wood chemistry and composition during the fabrication of wood-based composites affect the mechanical properties of the material. As a result, further mechanical characterization is necessary in addition to chemical analysis. Conventional mechanical-testing protocols do not offer sufficient spatial resolution, but these limitations have been overcome by new developments in AFM. Previously, AFM was intensively used for the nanostructural characterization of lignocellulosic materials, in which a very small tip is raster-scanned across the surface of the sample. The specific interactions (more specifically, van der Waals, electrostatic and capillary forces) between the tip and the sample surface are then converted into a high-resolution topographical image[188,189]. Aside from enabling these structural analyses, AFM modes have been developed for nanomechanical characterization that are mainly based on mapping the surface with a grid of force–distance (FD) curves, which provide valuable insight into mechanical parameters such as local stiffness and adhesion[31]. Mechanical characterization of wood-based materials using FD-curve-based AFM (FD-AFM) is already in a more advanced phase of development than the aforementioned near-field microscopy methods. Different types of lignocellulosic samples have been characterized and the first steps have been made towards the analysis of functionalized wood materials using FD-AFM[190] (FIG. 7b). However, AFM-based mechanical characterization with nanometre resolution is still at an exploratory stage, and unresolved questions must be addressed, specifically regarding the contact between the tip and the sample. Additionally, there is a troubling lack of consistency in the values obtained in studies using FD-AFM. A direct comparison of the individual AFM results is often impeded by the use of different measurement set-ups, including cantilever type and stiffness, the fitting procedure and measurement velocities, making it difficult to validate findings.

Synchrotron X-ray diffraction. Synchrotron radiation is another powerful tool for probing the innermost details of the cellular and hierarchical structure of wood. This capability is especially true for X-ray tomographic imaging, which had been, until recently, reserved for more conventional materials. In this technique, a structure's detail can be mapped in 3D, with a temporal dimension also possible, enabling real-time evaluations of complex materials. As discussions on how to apply this technique to porous structures are available elsewhere[191], we highlight some examples of where it has been applied to wood. One of the first studies to examine the wood structure in detail was a case study[192] on two species of wood — oak and beech. The conventional manual technique of optical micrography for wood anatomical characterization was compared with an automated tomographical approach. The findings indicated no differences between the approaches in terms of statistically significant measurements of the wood's porosity, as well as vessel surface area, inner diameter and density, suggesting that the techniques are comparable. Furthermore, tomography, specifically, X-ray computed microtomography (microCT), have the advantages of being non-destructive and faster than conventional optical micrographs[192]. Benefiting from these features, in vivo X-ray microCT enables the visualization of water movement in wood[193], negating the need for the time-consuming sample preparation that is necessary for conventional microscopy (for example, sectioning and slicing). Another application of synchrotron-based tomography is its ability to map in the temporal dimension, which allows dynamic measurements to be performed. As a result, it has been possible to observe the change in the structure of wood during compression, clarifying mechanisms of deformation[194].

In addition to morphological imaging, synchrotron radiation can determine the microfibril and crystal structure, as well as nanoscale spacing between cellulose fibrils of wood. For example, synchrotron XRD was used to determine the crystal structure of cellulose in a delignified wood membrane[24] (FIG. 7c). The synchrotron XRD pattern of the dry delignified wood membrane indicated the formation of cellulose II in the dry state, owing to the partial conversion of cellulose I into cellulose II that occurs during the delignification process with high concentrations of sodium hydroxide. Interestingly, when the delignified wood membrane was soaked in electrolyte, the spectrum revealed a new peak (220), suggesting the presence of the Na–cellulose complex structure (that is, sodium intercalating in the charged molecular chain of the delignified wood membrane). As a result, the delignified wood membrane exhibited a thermal gradient ratio of 24 mV K^{-1}, which is more than twice the highest value ever reported.

Other characterization techniques. Small-angle X-ray scattering (SAXS) has also been used to probe the structure and dimensions of wood cell walls. Fibril sizes obtained from SAXS measurements concur with measurements taken using electron microscopy, demonstrating that the regularity of the thickness of the fibrils is an indication of the structural stability of wood[195]. Detailed analysis of microfibril angles using SAXS in a complete branch of wood has shown that the mechanical properties adapt to loading situations by the variation of microfibril angles[196]. In addition, the microfibril angles in the wood cell walls can be determined using SAXS if the data are fitted appropriately[197]. However, a realistic model is required for SAXS (or small-angle neutron scattering (SANS)) data from wood to be fitted and for structure on the fibrillar and long-range order scale to be analysed. Although most small-angle results for conventional polymeric structures can rely on relatively simplistic constructions, wood requires more sophisticated approaches. For instance, a model featuring infinitely long cylinders packed in hexagonal arrays, and with paracrystalline distortions, has given reasonable estimates of the microfibril diameters, for both the wet and the dry states of wood[198].

Similarly, neutron scattering and solid-state NMR spectroscopy can be used to measure the nanosized spacing and/or crystal structure of wood. For example, the spacing between neighbouring cellulose microfibrils and the evolution of this spacing under various moisture conditions were determined by SANS, offering insights into the 3D nanostructure and moisture-induced swelling in wood[33]. This knowledge can be used to develop improved wood-protection treatments and wood adhesives in forest research. 2D NMR spectroscopy has been demonstrated as a non-destructive tool for elucidating the lignin subunit composition and the distribution of interunit linkage between subunits of lignin in the cell walls[199]. An advantage of this technique is that the spectra can be acquired from the cell walls of the whole plant without the cell walls being isolated or fractionated; thus, structural information can be preserved.

Computational-modelling approaches

Computational modelling performed on multiple scales, ranging from the atomic level to the nanoscale, mesoscale, microscale and continuum scale, can provide valuable insight into the structure, properties, function and behaviours of wood. The physico-chemical properties and multiscale structural evolution of wood under stimuli (for example, mechanical force, heat, light, water or other solvents) can be computed and the knowledge gained from these simulations used to guide the design of wood materials and modification strategies.

For example, MD simulations have been applied to investigate the temperature-induced structural change in cellulose crystals at the molecular level[200] and probe the deformation and nanomechanics in cellulose materials. It was found that the kink defects in cellulose nanofibrils caused by bending deformation facilitate localized hydrolysis[201]. Another MD-simulation study showed that the bending deformation could cause local amorphization at the kinking point and enable partial allomorphic transitions[202]. Furthermore, an MD-based investigation of the interactions between cellulose nanofibrils during tensile deformation has highlighted the role of hydrogen bonds in conferring enhanced toughness in cellulose nanopaper[35]. At the mesoscale, coarse-grained simulation models have been shown to capture the mechanical properties, such as the bending resistance of native cellulose nanofibres[203]. Moreover, a generic coarse-grained simulation scheme has been used to qualitatively reveal the underlying mechanism for the enhancement in the mechanical properties of densified wood, indicating that the hydrogen bonds formed between neighbouring cellulose nanofibrils make a pivotal contribution to the remarkably enhanced strength and toughness[63]. These hydrogen bonds, as a type of secondary bond, can repeatedly break and reform under tensile stress until fracture, which is desirable for the design of mechanically robust and biodegradable material. At the microscale and the continuum scale, numerical and finite-element simulations have the dominant role. Examples include numerical simulations of transverse compression and densification in wood[204] and failure in wooden structures[36], as well as deformation analysis for bulk composite wood[167,205].

