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Review Paper

Flexible Wood Composites from Rigidity to Twistability via Advanced Fabrication for Multidisciplinary Applications

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Abstract. Petroleum-based flexible composites face critical bottlenecks of non-degradability, high carbon footprint, and resource depletion, despite their excellent bendability. Wood, with its hierarchical porous architecture and renewable nature, offers an ideal substitute for petroleum-based matrices; however, cross-scale flexibilization mechanisms remain poorly systematized. This review systematically examines recent advances in the emerging field of flexible wood composites (FWCs). We begin with cross-scale structures from cellulose molecules to thin veneers, categorizing two primary flexibilization strategies: (i) the wood fiber route, encompassing melt compounding, continuous flat-pressing, and additive manufacturing; and (ii) the thin veneer route, involving lignin removal and polymer lamination. Their processing-structure-property relationships are critically evaluated. We further highlight state-of-the-art applications of FWCs in green construction, smart sensing, energy storage, environmental remediation, and biomedicine. Challenges for scalable implementation—environmental consistency, long-term durability, and functional integration—are also analyzed. Finally, future pathways are outlined for frontier applications including tissue scaffolds, shape-memory devices, and embodied intelligent systems. This review provides technical guidelines for cross-scale wood flexibilization across diverse scenarios, advances FWCs as a green alternative to petroleum-based functional materials, and supports high-value wood utilization toward carbon neutrality and sustainable material innovation.

Keywords: *Flexible wood composites; Cross-scale flexibilization; Green building materials; Smart sensing; Energy storage; 3D/4D printing*

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1 Introduction

Highly flexible composites, which can bend, twist, and fold under external forces while maintaining structural integrity, have become core carriers for cutting-edge applications such as wearable devices, flexible sensors, conformal energy devices, and biological tissue scaffolds. Currently, such materials still predominantly use petroleum-based polymers (e.g., polyurethane, polyimide, polycarbonate) as the continuous phase, achieving structure-function integration through physical blending or chemical crosslinking. However, the depletion risk of petrochemical resources and the environmental burden caused by non-degradable plastics limit their large-scale sustainable application. Developing green and environmentally friendly flexible composite materials using renewable biomass as the base material has become an inevitable path to replace petroleum-based systems.

Wood, as the most abundant and widely distributed natural renewable resource, possesses inherent characteristics such as a hierarchical porous structure, anisotropy, and modifiable interfaces, providing a unique structural template for flexible design. Through strategies like "preserving hierarchical structure—precisely disassembling components—interfacial engineering recombination," macroscopic bendability can be imparted while maintaining the wood's microscopic skeleton, thereby constructing Flexible Wood-based Composites (FWCs). Over the past five years, the research paradigm for FWCs has evolved from "simple blending and filling" to "structure-interface synergistic flexibilization," forming diverse preparation routes such as melt blending,

chemical modification, additive manufacturing, and in-situ polymerization. Conceptual validation has been achieved in fields like building materials and decoration, flexible electronics, energy storage devices, and biomedicine. However, the cross-scale correlation mechanisms between wood's microstructure (e.g., cell wall layered structure, pore gradient, hydrogen bond network) and macroscopic flexibilization behavior are not yet fully understood. Moreover, there is a lack of systematic summarization of the preparation strategies, application scenarios, performance comparisons, and industrialization potential of different flexible wood composites.

In view of this, this article starts from the hierarchical structure of wood, systematically reviews the preparation strategies and key processes of FWCs, and quantitatively compares the differences in efficiency, energy consumption, and performance among these strategies. Subsequently, following the "material-structure-function" logic, it summarizes the latest progress and performance optimization methods of FWCs in four major application scenarios: construction, information, energy storage, and biomedicine. Finally, based on the research progress and application status of FWCs, scientific bottlenecks and technical gaps are proposed, and future development directions are outlined. This article aims to construct a cross-scale (macro-micro-molecular) flexible design pathway system for wood, provide technical references for the design of flexible wood composites in different application scenarios, promote the high-value utilization of wood, and accelerate the substitution process for petroleum-based flexible materials.

2 Multi-scale Structure of Wood and Its Flexibilization Potential

Wood is a porous structural material composed of various cells. Its mechanical behavior is closely related to features such as cell arrangement and distribution, micro-nano scale porosity, and the hierarchical multi-level structure of the cell walls. These structural characteristics allow stress to be dispersed through deformation and self-adjustment when wood is under load, avoiding brittle fracture caused by stress concentration, thereby providing a physical basis for wood's flexibility and toughness. At the cellular level, the porous structure can disperse stress through deformation, folding, or interlayer slippage, endowing the material with higher reversible deformation capacity under compression or bending loads; conversely, restricted pores or uneven arrangement may lead to local stress concentration and brittle failure. At the cell wall level, the wall structure from outside to inside can be divided into the middle lamella (ML), primary wall (P), and secondary wall (S). The skeleton of each wall layer is composed of cellulose elementary fibrils. Elementary fibrils aggregate to form cellulose microfibrils, which stack layer by layer and intertwine, eventually forming the layered structure of the cell wall. This layered structure enhances inter-fiber layer slippage and compressibility, reducing the crosslinking rigidity of the cell wall, further granting wood flexibilization potential. At the molecular level, cellulose macromolecules have crystalline and amorphous regions. In the amorphous regions, molecular chains are arranged in a completely disordered, coiled manner. Furthermore, cellulose macromolecules have no branched chains, facilitating the breakage and reconstruction of intermolecular hydrogen bonds under external forces, allowing the molecular chains in the amorphous regions to exhibit reversible stretching and retraction capability in the length direction, providing softness and extensibility at the molecular scale. Simultaneously, the loose structure of molecular chains in amorphous regions facilitates water penetration, increasing the distance between molecular chains, expanding free volume, and reducing the attraction between chain segments, providing greater space for relative extension of molecular chains. Further, lignin contains a large number of rigid aromatic groups, limiting the relative slippage between cellulose, hemicellulose, and lignin. Selective removal of lignin can reduce the crosslinking of the rigid matrix in the cell wall, enhancing slippage and compressibility between fibers, thereby transforming the originally rigid cell skeleton into a flexible porous structure. It is precisely these multi-scale structural characteristics that lay the theoretical foundation for the precise design and functional reconstruction of wood's multi-level structure, and provide crucial support for the transformation of wood into flexible wood composites and its high-value utilization.

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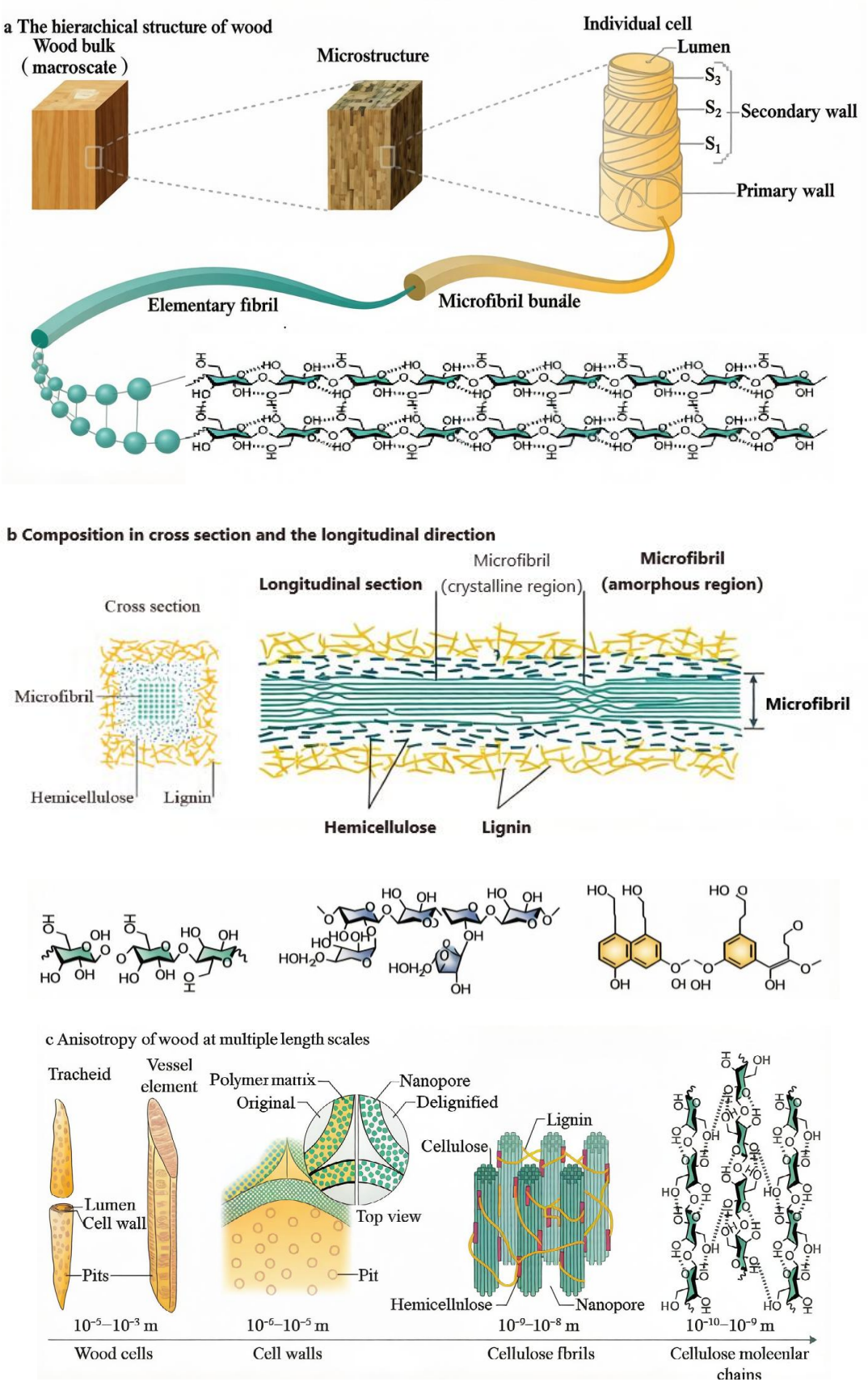


Figure 1 The multi-level structure of wood [8]

3 Preparation Strategies for Flexible Wood Composites

Natural solid wood possesses excellent mechanical strength and dimensional stability due to its highly ordered and dense cell wall structure, but its macroscopic bendability and flexibility are significantly limited. Therefore, directly using solid wood to prepare flexible materials has obvious limitations both in theory and practice. In contrast, decomposing wood into smaller structural units (such as wood fibers or thin wood veneers) not only preserves the basic chemical properties of wood components but also enhances structural designability and interface controllability. Based on this, starting from the structural hierarchy of wood, this study categorizes the structural units of flexible wood composites into two main types: fiber-based and thin veneer-based.

3.1 Wood Fiber-based Flexibilization Route

Wood fibers are micro-nano scale fine fiber units, primarily prepared through thermomechanical processes. Physically, wood fibers have a high aspect ratio and large specific surface area. Under stress, the internal stress can be dispersed more effectively along the length direction and can achieve multi-scale reorganization through relative sliding and rearrangement among fibers. When wood fibers are compounded with other polymer materials, the physical properties of the material can be significantly altered through interfacial interactions. This "collective behavior" greatly enhances the material's macroscopic flexibility and plasticity. For wood fiber-based materials, currently representative preparation strategies include melt blending extrusion, continuous flat-pressing, and additive manufacturing.

3.1.1 Melt Blending Extrusion Method

The melt blending extrusion method involves uniformly mixing wood fibers with thermoplastic resins, plasticizers, and other auxiliary agents, then extruding and cooling the mixture through a screw extruder at high temperatures. Hana Dai et al. used 70%~90% straw fiber and 10%~30% vinyl acetate-ethylene-ethyl acrylate copolymer to prepare high-density fiberboard with good flexibility via melt blending extrusion (extrusion temperature controlled between 170~230°C), suitable for various shaped components and furniture. The melt blending extrusion method offers advantages such as low energy consumption, high yield, mature technology, and stable quality. Moreover, its preparation process is formaldehyde-free, aligning with green and environmentally friendly trends, making it particularly suitable for flexible wood composites using wood flour and thermoplastic resins as raw materials. However, this method may reduce the aspect ratio of wood fibers, thereby affecting the mechanical properties of the composite. Therefore, it is necessary to optimize extrusion process parameters to achieve a balance between the flexibility and mechanical performance of wood-based materials.

3.1.2 Continuous Flat-Pressing Method

Flexible ultra-thin fiberboard is a new type of fiberboard independently innovated in China via the continuous flat-pressing method. Its core process includes sizing and drying wood fibers, followed by wedge-angle exhaust pre-pressing using a large-diameter roller heavy-duty pre-press. Finally, the pre-pressed fiber mat is fed into a continuous flat-press for hot-pressing and curing via flexible entry technology to obtain the fiberboard. The board thickness ranges from 0.5 to 1.5 mm, exhibiting excellent flexibility. During hot pressing, stable network structures are formed between fibers and adhesives through non-covalent bonds or chemical bonds, achieving a balance between strength and flexibility. Continuous flat-pressing is the mainstream hot-pressing process for modern fiberboard production, mainly comprising pre-pressing, continuous flat-pressing curing, and cooling stages. This process not only significantly reduces energy consumption but can also be combined with formaldehyde-free adhesives (e.g., lignin adhesive, soy adhesive, isocyanate adhesive) to produce environmentally friendly boards, reducing formaldehyde emissions to meet the demands of green home furnishings.