Simulations have also been performed to visualize the water-transport behaviour in wood using computational fluid dynamics. The results indicate that the low-tortuosity pores are beneficial for fast water transport, which is an attractive feature for water-treatment applications (for example, solar evaporation and water filtration)[124].

Although progress has been made, it remains challenging to fully capture the composition-dominated and/or structure-dominated properties and behaviours of wood-based materials through computational modelling, owing to their compositional and structural complexities. Such complexities were usually largely simplified in simulation models because of limitations in computation capability and/or computation time. In addition, previous computational-modelling efforts focused on the mechanical and fluidic behaviours of wood-based materials, yet, limited modelling methodologies have been developed to simulate the optical, thermal and ionic-transport behaviours[24,124].

Future perspective

Wood is a structural and morphological complex material with hierarchical anisotropy at multiple length scales. Since ancient times, the load-bearing behaviour of wood has been explored and tailored for use as a structural material in construction. The development of nanotechnology and new chemical and physical treatments has further expanded the structural and functional modifications of wood for such applications. In parallel, characterization techniques and simulation methodologies have improved our understanding of the structure and properties of wood, allowing us to more precisely control the mechanical properties, as well as the mass, ion, electron, photon and phonon transport behaviours of the material.

To bring more wood-based materials into practice and to benefit society, several challenges must be overcome. For example, achieving the cost-effective, green and scalable production of wood-based materials is required. Most structural modifications use significant amounts of chemicals, energy and water, and have only been conducted at the laboratory scale. Green chemicals (that provide performance and functionality while being environmentally benign throughout their life cycle) are also preferred to avoid polluting the environment and contaminating the wood. Additionally, rational harvest and use of wood and the use of value-added waste products from wood processing are important for the sustainable production of wood-based materials.

Scalability is another requirement for industrial practice and commercialization. This scale-up capability is a particular concern because the sufficient diffusion of chemicals into large (for example, with length, width and thickness over 10 cm) wood blocks for chemical treatment can be challenging. An improved understanding of the diffusive behaviour of chemical solutions within wood depending on the surface chemistry, pore structure and bulk size of the material is necessary to optimize the chemical-treatment process. Chemically treating small-sized veneers (thin slices of wood and, sometimes, bark) and their subsequent assembly into large panels is another promising direction that can balance the needs between chemical diffusion and the size of the final product. Both the technical realization and implementation of wood processing are necessary areas for future research to reduce the gap between academic studies and industrial practice.

To date, research into the structural modification and functionalization of wood has focused on improving performance, whereas little attention has been paid to stability. However, the stability of wood when exposed to water, fire, bacteria or weathering during long-term operation is an important consideration, given the hydrophilic and biodegradable nature of the lignocellulosic wood components. Thermal treatment has improved the stability of wood functional materials against water and bacteria[17], but the mechanical properties and/or mass-transport performance are compromised, owing to the substantial reduction of hydrogen bonds after thermal treatment. Coating of stable polymer or inorganic materials on the external surface and/or internal channels of wood can mitigate this trade-off by enhancing the stability without sacrificing the mechanical or mass-transport properties, owing to the protective coating layer and the good preservation of the wood structure. Crosslinking is another viable strategy to improve the stability of wood-based materials by forming robust bonding networks inside the wood structure. Conversely, for sustainability purposes, the wood product may need to be biodegradable, which will generally come at the cost of the material's stability. Reversible crosslinking with chemical bonds that are stable under operational conditions but easily broken in response to a stimulus (for example, high temperatures) represents a promising direction for achieving stable yet biodegradable wood materials.

Although various structural modification and functionalization strategies have been developed, the field is at an early stage, given the relatively limited functionality of wood and the limited success in its precise regulation at the sub-nanoscale and molecular scale. We can expect new functionalities from the application of the versatile chemistry available to the hierarchical structure of wood, along with the use of powerful characterization tools to improve our understanding and validate structure–property relationships. Molecular and nanoscale modification of the cell walls, including the modification of the molecular structure of the wood components and the manipulation of chemical and physical processes occurring in the confined pore spaces, can lead to enhanced properties, unforeseen yet useful functions and even the creation of new materials. Transparent wood[141], flexible wood[52], spongy wood[167] and strong wood[63] are examples of structural modifications at the macroscale, mesoscale, nanoscale and molecular scale that result in improved properties and new functions. In the future, regulation of the molecular structure of the cellulose fibrils and/or the hemicellulose–lignin matrix of wood may lead to more precise manipulation of the mechanical behaviour of wood, as well as its water, gas, ion, electron, photon and phonon transport behaviours.

In addition to post-structural modifications, the genetic engineering of trees is an attractive modification strategy. Genetic modification is a powerful means for modifying the structure and composition of plants, especially with the advent of clustered regularly interspaced short palindromic repeats (CRISPR) gene-editing technologies[206]. The concept of simply 'growing' wood with the desired hierarchical structure and composition, rather than post-processing to achieve the same result, is clearly attractive. For example, the lignin content of trees can be regulated via genetic modification to improve biomass characteristics for biofuels[207]. The number of new wood functionalities that we can expect by combining genetic engineering with post-structural modification is particularly intriguing.

Wood's multiscale hierarchical cellular structures also provide an attractive material platform for creating a wide range of wood-inspired synthetic materials with complex structure, morphology and anisotropy via the bottom-up assembly (for example, ice-templating followed by freeze-drying)[208] of various monomers and building blocks (for example, phenol-formaldehyde resin, melamine-formaldehyde resin and chitosan)[208], which further extends the potential of wood's unique structure in functional-materials design. By mimicking wood's hierarchical structure, new properties and even functions can be added to wood-inspired synthetic materials. These properties and functions can vary in a wide range and be substantially distinct from wood and existing synthetic materials owing to the combination of wood-mimetic structures and non-lignocellulosic compositions. However, in most cases, synthetic assembly fails to fully duplicate the complexity of the biological wood structure. Thus, manufacturing processes that can more precisely control the assembly of monomers or building blocks from macroscale to nanoscale (for example, 3D printing) hold promise for improving the structural and morphological complexity of artificial wood materials[209].

In addition, advanced characterization techniques (such as transmission electron microscopy, Raman microscopy, AFM, X-ray microCT, chemical force microscopy and scanning near-field optical microscopy) with high-resolution time and length scales could help visualize various chemical and physical processes occurring in wood functional materials either at rest or under certain conditions (for example, tension, compression, bending, elevated temperature, water or other chemical solutions). Such tools will help us to unravel the fundamental structure–property relationships of wood-based materials, which can guide rational multiscale material design with optimized properties and performance. Future research should focus on developing advanced in situ characterization techniques that are able to observe the dynamic evolution of the material in response to physical or chemical stimuli.