3.1.3 Additive Manufacturing (3D/4D Printing)

Additive manufacturing is a technique for constructing three-dimensional objects layer by layer, with the core principle being "layered manufacturing, layer-by-layer stacking." This technology typically includes key steps such as digital modeling, material selection, layer-by-layer processing (e.g., fused deposition, photopolymerization), and post-processing. 3D printing technology offers advantages like high precision, controllable performance,

great design freedom, and environmental friendliness, providing a viable path for preparing flexible wood composites. Bi et al. used thermoplastic polyurethane and wood flour as raw materials. After drying in an oven at 103°C for 12 hours, they prepared flexible wood flour/polyurethane composites using additive manufacturing technology. This material combines good flexibility and environmental characteristics, suitable for flexible decoration and functional products. Guo et al. used polylactic acid (PLA) and wood flour as raw materials. After drying PLA at 50°C for 8 hours and wood flour at 103°C for 12 hours, they prepared wood composites with both flexibility and conductivity via additive manufacturing technology. This material not only combines the biodegradability of PLA and the conductivity of the filler but also integrates the natural characteristics of wood fibers with the plasticity of thermoplastic polymers, exhibiting excellent flexibility and environmental performance, suitable for flexible electronic devices, smart materials, and lightweight, bendable decorative and furniture components. Keck et al. used liquid methacrylate resin as the raw material to prepare wood-based 3D printing materials with both flexibility and sustainability via additive manufacturing technology. By controlling the pore structure, this process not only reduces the material's modulus and enhances flexibility but also provides space for functional filling (e.g., electrolytes, drug molecules).

3.2 Thin Wood Veneer-based Flexibilization Route

Thin wood veneer structural units are primarily manufactured through rotary cutting or slicing processes, retaining the macroscopic grain and continuous fiber orientation characteristics of wood. Their thickness typically ranges from 100 μm to 1 mm. The extreme thinness significantly reduces internal stress and structural resistance within the wood, fundamentally decreasing the force required for bending, thus partially overcoming the macroscopic rigidity of wood. Furthermore, the rigidity of macroscopic wood also stems from its rigid lignin and complex cell wall structure. Chemical methods for dissociating lignin can effectively soften thin veneers. Therefore, under the combined effect of these multiple factors, utilizing thin wood veneers to prepare flexible composites shows great potential. Representative preparation methods include chemical delignification and polymer film lamination.

3.2.1 Chemical Delignification Method

The wood cell wall is primarily composed of three major components: cellulose, hemicellulose, and lignin. In the cell wall structure, lignin acts as a binder, making the fiber structure tighter, thereby reducing its deformability and affecting the overall flexibility and deformability of the fibers. The chemical delignification method makes the wood structure porous by removing lignin and/or hemicellulose matrix components from the wood cell wall while retaining the cellulose skeleton. Subsequently, flexible polymers can be filled into the delignified wood via in-situ impregnation or vacuum impregnation to prepare flexible wood composites. Currently, common delignification methods include sodium sulfite (Na_2SO_3) method, sodium chlorite ($NaClO_2$) method, hydrogen peroxide (H_2O_2) modification method, and biological enzyme methods. Gao et al. treated balsa wood with an alkaline solution to partially remove lignin and hemicellulose. They then introduced quaternized gelatin and an acrylic acid/acrylamide copolymer precursor solution into this wood structure, preparing a composite material via in-situ polymerization. The introduction of quaternized gelatin not only allowed the composite to inherit the mechanical support properties of the wood skeleton but also endowed it with good flexibility and excellent comprehensive electrochemical performance. Chemical delignification treatment not only increases wood's porosity and specific surface area (reducing Young's modulus, enhancing flexibility) but also provides more binding sites for the introduction of functional molecules or nano-components, thereby endowing the composite with functional properties like conductivity, energy storage, or optical regulation. Although delignification methods can efficiently regulate the microstructure of wood units, issues such as high cost, high energy consumption, and waste liquid pollution limit their further industrial application. Therefore, developing more environmentally friendly delignification methods (e.g., ionic liquids, deep eutectic solvents, and biological enzyme methods) will be a future research direction.

To scientifically evaluate the applicability of different chemical delignification strategies in wood structure regulation and performance construction, it is necessary to systematically compare them from the perspectives of process feasibility and structural effects. On one hand, different delignification methods show significant differences in delignification efficiency, reagent cost, process complexity, and environmental impact; these factors directly determine the implementability and scalability potential of the process. On the other hand, the regulatory effect of key process parameters on wood pore structure is particularly crucial; it not only affects the

integrity of the cell wall and the evolution of porosity but also further constrains the introduction efficiency of subsequent functional components and the overall material performance. Therefore, this article separately compares the comprehensive process characteristics of common chemical delignification methods and the impact of key process conditions on porosity changes, to reveal the intrinsic relationship between "process-structure-performance" for different delignification strategies, providing a basis for the rational selection and parameter optimization of subsequent preparation processes.

Table 1 Comparison of chemical delignification methods in efficiency, cost, process difficulty, and environmental impact

Method	Delignification Efficiency	Processing Time	Reagent Cost	Process Difficulty	Environmental Impact
Na_2SO_3 Method	High (80%~95%)[14]	Medium (4~8h)[15]	Low	Medium[16]	Moderate Pollution[15]
$NaClO_2$ Method	Very High (>95%)[17]	Medium (3~6h)[18]	Medium[18]	High (acidic conditions required)[18]	High Pollution (chlorine-containing waste)[17]
H_2O_2 Method	Medium-High (75%~90%)[19]	Short (2~4h)[20]	Medium	Medium	Relatively Eco-friendly[19]
Biological Enzyme Method	Medium (60%~85%)[21]	Long (12~72 h)	High[22] (enzymes expensive)	Low-temperature operation	Eco-friendly[21]

Table 2 Comparative effects of key process parameters on porosity in common chemical delignification

Method	Reagent Condition	Treatment Temperature	Time	Porosity Change Trend	Explanation
Na_2SO_3 Method	Na_2SO_3 mass fraction 5%~15%[16]	80~100℃	4~8h[15]	Moderate Increase[23]	Increased temperature promotes lignin dissolution, but too high causes fiber collapse[15]
$NaClO_2$ Method	$NaClO_2$ mass fraction 1%~3% (acidic conditions)	70~90℃[24]	3~6h[18]	Significant Increase[24]	Thorough removal, high fiber bundle separation
H_2O_2 Method	H_2O_2 mass fraction 3%~10%	60~80℃	2~4h[20]	Maintained or Slight Increase[26]	Mild oxidation, good preservation of microporous structure[27]
Biological Enzyme Method	Enzyme activity 50~100U/mL	30~50℃[28]	12~72 h	Slow Increase[28]	Good pore structure integrity, but low efficiency

3.2.2 Polymer Film Lamination Method

The polymer film lamination method involves laminating a certain flexible plastic film (e.g., polyvinyl chloride PVC, polyethylene terephthalate PET) onto the material surface through hot pressing (hot-pressing temperature typically 120~180℃, applied pressure generally 0.5~1.5 MPa, hot-pressing time usually 30s~5min) or bonding processes. This method primarily achieves tight bonding between the polymer film and the wood surface through hot pressing, utilizing hydrogen bonds, dipole interactions, or physical interlocking formed at the interface to create a "wood-polymer film" layered composite. This preserves the wood skeleton while imparting flexibility to the composite. Peng Xiaorui et al. used maleic anhydride grafted polyethylene (PE) coupling agent to modify the interface between plastic film and wood veneer, preparing a plastic film-reinforced flexible wood veneer composite for wood product veneering. This material has advantages such as good environmental performance, low cost, strong water resistance, and simple process, holding significant practical importance for saving precious wood resources and enhancing product comprehensive performance and added value.

3.3 Comparison of Preparation Strategies

To systematically compare the preparation strategies of different flexible wood composites, this article selects five representative methods from current research for comparative analysis (Table 3). It is noteworthy that different preparation strategies show significant differences in flexibility enhancement effect, mechanical property retention, and process complexity. These differences stem not from the process parameters themselves but mainly from the structural hierarchy they act upon and their regulation method of the wood cell wall load-bearing network.

Table 3 Preparation strategies and performance comparison of flexible wood-based composites

Preparation Method	Efficiency	Energy Consumption	Advantages	Disadvantages
Melt Blending Extrusion	High (industrially mature, suitable for large-scale production)	Relatively High (requires high-temperature melting and extrusion)	Superior mechanical properties; Good uniformity; Suitable for thermoplastic material compounding	High equipment cost; Poor wood flour/matrix interface compatibility requires modification[9]
Continuous Flat-Pressing	Medium (suitable for large-area pressing, efficiency depends on equipment)	Medium (hot-pressing process consumption)	Good dimensional stability; Suitable for decorative and structural applications	Limited flexibility; Mostly used for boards, difficult to achieve high flexibility
Additive Manufacturing	Medium (allows customized complex structures, but molding speed is slow)	Medium-High (printing heating and layer-by-layer deposition)	Enables complex shapes; Functional materials can be directly printed; Suitable for personalized devices[10]	Slow molding speed, high equipment cost, limited material adaptability
Chemical Delignification	Low (requires chemical treatment, multiple steps, long cycle)	Relatively High (chemical solutions, heating, washing)	Can impart flexibility, transparency, and high ionic conductivity to wood (e.g., for electrochemical devices)[14]	Time and energy-consuming process; May compromise wood's mechanical properties
Polymer Film Lamination	High (hot pressing + film lamination, short cycle, simple process)	Low (low-temperature hot pressing or UV curing sufficient)	Simple process; Good surface decorative effect; Eco-friendly[29]	Primarily improves decoration and flexibility, limited enhancement of functionality

4 Multidisciplinary Multifunctional Applications

Since the emergence of humanity, wood has played a vital role in the development of human civilization, often used as building material, furniture raw material, tools, and fuel. During its growth, wood undergoes a complex and unique self-assembly process, forming natural basic characteristics of being porous, structurally complex, and distinctly hierarchical. In recent years, with the rapid development of nanotechnology and materials science, researchers have performed precise functional modifications on the chemical components and wall-layer structures of wood cells, developing a series of advanced multifunctional wood composites. These materials have achieved demonstration applications and yielded abundant results in fields such as building materials and decoration, sensors, ion-conductive hydrogels, electromagnetic shielding, supercapacitors, lithium-ion batteries, solar-driven seawater desalination, and biomedicine.

4.1 Green Building and Decorative Materials

As the concept of global sustainable development deepens, the demand for new green building materials in the construction field becomes increasingly urgent. Although traditional wood has inherent environmental advantages, its poor flexibility limits its application in complex-shaped structural areas within building decoration.

Ultra-thin fiberboard refers to high-density fiberboard with a thickness of 0.5~1.5 mm. Its ultra-thin nature endows it with bendable and rollable properties, leading to widespread application in shaped furniture, curved architectural structures, and other fields. Zhang Wenzhi used the continuous flat-pressing method to manufacture ultra-thin high-density fiberboard. This board exhibits excellent flatness, hardness, and bending performance, and can replace natural wood veneers, engineered wood veneers, and paper-based decorative materials, serving as a buffer layer between surface-decorated wood-based panels, engineered wood flooring, engineered wood doors, and furniture panels and surface materials. Zhou et al. prepared ultra-thin high-density fiberboard via the continuous flat-pressing method. This material can be used in gift box packaging, printed circuit board backing plates, and home decoration fields.

Due to its characteristics of being thin, lightweight, high-density, bendable, and moldable, ultra-thin high-density fiberboard can be applied to curved design in interior decoration, enhancing the decorative and functional properties of substrates, thereby meeting modern architecture's demand for curves and complex shapes. Although currently ultra-thin high-density fiberboard is primarily used as a surface overlay for plywood and blockboard, its excellent performance and broad market potential indicate that more innovative application scenarios will emerge in the construction field in the future.

(a) Flexible ultra-thin fiberboard; (b) Processed flexible ultra-thin fiberboard; (c) Application case