In parallel, powerful and precise modelling tools and theories are needed to predict the physical or chemical dynamic processes and behaviours in wood-based materials. Computational challenges remain in terms of improving the precision of modelling tool kits and the prediction of specific functional outcomes. Additionally, machine learning and high-throughput computational screening might offer opportunities for the visualization and simulation of chemical and physical processes and/or behaviours in wood-based materials. However, as a consequence of the complexity of the structure of wood, which varies widely across species, the properties of wood-based materials are likely to vary considerably, and some modification strategies might not be effective for all wood species. Such variations in wood properties and modification strategies increase the difficulty of wood functionalization and utilization. Artificial intelligence offers a way of determining the structures and properties of different wood species by analysing large amounts of images, spectra and other data in a high-throughput manner, which, in turn, facilitates the structural modification and functionalization process[210,211]. The structures and properties of various wood species can be collected and organized in a database to accelerate the design and manufacturing of wood-based functional materials.

Forests are abundant renewable resources and provide essential ecosystem services (such as climate-change mitigation, soil and water conservation, and habitat preservation) and support the production of pulp, paper, wood products and energy. Restructuring industries by replacing non-renewable resources with wood has great potential to support the sustainable development needs of our society. Despite the rapid development of wood research and its great potential to transform existing industries into more resource-efficient systems, there has been little large-scale implementation. The major barriers are our lack of knowledge about the technical performance, economic feasibility, environmental impacts and social implications of using different wood species, processing technologies and applications of wood-based materials. Future research should focus on addressing these gaps in knowledge by developing system-analysis models integrating life-cycle analysis, techno-economic assessment and dynamic modelling to determine optimal sustainable-wood utilization and forest-management practices. Although tremendous challenges remain, we believe wood-based materials will come to fruition given the sustained research efforts investigating experimental manufacturing and multiscale modelling. Rethinking and redesigning wood through rational structural modification and functionalization will surely pave the way for a range of functional wood materials to support a sustainable modern lifestyle.

1. Food and Agriculture Organization of the United Nations. Global production and trade of forest products in 2018. *FAO* http://www.fao.org/forestry/statistics/80938/en/ (2018).
2. Wimmers, G. Wood: a construction material for tall buildings. *Nat. Rev. Mater.* **2**, 17051 (2017).
3. Balat, M. & Bozbas, K. Wood as an energy source: potential trends, usage of wood, and energy politics. *Energ. Source. Part A* **28**, 837–844 (2006).
4. Sjostrom, E. *Wood Chemistry: Fundamentals and Applications* (Elsevier, 1993).
5. Ling, S., Kaplan, D. L. & Buehler, M. J. Nanofibrils in nature and materials engineering. *Nat. Rev. Mater.* **3**, 18016 (2018).
6. Zhu, H. et al. Wood-derived materials for green electronics, biological devices, and energy applications. *Chem. Rev.* **116**, 9305–9374 (2016).
7. Gibson, L. J., Ashby, M. F. & Harley, B. A. *Cellular Materials in Nature and Medicine* (Cambridge Univ. Press, 2010).
8. Meyers, M. A., Chen, P.-Y., Lin, A. Y.-M. & Seki, Y. Biological materials: structure and mechanical properties. *Prog. Mater. Sci.* **53**, 1–206 (2008).
9. Fratzl, P. & Weinkamer, R. Nature's hierarchical materials. *Prog. Mater. Sci.* **52**, 1263–1334 (2007).
10. Fahlén, J. & Salmén, L. Cross-sectional structure of the secondary wall of wood fibers as affected by processing. *J. Mater. Sci.* **38**, 119–126 (2003).
11. Berglund, L. A. & Burgert, I. Bioinspired wood nanotechnology for functional materials. *Adv. Mater.* **30**, 1704285 (2018).
12. Hill, C. A. S. *Wood Modification: Chemical, Thermal and Other Processes* Vol. 5 (John Wiley & Sons, 2007).
13. Evans, P. D., Michell, A. J. & Schmalzl, K. J. Studies of the degradation and protection of wood surfaces. *Wood Sci. Technol.* **26**, 151–163 (1992).
14. Evans, P., Matsunaga, H. & Kiguchi, M. Large-scale application of nanotechnology for wood protection. *Nat. Nanotechnol.* **3**, 577 (2008).
15. Hill, C. A. S. Wood modification: An update. *BioResources* **6**, 918–919 (2011).
16. Rowell, R. M. in *Handbook of Engineering Biopolymers, Homopolymers, Blends, and Composites* (eds Fakirov, S. & Bhattacharyya, D.) 673–691 (Hanser Gardner Publications, 2007).
17. Homan, W. J. & Jorissen, A. J. Wood modification developments. *Heron* **49**, 360–369 (2004).
18. Esteves, B. & Pereira, H. Wood modification by heat treatment: a review. *BioResources* **4**, 370–404 (2008).
19. Fuchs, W. Genuine lignin. I. Acetylation of pine wood. *Ber. Deutsch. Chem. Gesellsch. B* **61**, 948–951 (1928).
20. Lande, S., Westin, M. & Schneider, M. Properties of furfurylated wood. *Scand. J. For. Res.* **19**, 22–30 (2004).
21. Fujimura, T., Uemura, I. & Inoue, M. Study on the high durability of wood with acryl high polymer (I). Interaction between wood and acryl high polymer. *Wood Protect.* **15**, 62–71 (1989).
22. Jiang, F. et al. Wood-based nanotechnologies toward sustainability. *Adv. Mater.* **30**, 1703453 (2018).
23. Fu, Q., Ansari, F., Zhou, Q. & Berglund, L. A. Wood nanotechnology for strong, mesoporous, and hydrophobic biocomposites for selective separation of oil/water mixtures. *ACS Nano* **12**, 2222–2230 (2018).
24. Li, T. et al. Cellulose ionic conductors with high differential thermal voltage for low-grade heat harvesting. *Nat. Mater.* **18**, 608–613 (2019).
25. Guan, H., Cheng, Z. & Wang, X. Highly compressible wood sponges with a spring-like lamellar structure as effective and reusable oil absorbents. *ACS Nano* **12**, 10365–10373 (2018).
26. Zhu, M. et al. Highly anisotropic, highly transparent wood composites. *Adv. Mater.* **28**, 5181–5187 (2016).
27. Foster, E. J. et al. Current characterization methods for cellulose nanomaterials. *Chem. Soc. Rev.* **47**, 2609–2679 (2018).
28. Utsumi, Y., Sano, Y., Fujikawa, S., Funada, R. & Ohtani, J. Visualization of cavitated vessels in winter and refilled vessels in spring in diffuse-porous trees by cryo-scanning electron microscopy. *Plant. Physiol.* **117**, 1463–1471 (1998).
29. Gierlinger, N., Keplinger, T. & Harrington, M. Imaging of plant cell walls by confocal Raman microscopy. *Nat. Protoc.* **7**, 1694–1708 (2012).
30. Agarwal, U. P. Raman imaging to investigate ultrastructure and composition of plant cell walls: distribution of lignin and cellulose in black spruce wood (*Picea mariana*). *Planta* **224**, 1141 (2006).
31. Zlotnikov, I., Zolotoyabko, E. & Fratzl, P. Nano-scale modulus mapping of biological composite materials: Theory and practice. *Prog. Mater. Sci.* **87**, 292–320 (2017).
32. Saito, K. et al. Direct mapping of morphological distribution of syringyl and guaiacyl lignin in the xylem of maple by time-of-flight secondary ion mass spectrometry. *Plant. J.* **69**, 542–552 (2012).
33. Plaza, N. Z., Pingali, S. V., Qian, S., Heller, W. T. & Jakes, J. E. Informing the improvement of forest products durability using small angle neutron scattering. *Cellulose* **23**, 1593–1607 (2016).
34. Fernandes, A. N. et al. Nanostructure of cellulose microfibrils in spruce wood. *Proc. Natl Acad. Sci. USA* **108**, E1195–E1203 (2011).
35. Zhu, H. et al. Anomalous scaling law of strength and toughness of cellulose nanopaper. *Proc. Natl Acad. Sci. USA* **112**, 8971–8976 (2015).
36. Schmidt, J. & Kaliske, M. Models for numerical failure analysis of wooden structures. *Eng. Struct.* **31**, 571–579 (2009).
37. Yano, H., Hirose, A. & Inaba, S. High-strength wood-based materials. *J. Mater. Sci. Lett.* **16**, 1906–1909 (1997).
38. Donaldson, L. A. Lignification and lignin topochemistry — an ultrastructural view. *Phytochemistry* **57**, 859–873 (2001).
39. Barnett, J. R. & Bonham, V. A. Cellulose microfibril angle in the cell wall of wood fibres. *Biol. Rev.* **79**, 461–472 (2004).
40. Weinkamer, R. & Fratzl, P. Mechanical adaptation of biological materials—The examples of bone and wood. *Mater. Sci. Eng. C* **31**, 1164–1173 (2011).
41. Gordon, J. E. & Mattis, D. C. in *The New Science of Strong Materials, or, Why You Don't Fall Through the Floor* (AAPT, 1985).
42. Fang, C.-H., Mariotti, N., Cloutier, A., Koubaa, A. & Blanchet, P. Densification of wood veneers by compression combined with heat and steam. *Eur. J. Wood Prod.* **70**, 155–163 (2012).
43. Bekhta, P., Hiziroglu, S. & Shepelyuk, O. Properties of plywood manufactured from compressed veneer as building material. *Mater. Des.* **30**, 947–953 (2009).
44. Par˘il, P. et al. Comparison of selected physical and mechanical properties of densified beech wood plasticized by ammonia and saturated steam. *Eur. J. Wood Prod.* **72**, 583–591 (2014).
45. Keplinger, T. et al. A versatile strategy for grafting polymers to wood cell walls. *Acta Biomater.* **11**, 256–263 (2015).
46. Vitas, S., Keplinger, T., Reichholf, N., Figi, R. & Cabane, E. Functional lignocellulosic material for the remediation of copper (II) ions from water: towards the design of a wood filter. *J. Hazard. Mater.* **355**, 119–127 (2018).
47. Chen, F. et al. Mesoporous, three-dimensional wood membrane decorated with nanoparticles for highly efficient water treatment. *ACS Nano* **11**, 4275–4282 (2017).
48. Zhu, M. et al. Plasmonic wood for high-efficiency solar steam generation. *Adv. Energy Mater.* **8**, 1701028 (2018).