Figure 2 Flexible ultra-thin fiber board

4.2 Intelligent Sensing and Electromagnetic Functional Materials

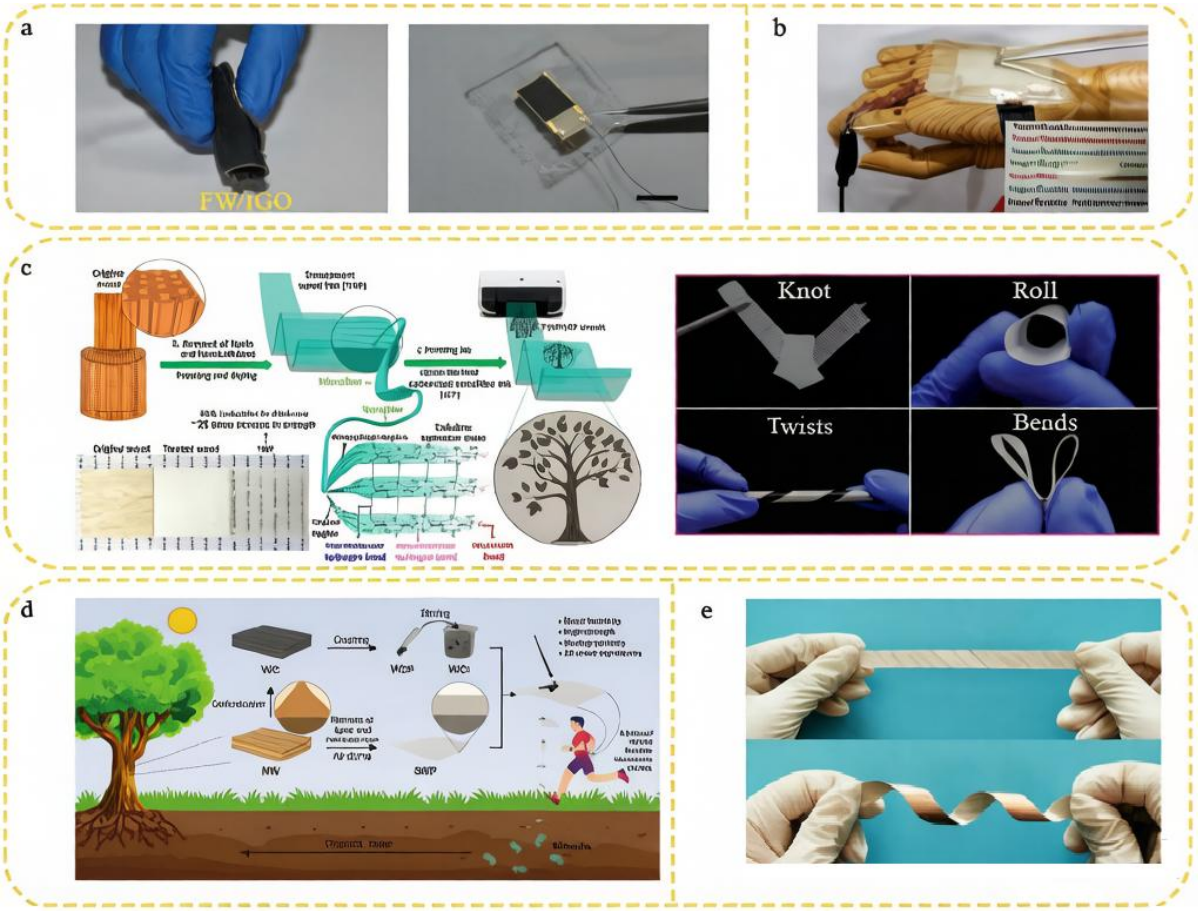
4.2.1 Flexible Sensors

Traditional electronic sensors are typically made of rigid materials, and their fixed working modes struggle to meet the needs for flexible and lightweight applications, thus limiting their use in many modern high-tech fields. As core components of wearable devices, flexible sensors, due to their unique flexibility and stretchability, can conveniently adhere to human skin or robot surfaces to perceive external stimuli (e.g., pressure, temperature), attracting widespread attention from academia and industry in fields like health monitoring, electronic skin, human-computer interaction, and motion tracking. Natural wood, with its advantages of abundant raw materials, low cost, good biocompatibility, high porosity, and large specific surface area, shows great potential in preparing flexible sensor composites.

Tang et al. used delignified wood skin and polyethylene glycol diacrylate as raw materials to prepare an ultra-flexible and transparent wood-based film. This film exhibits a transparency as high as 91.2% in the visible light range and a curvature radius of only 2 mm, demonstrating excellent flexibility and transparency, showing broad application prospects in fields like electronic skin, wearable devices, and robotics. Fu et al. used delignified balsa wood as raw material, prepared a wood-based film with both excellent flexibility and optical transparency via a compression densification method, and developed a fully wood-based high-performance strain sensor using green conductive ink containing carbon nanofibers as the conductive layer, demonstrating potential application value in flexible electronics, smart packaging, and wearable devices. Zhang et al. used natural willow wood as raw material, prepared high-strength, foldable semi-transparent wood-derived paper through chemical treatment and self-densification processes, and constructed fully wood-based flexible electronic devices based on it. This device has a simple structure, is non-toxic and environmentally friendly, exhibits excellent mechanical bending resistance, and is biodegradable, suitable for wearable flexible pressure sensors, holding significant

application potential in health monitoring and human-computer interaction. Shi et al. used natural wood as substrate, successfully prepared a highly flexible and sensitive wood-based triboelectric self-powered sensor (WTSS) through simple chemical treatment, and developed a self-powered smart home control system based on WTSS, achieving remote control of home appliances and software. In strain sensors made from flexible wood composites, physical and chemical mechanisms complement each other. The compressibility and reversible deformation characteristics of the wood fiber skeleton not only provide good mechanical strength and flexibility but also enable high-sensitivity detection through carbonization or adding conductive materials (e.g., nanocarbon, conductive polymers).

However, the anisotropy of wood leads to anisotropic performance in the composite's mechanical properties and long-term environmental stability. Therefore, in the future, novel biomimetic composites and dynamic adaptive materials can be developed through biomimetic methods, combining multi-level structural optimization strategies to balance sensitivity and mechanical performance, thereby enhancing device stability and durability in complex environments to meet dynamic wearable scenario demands.



a. The morphology of flexible sensors [33]; b. Schematic diagram of electronic skin and its flexibility on the surface of prostheses [34]; c. Preparation principle and process of flexible transparent wooden film [35]; d. The manufacturing and degradation process of all wood flexible electronic devices [36]; e. Flexible schematic diagram of wood-based friction self powered sensor [37]

Figure 3 Schematic illustration of the morphology and specific applications of flexible sensors

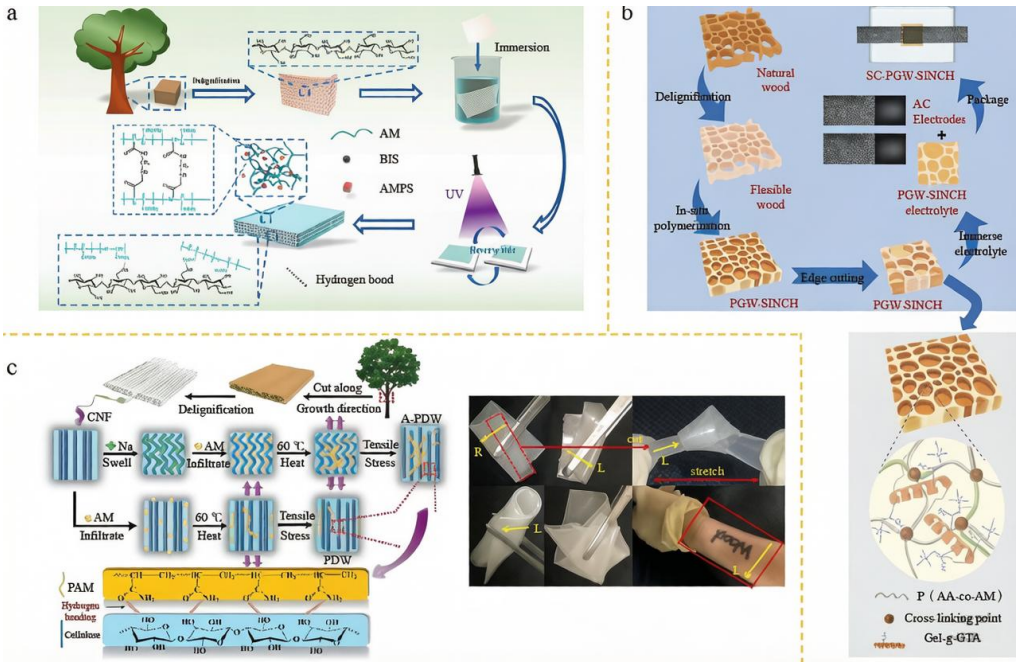
4.2.2 Ion-Conductive Hydrogels

Hydrogels are composite materials with a three-dimensional network structure formed by hydrophilic polymers through chemical or physical crosslinking. Due to their good flexibility and resilience, they are widely used in

wound dressings, flexible sensing, and environmental protection. Wood's unique multi-scale pore structure and aligned cellulose nanofiber characteristics make it an ideal material for preparing high-strength, high-modulus hydrogels.