49. Li, T. et al. Anisotropic, lightweight, strong, and super thermally insulating nanowood with naturally aligned nanocellulose. *Sci. Adv.* **4**, eaar3724 (2018).
50. Li, T. et al. A nanofluidic ion regulation membrane with aligned cellulose nanofibers. *Sci. Adv.* **5**, eaau4238 (2019).
51. Song, J. et al. Highly compressible, anisotropic aerogel with aligned cellulose nanofibers. *ACS Nano* **12**, 140–147 (2018).
52. Song, J. et al. Superflexible wood. *ACS Appl. Mater. Interfaces* **9**, 23520–23527 (2017).
53. Kawamata, Y. et al. Kinetic analysis of delignification of cedar wood during organosolv treatment with a two-phase solvent using the unreacted-core model. *Chem. Eng. J.* **368**, 71–78 (2019).
54. Shen, F. et al. Ultra-thick, low-tortuosity, and mesoporous wood carbon anode for high-performance sodium-ion batteries. *Adv. Energy Mater.* **6**, 1600377 (2016).
55. Ermeydan, M. A., Cabane, E., Hass, P., Koetz, J. & Burgert, I. Fully biodegradable modification of wood for improvement of dimensional stability and water absorption properties by poly (ε-caprolactone) grafting into the cell walls. *Green Chem.* **16**, 3313–3321 (2014).
56. Cabane, E., Keplinger, T., Künniger, T., Merk, V. & Burgert, I. Functional lignocellulosic materials prepared by ATRP from a wood scaffold. *Sci. Rep.* **6**, 31287 (2016).
57. Cabane, E., Keplinger, T., Merk, V., Hass, P. & Burgert, I. Renewable and functional wood materials by grafting polymerization within cell walls. *ChemSusChem* **7**, 1020–1025 (2014).
58. Trey, S., Jafarzadeh, S. & Johansson, M. In situ polymerization of polyaniline in wood veneers. *ACS Appl. Mater. Interfaces* **4**, 1760–1769 (2012).
59. Donath, S., Militz, H. & Mai, C. Wood modification with alkoxysilanes. *Wood Sci. Technol.* **38**, 555–566 (2004).
60. Kong, L., Guan, H. & Wang, X. 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**, 3349–3357 (2018).
61. Merk, V., Chanana, M., Gaan, S. & Burgert, I. Mineralization of wood by calcium carbonate insertion for improved flame retardancy. *Holzforschung* **70**, 867–876 (2016).
62. Shin, Y., Liu, J., Chang, J. H., Nie, Z. & Exarhos, G. J. Hierarchically ordered ceramics through surfactant-templated sol-gel mineralization of biological cellular structures. *Adv. Mater.* **13**, 728–732 (2001).
63. Song, J. et al. Processing bulk natural wood into a high-performance structural material. *Nature* **554**, 224–228 (2018).
64. Li, Y. et al. Lignin-retaining transparent wood. *ChemSusChem* **10**, 3445–3451 (2017).
65. He, S. et al. An energy-efficient, wood-derived structural material enabled by pore structure engineering towards building efficiency. *Small Methods* **4**, 1900747 (2020).
66. Kong, W. et al. Muscle-inspired highly anisotropic, strong, ion-conductive hydrogels. *Adv. Mater.* **30**, 1801934 (2018).
67. Chen, C. et al. All-wood, low tortuosity, aqueous, biodegradable supercapacitors with ultra-high capacitance. *Energy Environ. Sci.* **10**, 538–545 (2017).
68. Keckes, J. et al. Cell-wall recovery after irreversible deformation of wood. *Nat. Mater.* **2**, 810–813 (2003).
69. Guindos, P. & Guaita, M. A three-dimensional wood material model to simulate the behavior of wood with any type of knot at the macro-scale. *Wood Sci. Technol.* **47**, 585–599 (2013).
70. Glass, S. V. & Zelinka, S. L. in *Wood Handbook: Wood as an Engineering Material* Ch. 4 (US Dept. Agriculture, Forest Service, Forest Products Laboratory, 2010).
71. Holbrook, N. M. Transporting water to the tops of trees. *Phys. Today* **61**, 76–77 (2008).
72. McCulloh, K. A., Sperry, J. S. & Adler, F. R. Water transport in plants obeys Murray's law. *Nature* **421**, 939–942 (2003).
73. Li, Y., Vasileva, E., Sychugov, I., Popov, S. & Berglund, L. Optically transparent wood: Recent progress, opportunities, and challenges. *Adv. Opt. Mater.* **6**, 1800059 (2018).
74. Ross, R. J. (ed.) *Wood Handbook: Wood as an Engineering Material* (US Dept. Agriculture, Forest Service, Forest Products Laboratory, 2010).
75. Gustavsson, L. & Sathre, R. Variability in energy and carbon dioxide balances of wood and concrete building materials. *Build. Environ.* **41**, 940–951 (2006).
76. Brandner, R., Flatscher, G., Ringhofer, A., Schickhofer, G. & Thiel, A. Cross laminated timber (CLT): overview and development. *Eur. J. Wood Prod.* **74**, 331–351 (2016).
77. Mora Mendez, D. F. et al. Mechanical behavior of chemically modified Norway spruce: a generic hierarchical model for wood modifications. *Wood Sci. Technol.* **53**, 447–467 (2019).
78. Niska, K. O. & Sain, M. *Wood-Polymer Composites* (Elsevier, 2008).
79. Csizmadia, R., Faludi, G., Renner, K., Móczó, J. & Pukánszky, B. PLA/wood biocomposites: Improving composite strength by chemical treatment of the fibers. *Compos. Part A Appl. Sci. Manuf.* **53**, 46–53 (2013).
80. Stamm, A. J. & Seborg, R. M. *Forest Products Laboratory Resin-Treated, Laminated, Compressed Wood (Compreg)* (US Dept. of Agriculture, Forest Service, 1960).
81. Laine, K. et al. Measuring the thickness swelling and set-recovery of densified and thermally modified Scots pine solid wood. *J. Mater. Sci.* **48**, 8530–8538 (2013).
82. Kamke, F. A. Densified radiata pine for structural composites. *Maderas. Cienc. y. Tecnología* **8**, 83–92 (2006).
83. Shams, M. I., Yano, H. & Endou, K. Compressive deformation of wood impregnated with low molecular weight phenol formaldehyde (PF) resin I: effects of pressing pressure and pressure holding. *J. Wood Sci.* **50**, 337–342 (2004).
84. Shams, M. I., Yano, H. & Endou, K. Compressive deformation of wood impregnated with low molecular weight phenol formaldehyde (PF) resin III: effects of sodium chlorite treatment. *J. Wood Sci.* **51**, 234–238 (2005).
85. Frey, M. et al. Delignified and densified cellulose bulk materials with excellent tensile properties for sustainable engineering. *ACS Appl. Mater. Interfaces* **10**, 5030–5037 (2018).
86. Zhu, M. et al. Anisotropic, transparent films with aligned cellulose nanofibers. *Adv. Mater.* **29**, 1606284 (2017).
87. Jia, C. et al. Scalable, anisotropic transparent paper directly from wood for light management in solar cells. *Nano Energy* **36**, 366–373 (2017).