He et al. compounded acrylamide (AM), 2-acrylamido-2-methyl-1-propanesulfonic acid (AMPS) with delignified wood to prepare a flexible AM/AMPS wood hydrogel (AWH) composite. This material combines the aligned structure of wood cells with the flexibility of hydrogels, endowing it with excellent mechanical strength and flexibility, showing broad application potential in wearable motion monitoring, energy harvesting, and writing sensing. Gao et al. built a semi-interpenetrating network cellulose scaffold by combining quaternized gelatin (Gel-g-GTA) with a crosslinked polymer (acrylic acid-co-acrylamide) (P(AA-co-AM)), and immersed it into a porous wood skeleton for in-situ gelation, successfully preparing a composite hydrogel electrolyte for flexible supercapacitors. The cellulose skeleton and quaternary ammonium groups in gelatin effectively enhanced the ionic conductivity of the composite hydrogel electrolyte. The supercapacitor maintained nearly 90% capacitance after 1000 bending cycles at 180°, demonstrating excellent cycling stability, providing new ideas for designing high-performance flexible supercapacitors. Chen et al. extracted a highly ordered cellulose skeleton retaining anisotropic structure from natural wood via delignification, softened the cellulose skeleton with alkali treatment to enhance its flexibility, and then compounded it with polyacrylamide hydrogel to form a highly flexible, high-strength hydrogel composite. This hydrogel has excellent mechanical properties, can be arbitrarily knotted and folded without breaking, and exhibits an optical transmittance of 69% at 600 nm wavelength, suitable for detecting macro-scale human motions like finger, wrist, and elbow bending.

Delignified wood forms a lignocellulosic skeleton with porous structural characteristics, providing channels for water molecule and ion storage and transport, while increasing the hydrogel's water content and ionic conductivity. Moreover, the abundant hydroxyl groups on cellulose and lignin molecular chains can form stable crosslinked networks with functional groups like carboxyl and amide groups in the hydrogel matrix through chemical bonds, hydrogen bonds, electrostatic interactions, and π-π interactions. This interfacial bonding not only enhances the hydrogel's mechanical strength and flexibility but also endows it with excellent reversibility and self-healing capabilities.



a. Preparation process of AM/AMPS wood-based hydrogel [41]; b. The preparation process of SC-PGW-SINOCH [14]; c. Preparation mechanism and flexibility diagram of composite hydrogel [42]

Figure 4 Schematic illustration of the hydrogel preparation process and its flexibility

4.2.3 Electromagnetic Shielding Films

With the rapid development of electronic information technology, the application of electronic devices like telephones and computers is becoming increasingly widespread, making electromagnetic radiation interference and pollution problems more severe, directly threatening human health. Traditional electromagnetic shielding materials are mostly metallic. Although they can achieve good shielding effectiveness, due to disadvantages like heavy weight and high energy consumption during manufacturing, researchers have begun exploring natural, lightweight, and renewable biomass materials like wood as alternatives.

Jiang et al. used two-dimensional nanomaterial MXene (Ti_3AlC_2) and delignified wood as raw materials to construct a flexible MXene/wood composite (F-MWC) with a sandwich structure. Compared to natural wood, this material exhibits outstanding flexibility, capable of bending into complex shapes without fracture, providing a green, lightweight solution for electromagnetic shielding in electronic devices and building materials. Muhammad et al. prepared highly transparent flexible wood composites for X-ray radiation shielding by combining chemically treated and delaminated wood with polymers (PVA, gelatin) and oxide ($BaCO_3$) through chemical treatment and lamination technology. Studies showed that adding different concentrations of $BaCO_3$ significantly enhanced the material's radiation absorption capacity, and the absorption efficiency gradually increased with concentration. Its minimum half-value layer (HVL) was 0.73 cm, indicating excellent electromagnetic shielding performance.

The hierarchical pore structure of wood provides natural channels for the penetration and aligned arrangement of conductive fillers, enabling the composite to form a continuous conductive network. This structure effectively prevents filler detachment during repeated bending, allowing flexible wood composites to maintain stable electromagnetic shielding efficiency even under high-frequency folding environments.

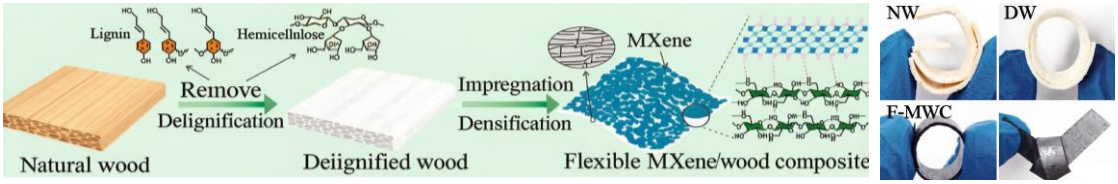


Figure 5 The fabrication process of flexible MXene/wood composite materials and its flexible schematic diagram [44]

4.3 Energy Storage and Conversion

4.3.1 Supercapacitors

Supercapacitors, also known as electrochemical capacitors, have become an important component in modern energy storage systems due to their extremely long cycle life and excellent energy storage capacity. With the rapid development of smart wearable devices, flexible supercapacitors, with advantages like high specific capacitance, high power density, fast charge/discharge capability, and good flexibility, are gradually becoming the main energy storage components for such electronic products. Delignified wood exhibits abundant micro-nano scale pores and unique microchannel alignment structures. This not only facilitates rapid electrolyte infiltration and ion transport but also endows wood with excellent flexibility and high conductivity, providing ordered pathways for efficient energy storage.

However, research on using wood to manufacture flexible supercapacitors has found that the conductivity of wood-based electrode materials and the charge transfer efficiency between various interfaces of the capacitor still need improvement. Future research should focus on effectively regulating the pore structure of wood-based carbon materials and systematically designing interface structures to further enhance the electrochemical performance of capacitors, thereby promoting the practical application of flexible wood-based supercapacitors.