88. Frey, M. et al. Tunable wood by reversible interlocking and bioinspired mechanical gradients. *Adv. Sci.* **6**, 1802190 (2019).
89. Gibson, L. J. The hierarchical structure and mechanics of plant materials. *J. R. Soc. Interface* **9**, 2749–2766 (2012).
90. Ashby, M. F. *Materials Selection in Mechanical Design* (Butterworth-Heinemann, 2011).
91. Garcia, M., Hidalgo, J., Garmendia, I. & García-Jaca, J. Wood–plastics composites with better fire retardancy and durability performance. *Compos. Part A Appl. Sci. Manuf.* **40**, 1772–1776 (2009).
92. Guo, H. et al. Bioinspired struvite mineralization for fire resistant wood. *ACS Appl. Mater. Interfaces* **11**, 5427–5434 (2019).
93. Liu, J. et al. Hexagonal boron nitride nanosheets as high-performance binder-free fire-resistant wood coatings. *Small* **13**, 1602456 (2017).
94. Carosio, F., Cuttica, F., Medina, L. & Berglund, L. A. Clay nanopaper as multifunctional brick and mortar fire protection coating—wood case study. *Mater. Des.* **93**, 357–363 (2016).
95. Plackett, D. V., Dunningham, E. A. & Singh, A. P. Weathering of chemically modified wood. *Holz als Roh-und Werkst.* **50**, 135 (1992).
96. Gan, W. et al. Dense, self-formed char layer enables a fire-retardant wood structural material. *Adv. Funct. Mater.* **29**, 1807444 (2019).
97. Merk, V., Chanana, M., Keplinger, T., Gaan, S. & Burgert, I. Hybrid wood materials with improved fire retardance by bio-inspired mineralisation on the nano- and submicron level. *Green Chem.* **17**, 1423–1428 (2015).
98. Fu, Q. et al. Nanostructured wood hybrids for fire-retardancy prepared by clay impregnation into the cell wall. *ACS Appl. Mater. Interfaces* **9**, 36154–36163 (2017).
99. Rowell, R. M., Ibach, R. E., McSweeny, J. & Nilsson, T. Understanding decay resistance, dimensional stability and strength changes in heat-treated and acetylated wood. *Wood Mater. Sci. Eng.* **4**, 14–22 (2009).
100. Maier, J. Nanoionics: ion transport and electrochemical storage in confined systems. *Nat. Mater.* **4**, 805–815 (2005).
101. Chen, C., Kuang, Y. & Hu, L. Challenges and opportunities for solar evaporation. *Joule* **3**, 683–718 (2019).
102. Stein, D., Kruithof, M. & Dekker, C. Surface-charge-governed ion transport in nanofluidic channels. *Phys. Rev. Lett.* **93**, 035901 (2004).
103. Weigl, B. H. & Yager, P. Microfluidic diffusion-based separation and detection. *Science* **283**, 346–347 (1999).
104. Jia, C. et al. Anisotropic, mesoporous microfluidic frameworks with scalable, aligned cellulose nanofibers. *ACS Appl. Mater. Interfaces* **10**, 7362–7370 (2018).
105. Pendergast, M. M. & Hoek, E. M. A review of water treatment membrane nanotechnologies. *Energy Environ. Sci.* **4**, 1946–1971 (2011).
106. Chen, C. et al. Na$^+$ intercalation pseudocapacitance in graphene-coupled titanium oxide enabling ultra-fast sodium storage and long-term cycling. *Nat. Commun.* **6**, 6929 (2015).
107. Jakes, J. E. Mechanism for diffusion through secondary cell walls in lignocellulosic biomass. *J. Phys. Chem. B* **123**, 4333–4339 (2019).
108. Chen, C. & Hu, L. Nanocellulose toward advanced energy storage devices: structure and electrochemistry. *Acc. Chem. Res.* **51**, 3154–3165 (2018).
109. Chen, C. et al. Nature-inspired tri-pathway design enabling high-performance flexible Li–O$_2$ batteries. *Adv. Energy Mater.* **9**, 1802964 (2019).
110. Peng, X. et al. Hierarchically porous carbon plates derived from wood as bifunctional ORR/OER electrodes. *Adv. Mater.* **31**, 1900341 (2019).
111. Zhang, Y. et al. High-capacity, low-tortuosity, and channel-guided lithium metal anode. *Proc. Natl Acad. Sci. USA* **114**, 3584–3589 (2017).
112. Luo, W. et al. Encapsulation of metallic Na in an electrically conductive host with porous channels as a highly stable Na metal anode. *Nano Lett.* **17**, 3792–3797 (2017).
113. Chen, C. et al. Highly conductive, lightweight, low-tortuosity carbon frameworks as ultrathick 3D current collectors. *Adv. Energy Mater.* **7**, 1700595 (2017).
114. Li, Y. et al. Enabling high-areal-capacity lithium–sulfur batteries: designing anisotropic and low-tortuosity porous architectures. *ACS Nano* **11**, 4801–4807 (2017).
115. Song, H. et al. Hierarchically porous, ultrathick, "breathable" wood-derived cathode for lithium-oxygen batteries. *Adv. Energy Mater.* **8**, 1701203 (2018).
116. Wang, Y. et al. Wood-derived hierarchically porous electrodes for high-performance all-solid-state supercapacitors. *Adv. Funct. Mater.* **28**, 1806207 (2018).
117. Tang, Z. et al. Highly anisotropic, multichannel wood carbon with optimized heteroatom doping for supercapacitor and oxygen reduction reaction. *Carbon* **130**, 532–543 (2018).
118. Xu, S. et al. Flexible lithium–CO$_2$ battery with ultrahigh capacity and stable cycling. *Energy Environ. Sci.* **11**, 3231–3237 (2018).
119. Cheremisinoff, N. P. *Handbook of Water and Wastewater Treatment Technologies* (Butterworth-Heinemann, 2002).
120. Khawaji, A. D., Kutubkhanah, I. K. & Wie, J.-M. Advances in seawater desalination technologies. *Desalination* **221**, 47–69 (2008).
121. Che, W. et al. Wood-based mesoporous filter decorated with silver nanoparticles for water purification. *ACS Sustain. Chem. Eng.* **7**, 5134–5141 (2019).
122. Wang, K. et al. Two-dimensional membrane and three-dimensional bulk aerogel materials via top-down wood nanotechnology for multibehavioral and reusable oil/water separation. *Chem. Eng. J.* **371**, 769–780 (2019).
123. Bai, X. et al. Facile fabrication of superhydrophobic wood slice for effective water-in-oil emulsion separation. *Sep. Purif. Technol.* **210**, 402–408 (2019).
124. Zhu, M. et al. Tree-inspired design for high-efficiency water extraction. *Adv. Mater.* **29**, 1704107 (2017).
125. Xue, G. et al. Robust and low-cost flame-treated wood for high-performance solar steam generation. *ACS Appl. Mater. Interfaces* **9**, 15052–15057 (2017).
126. Liu, H. et al. High-performance solar steam device with layered channels: artificial tree with a reversed design. *Adv. Energy Mater.* **8**, 1701616 (2018).