To more clearly demonstrate the unique advantages of wood composites in different application fields, a comparison with common biomass materials and traditional materials is presented. The results show that wood materials have significant advantages in flexibility, processability, and green sustainability.

4.3.2 Lithium-Ion Batteries

Xiong et al. used balsa wood treated for lignin and hemicellulose removal as raw material, filled polyaniline (PANI) nanofibers into the pores of delignified wood via vacuum infusion and in-situ polymerization, preparing a somewhat flexible wood@polyaniline (LFW@PANI) composite. The electrode based on this composite maintained about 96% capacity stability after 5000 cycles, exhibiting excellent cycling performance, high specific capacity (about 800 F/g), energy density (41 Wh/kg), and efficient charge/discharge capability.

Table 4 Comparison of key properties between wood-based composites and petroleum-based flexible materials

Material Type	Conductivity/ ($S \cdot cm^{-1}$)	Shielding Effectiveness/ dB	Elongation at Break/ %	Sensitivity/ Specific Capacitance	Characteristics and Shortcomings
Wood-based Composites	100~1000 (High)	40~60	5~15	High specific capacitance, up to 200~400 F/g	Pore structure facilitates doping and modification, balanced performance
Bamboo-based Materials	10~100 (Medium)	30~50	3~10	Medium	High mechanical strength, relatively low conductivity
PI Composite Films	100~1000 (High)	50~80	50~100	Medium	High strength and flexibility, but non-degradable, high cost
PET Composite Films	10~200 (Medium)	40~70	80~150	Medium	Good flexibility, but poor environmental friendliness

As an energy storage device with cost advantages, long cycle life, and high energy density, lithium-ion batteries show significant advantages in many fields, attracting widespread attention from researchers. With the rapid development of wearable electronic devices (e.g., smartwatches, flexible displays), traditional rigid lithium-ion batteries (LIBs) struggle to meet the devices' demands for flexibility and stretchability. Therefore, researchers have begun exploring flexible lithium-ion batteries with bending, foldable characteristics and high performance. After carbonization and activation treatment, wood can form porous carbon materials. This material not only possesses excellent conductivity and mechanical strength but can also serve as an efficient electrode material. Moreover, wood's abundant pore structure and high specific surface area facilitate lithium-ion storage and transport, reducing interfacial impedance, thereby providing sufficient reactive surface area for lithium ions, helping to improve battery energy density and charge/discharge efficiency.

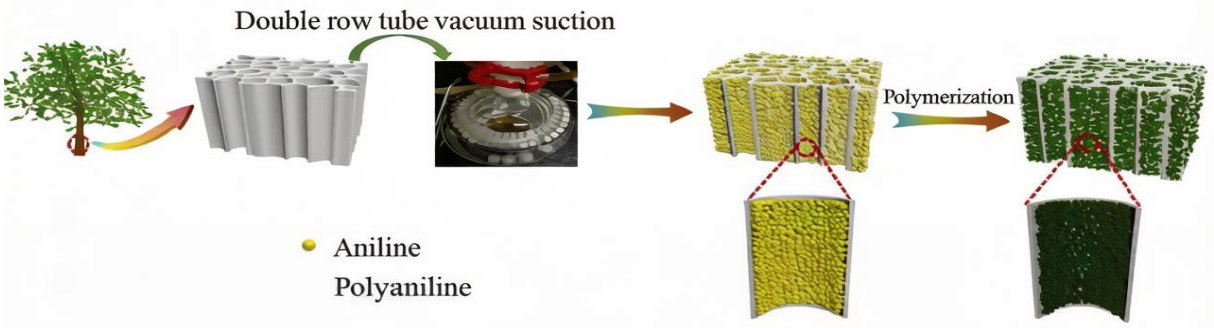


Figure 6 The fabrication process of LWF@PANI composite materials

Zhang Xuan et al. innovatively proposed a "from thick to thin" strategy, loading MXene ($Ti_3C_2T_x$) onto a thick

wood electrode (500 μm thick) via densification and low-temperature treatment, and used this electrode to prepare a solid-state supercapacitor. At a scan rate of 50 mV/s, the cyclic voltammetry (CV) curves remained essentially consistent as the capacitor's bending angle changed from 0° to 90°. This supercapacitor exhibited high flexibility, high specific capacitance, excellent mechanical performance, and stable energy and power density, suitable for wearable devices and green energy storage systems.

4.3.3 Solar-Driven Seawater Desalination

As global freshwater resources become increasingly scarce, abundant and widely distributed seawater is gradually becoming an important alternative source to alleviate water shortages. To address this challenge, a green process based on "air-water interfacial solar heating" is applied to seawater desalination. This technology can not only meet the demands for drinking water, agricultural irrigation, and industrial production but also provides new solutions for alleviating global water stress, promoting regional economic development, and improving residents' quality of life.

Zhang et al. developed a solar seawater desalination evaporator based on a wood-derived aerogel. By combining a gold-reduced graphene oxide (Au-rGO) photothermal layer with a wood aerogel substrate, this evaporator achieved efficient and stable solar-driven evaporation. As nutrients required for mold growth were removed during chemical treatment, the wood aerogel evaporator maintained structural integrity and efficient light absorption even when floating on water for extended periods, demonstrating excellent long-term stability. Chao et al. developed a novel wood-derived indirect contact (suspended) photothermal evaporation system for efficient seawater desalination. The research team prepared a wood-derived aerogel (WA) with an oriented structure by removing lignin and part of the hemicellulose from natural wood, and deposited reduced graphene oxide (rGO) on its surface to form a somewhat flexible reduced graphene oxide-wood aerogel (rGO-WA) composite. Under 1 kW/m² illumination, the system achieved an evaporation rate of 1.351 kg/(m²·h) and an evaporation efficiency of 90.89%, indicating its ability to efficiently remove ions from seawater. Furthermore, the multi-level pore channel structure of flexible wood composites effectively promotes capillary water transport, and their flexible properties ensure stable moisture transport and photothermal conversion performance even under bending or curved conditions, thereby accelerating the process of seawater conduction from the bulk to the evaporation interface. This research provides new ideas for developing efficient, environmentally friendly seawater desalination systems using wood resources.