127. Wang, Y. et al. All natural, high efficient groundwater extraction via solar steam/vapor generation. *Adv. Sustain. Syst.* **3**, 1800055 (2019).
128. Jia, C. et al. Rich mesostructures derived from natural woods for solar steam generation. *Joule* **1**, 588–599 (2017).
129. Liu, K.-K. et al. Wood–graphene oxide composite for highly efficient solar steam generation and desalination. *ACS Appl. Mater. Interfaces* **9**, 7675–7681 (2017).
130. Chen, C. et al. Highly flexible and efficient solar steam generation device. *Adv. Mater.* **29**, 1701756 (2017).
131. Li, T. et al. Scalable and highly efficient mesoporous wood-based solar steam generation device: localized heat, rapid water transport. *Adv. Funct. Mater.* **28**, 1707134 (2018).
132. Liu, H. et al. Narrow bandgap semiconductor decorated wood membrane for high-efficiency solar-assisted water purification. *J. Mater. Chem. A* **6**, 18839–18846 (2018).
133. Kuang, Y. et al. A high-performance self-regenerating solar evaporator for continuous water desalination. *Adv. Mater.* **31**, 1900498 (2019).
134. He, S. et al. Nature-inspired salt resistant bimodal porous solar evaporator for efficient and stable water desalination. *Energy Environ. Sci.* **12**, 1558–1567 (2019).
135. Siria, A. et al. Giant osmotic energy conversion measured in a single transmembrane boron nitride nanotube. *Nature* **494**, 455–458 (2013).
136. Kim, S. J., Ko, S. H., Kang, K. H. & Han, J. Direct seawater desalination by ion concentration polarization. *Nat. Nanotechnol.* **5**, 297–301 (2010).
137. An, N., Fleming, A. M., White, H. S. & Burrows, C. J. Crown ether–electrolyte interactions permit nanopore detection of individual DNA abasic sites in single molecules. *Proc. Natl Acad. Sci. USA* **109**, 11504–11509 (2012).
138. Fan, R., Huh, S., Yan, R., Arnold, J. & Yang, P. Gated proton transport in aligned mesoporous silica films. *Nat. Mater.* **7**, 303–307 (2008).
139. Chen, G. et al. A highly conductive cationic wood membrane. *Adv. Funct. Mater.* **29**, 1902772 (2019).
140. Fink, S. Transparent wood–a new approach in the functional study of wood structure. *Holzforschung* **46**, 403–408 (1992).
141. Li, Y., Fu, Q., Yu, S., Yan, M. & Berglund, L. Optically transparent wood from a nanoporous cellulosic template: combining functional and structural performance. *Biomacromolecules* **17**, 1358–1364 (2016).
142. Zhu, M. et al. Transparent and haze wood composites for highly efficient broadband light management in solar cells. *Nano Energy* **26**, 332–339 (2016).
143. Li, Y. et al. Towards centimeter thick transparent wood through interface manipulation. *J. Mater. Chem. A* **6**, 1094–1101 (2018).
144. Wu, J. et al. Impact of delignification on morphological, optical and mechanical properties of transparent wood. *Compos. Part A Appl. Sci. Manuf.* **117**, 324–331 (2019).
145. Vasileva, E. et al. Light scattering by structurally anisotropic media: a benchmark with transparent wood. *Adv. Opt. Mater.* **6**, 1800999 (2018).
146. Li, T. et al. Wood composite as an energy efficient building material: guided sunlight transmittance and effective thermal insulation. *Adv. Energy Mater.* **6**, 1601122 (2016).
147. Yu, Z. et al. Transparent wood containing Cs_xWO_3 nanoparticles for heat-shielding window applications. *J. Mater. Chem. A* **5**, 6019–6024 (2017).
148. Vasileva, E. et al. Lasing from organic dye molecules embedded in transparent wood. *Adv. Opt. Mater.* **5**, 1700057 (2017).
149. Li, Y. et al. Luminescent transparent wood. *Adv. Opt. Mater.* **5**, 1600834 (2017).
150. Gan, W. et al. 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**, 3855–3862 (2017).
151. Gan, W. et al. Transparent magnetic wood composites based on immobilizing Fe_3O_4 nanoparticles into a delignified wood template. *J. Mater. Sci.* **52**, 3321–3329 (2017).
152. Qiu, Z. et al. 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 (2019).
153. Zhang, T. et al. Flexible transparent sliced veneer for alternating current electroluminescent devices. *ACS Sustain. Chem. Eng.* **7**, 11464–11473 (2019).
154. Jia, C. et al. Clear wood toward high-performance building materials. *ACS Nano* **13**, 9993–10001 (2019).
155. Kawasaki, T. & Kawai, S. Thermal insulation properties of wood-based sandwich panel for use as structural insulated walls and floors. *J. Wood Sci.* **52**, 75–83 (2006).
156. Cetiner, I. & Shea, A. D. Wood waste as an alternative thermal insulation for buildings. *Energy Build.* **168**, 374–384 (2018).
157. Chen, L., Song, N., Shi, L. & Ding, P. Anisotropic thermally conductive composite with wood-derived carbon scaffolds. *Compos. Part A Appl. Sci. Manuf.* **112**, 18–24 (2018).
158. Kuang, Y. et al. Bioinspired solar-heated carbon absorbent for efficient cleanup of highly viscous crude oil. *Adv. Funct. Mater.* **29**, 1900162 (2019).
159. Wan, J. et al. Highly anisotropic conductors. *Adv. Mater.* **29**, 1703331 (2017).
160. Ma, L., Wang, Q. & Li, L. Delignified wood/capric acid-palmitic acid mixture stable-form phase change material for thermal storage. *Sol. Energy Mater. Sol. Cell* **194**, 215–221 (2019).
161. Raman, A. P., Anoma, M. A., Zhu, L., Rephaeli, E. & Fan, S. Passive radiative cooling below ambient air temperature under direct sunlight. *Nature* **515**, 540–544 (2014).
162. Tian, L. et al. A radiative cooling structural material. *Science* **364**, 760–763 (2019).
163. Dong, A. et al. Zeolitic tissue through wood cell templating. *Adv. Mater.* **14**, 926–929 (2002).
164. Ye, R. et al. Laser-induced graphene formation on wood. *Adv. Mater.* **29**, 1702211 (2017).
165. Yang, H. et al. Self-luminous wood composite for both thermal and light energy storage. *Energy Storage Mater.* **18**, 15–22 (2019).
166. Hai, J., Chen, F., Su, J., Xu, F. & Wang, B. Porous wood members-based amplified colorimetric sensor for Hg^{2+} detection through Hg^{2+}-triggered methylene blue reduction reactions. *Anal. Chem.* **90**, 4909–4915 (2018).
167. Chen, C. et al. Scalable and sustainable approach toward highly compressible, anisotropic, lamellar carbon sponge. *Chem* **4**, 544–554 (2018).
168. Le, T.-S. D., Park, S., An, J., Lee, P. S. & Kim, Y.-J. Ultrafast laser pulses enable one-step graphene patterning on woods and leaves for green electronics. *Adv. Funct. Mater.* **29**, 1902771 (2019).
169. Xi, J. et al. Wood-based straightway channel structure for high performance microwave absorption. *Carbon* **124**, 492–498 (2017).
170. Yuan, Y. et al. Stiff, thermally stable and highly anisotropic wood-derived carbon composite monoliths for electromagnetic interference shielding. *ACS Appl. Mater. Interfaces* **9**, 21371–21381 (2017).
171. Wang, Y. et al. A high-performance, low-tortuosity wood-carbon monolith reactor. *Adv. Mater.* **29**, 1604257 (2017).
172. Tampieri, A. et al. From wood to bone: multi-step process to convert wood hierarchical structures into biomimetic hydroxyapatite scaffolds for bone tissue engineering. *J. Mater. Chem.* **19**, 4973–4980 (2009).
173. Chen, C. et al. Catalyst-free in situ carbon nanotube growth in confined space via high temperature gradient. *Research* **2018**, 1793784 (2018).
174. Li, Y. et al. In situ “Chainmail Catalyst” assembly in low-tortuosity, hierarchical carbon frameworks for efficient and stable hydrogen generation. *Adv. Energy Mater.* **8**, 1801289 (2018).
175. Jakes, J. E. et al. Not just lumber—using wood in the sustainable future of materials, chemicals, and fuels. *JOM* **68**, 2395–2404 (2016).
176. Burgert, I., Cabane, E., Zollfrank, C. & Berglund, L. Bio-inspired functional wood-based materials–hybrids and replicates. *Int. Mater. Rev.* **60**, 431–450 (2015).
177. Stanzl-Tschegg, S. E. Wood as a bioinspiring material. *Mater. Sci. Eng. C* **31**, 1174–1183 (2011).
178. Segmehl, J. S., Lauria, A., Keplinger, T., Berg, J. K. & Burgert, I. Tracking of short distance transport pathways in biological tissues by ultra-small nanoparticles. *Front. Chem.* **6**, 28 (2018).
179. Merk, V., Berg, J. K., Krywka, C. & Burgert, I. Oriented crystallization of barium sulfate confined in hierarchical cellular structures. *Cryst. Growth Des.* **17**, 677–684 (2017).
180. Gierlinger, N. & Schwanninger, M. Chemical imaging of poplar wood cell walls by confocal Raman microscopy. *Plant. Physiol.* **140**, 1246–1254 (2006).
181. Keplinger, T. et al. Smart hierarchical bio-based materials by formation of stimuli-responsive hydrogels inside the microporous structure of wood. *Adv. Mater. Interfaces* **3**, 1600233 (2016).
182. Segmehl, J. S., Studer, V., Keplinger, T. & Burgert, I. Characterization of wood derived hierarchical cellulose scaffolds for multifunctional applications. *Materials* **11**, 517 (2018).
183. Synge, E. XXXVIII. A suggested method for extending microscopic resolution into the ultra-microscopic region. *London Edinburgh Dublin Philos. Mag. J. Sci.* **6**, 356–362 (1928).
184. Pohl, D. W., Denk, W. & Lanz, M. Optical stethoscopy: image recording with resolution $\lambda/20$. *Appl. Phys. Lett.* **44**, 651–653 (1984).
185. Deckert-Gaudig, T., Taguchi, A., Kawata, S. & Deckert, V. Tip-enhanced Raman spectroscopy–from early developments to recent advances. *Chem. Soc. Rev.* **46**, 4077–4110 (2017).
186. Sharma, G., Deckert-Gaudig, T. & Deckert, V. Tip-enhanced Raman scattering—Targeting structure-specific surface characterization for biomedical samples. *Adv. Drug Deliv. Rev.* **89**, 42–56 (2015).
187. Keplinger, T. et al. A zoom into the nanoscale texture of secondary cell walls. *Plant Methods* **10**, 1 (2014).
188. Fahlén, J. & Salmén, L. Pore and matrix distribution in the fiber wall revealed by atomic force microscopy and image analysis. *Biomacromolecules* **6**, 433–438 (2005).
189. Casdorff, K., Keplinger, T., Rüggeberg, M. & Burgert, I. A close-up view of the wood cell wall ultrastructure and its mechanics at different cutting angles by atomic force microscopy. *Planta* **247**, 1123–1132 (2018).
190. Casdorff, K., Keplinger, T. & Burgert, I. Nano-mechanical characterization of the wood cell wall by AFM studies: comparison between AC-and QI™ mode. *Plant Methods* **13**, 60 (2017).
191. Maire, E. X-ray tomography applied to the characterization of highly porous materials. *Annu. Rev. Mater. Res.* **42**, 163–178 (2012).
192. Steppe, K. et al. Use of X-ray computed microtomography for non-invasive determination of wood anatomical characteristics. *J. Struct. Biol.* **148**, 11–21 (2004).
193. Brodersen, C. R., Knipfer, T. & McElrone, A. J. In vivo visualization of the final stages of xylem vessel refilling in grapevine (*Vitis vinifera*) stems. *New Phytol.* **217**, 117–126 (2018).
194. Zauner, M., Stampanoni, M. & Niemz, P. Failure and failure mechanisms of wood during longitudinal compression monitored by synchrotron micro-computed tomography. *Holzforschung* **70**, 179–185 (2016).
195. Jakob, H., Fengel, D., Tschegg, S. & Fratzl, P. The elementary cellulose fibril in *Picea abies*: comparison of transmission electron microscopy, small-angle X-ray scattering, and wide-angle X-ray scattering results. *Macromolecules* **28**, 8782–8787 (1995).
196. Färber, J., Lichtenegger, H., Reiterer, A., Stanzl-Tschegg, S. & Fratzl, P. Cellulose microfibril angles in a spruce branch and mechanical implications. *J. Mater. Sci.* **36**, 5087–5092 (2001).
197. Entwistle, K. M., Eichhorn, S. J. & Navaranjan, N. The derivation of the cellulose microfibril angle by small-angle X-ray scattering from structurally characterized softwood cell-wall populations. *J. Appl. Crystallogr.* **38**, 505–511 (2005).
198. Penttilä, P. A., Rautkari, L., Österberg, M. & Schweins, R. Small-angle scattering model for efficient characterization of wood nanostructure and moisture behaviour. *J. Appl. Crystallogr.* **52**, 369–377 (2019).
199. Mansfield, S. D., Kim, H., Lu, F. & Ralph, J. Whole plant cell wall characterization using solution-state 2D NMR. *Nat. Protoc.* **7**, 1579–1589 (2012).
200. Bergenstråhle, M., Berglund, L. A. & Mazeau, K. Thermal response in crystalline $I\beta$ cellulose: a molecular dynamics study. *J. Phys. Chem. B* **111**, 9138–9145 (2007).
201. Ciesielski, P. N. et al. Nanomechanics of cellulose deformation reveal molecular defects that facilitate natural deconstruction. *Proc. Natl Acad. Sci. USA* **116**, 9825–9830 (2019).
202. Chen, P., Ogawa, Y., Nishiyama, Y., Ismail, A. E. & Mazeau, K. $I\alpha$ to $I\beta$ mechano-conversion and amorphization in native cellulose simulated by crystal bending. *Cellulose* **25**, 4345–4355 (2018).
203. López, C. A. et al. MARTINI coarse-grained model for crystalline cellulose microfibers. *J. Phys. Chem. B* **119**, 465–473 (2015).
204. Nairn, J. A. Numerical simulations of transverse compression and densification in wood. *Wood Fiber Sci.* **38**, 576–591 (2007).
205. O'Loinsigh, C., Oudjene, M., Shotton, E., Pizzi, A. & Fanning, P. Mechanical behaviour and 3D stress analysis of multi-layered wooden beams made with welded-through wood dowels. *Compos. Struct.* **94**, 313–321 (2012).

206. Belhaj, K., Chaparro-Garcia, A., Kamoun, S., Patron, N. J. & Nekrasov, V. Editing plant genomes with CRISPR/Cas9. *Curr. Opin. Biotechnol.* **32**, 76–84 (2015).
207. Fu, C. et al. Genetic manipulation of lignin reduces recalcitrance and improves ethanol production from switchgrass. *Proc. Natl Acad. Sci. USA* **108**, 3803–3808 (2011).
208. Yu, Z.-L. et al. Bioinspired polymeric woods. *Sci. Adv.* **4**, eaat7223 (2018).
209. Zorzetto, L. & Ruffoni, D. Wood-inspired 3D-printed helical composites with tunable and enhanced mechanical performance. *Adv. Funct. Mater.* **29**, 1805888 (2019).
210. Kobayashi, K., Akada, M., Torigoe, T., Imazu, S. & Sugiyama, J. Automated recognition of wood used in traditional Japanese sculptures by texture analysis of their low-resolution computed tomography data. *J. Wood Sci.* **61**, 630–640 (2015).
211. Kobayashi, K., Hwang, S.-W., Okochi, T., Lee, W.-H. & Sugiyama, J. Non-destructive method for wood identification using conventional X-ray computed tomography data. *J. Cult. Herit.* **38**, 88–93 (2019).
212. Barthelat, F., Yin, Z. & Buehler, M. J. Structure and mechanics of interfaces in biological materials. *Nat. Rev. Mater.* **1**, 16007 (2016).

Acknowledgements

The authors thank A. H. Brozena for valuable comments on the manuscript and J. Dai for the helpful discussion on Fig. 1.

Author contributions

L.H. and C.C. researched data for the manuscript. All authors made substantial contributions to the discussion of the content. C.C., L.H., Y.K., S.Z., I.B., T.K., T.L. and S.J.E. contributed to writing the manuscript. All authors reviewed and/or edited the manuscript before submission.

Competing interests

The authors declare no competing interests.

Publisher's note