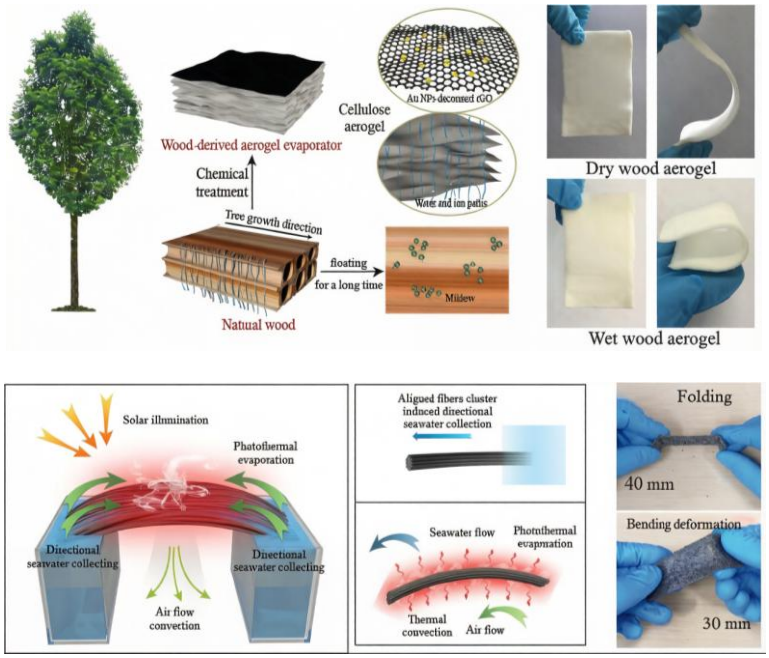


Figure 7 Schematic illustration of the fabrication process of the seawater-desalination evaporator system and its flexibility

4.4 Biomedicine and Tissue Interfaces

Flexible wood composites not only possess mechanical adaptability like bending and folding but also show unique advantages in biomedical fields such as tissue engineering scaffolds and drug-controlled release carriers due to their porous structure, excellent breathability, and biocompatibility. Therefore, exploring the application of flexible wood composites in the biomedical field not only helps expand the functional boundaries of materials but also provides new ideas for the development of green sustainable medical devices and health monitoring technologies.

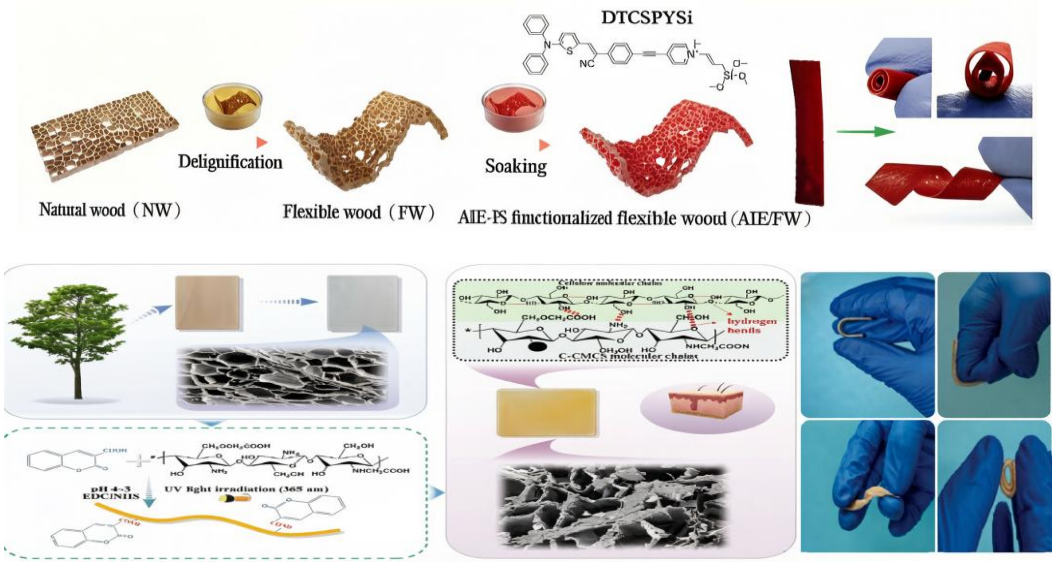


Figure 8 Schematic illustration of the preparation process for biological dressings

Kong et al., inspired by the highly ordered microstructure of muscle tissue, developed a wood-based hydrogel with excellent anisotropy and high strength. This material combines robust wood fibers with a soft polyacrylamide matrix, achieving a tensile strength as high as 36 MPa and possessing good optical transparency. Its excellent biocompatibility supports cell adhesion and growth, demonstrating potential for biomedical material applications. Huang et al. used a simple and efficient top-down assembly strategy to prepare an aggregation-induced emission photosensitizer (AIE-PS) functionalized flexible wood (AIE/FW) dressing with synergistic photodynamic therapy and moisture management functions, effectively promoting the healing of infected wounds. Zhang et al. developed a flexible wood-based hydrogel dressing (FW@PA-hydrogel) based on natural wood through a similar top-down assembly strategy. This hydrogel dressing has enhanced mechanical properties, antibacterial activity, and antioxidant capacity, retaining the oriented porous structure of wood, mimicking the arrangement of collagen fibers in skin. Simultaneously, by introducing phytic acid (PA), it is endowed with significant antibacterial and antioxidant properties, thereby effectively promoting the healing of infected wounds, granulation tissue formation, and collagen deposition.

The application of flexible wood composites in the biomedical field is closely related to their chemical composition, filler types, and performance regulation. The abundant hydroxyl groups on the cellulose surface can promote cell adhesion and proliferation, while lignin degradation products exhibit certain antioxidant and antibacterial effects, helping to improve the cellular microenvironment. By introducing biocompatible components (e.g., gelatin, chitosan) into the composite system, hydrogen bond networks can be further formed with cellulose, thereby regulating the scaffold's mechanical properties and degradation rate. This allows flexible wood composites to not only provide mechanical support but also promote tissue regeneration at the molecular level.

5 Challenges

Based on the above research status, although significant progress has been made in the research of flexible wood

composites, the mechanism of how their microstructure characteristics affect macroscopic performance remains unclear. Furthermore, the development of most flexible wood composites is still at the laboratory stage, facing multiple key technical bottlenecks in the industrialization process. Therefore, the main challenges currently facing flexible wood composites include the lack of structure-property relationships, the contradiction between large-scale manufacturing and environmental friendliness, insufficient long-term durability, and functional singularity.

5.1 Lack of Microstructure-Macroscopic Performance Relationship

The structure-property relationship between a material's microstructure and its macroscopic performance has always been a core issue in composite research. The future development of flexible wood composites faces the challenge of balancing flexibility with multifunctionality. Revealing the interfacial interaction mechanisms and structural evolution laws between wood and polymers/functional nanoparticles at multiple scales has become a key issue that needs urgent resolution. Moreover, precise design and synergistic optimization of material performance can be achieved by regulating the microstructure. Therefore, there is an urgent need to deeply understand and precisely control the relationship mechanism between material structure and performance from the microscopic level, thereby revealing the essence of their physical and chemical properties.

5.2 Imbalance between Large-scale Manufacturing and Environmental Consistency

Flexible wood composites prepared based on delignification methods often generate a certain amount of waste during chemical treatment, causing environmental pollution. To achieve industrial application, it is imperative to explore efficient delignification methods, adopt more environmentally friendly processes, improve yield, and simplify procedures to achieve a balance between large-scale manufacturing and environmental friendliness.

5.3 Insufficient Long-term Durability

In rainy and humid environments, materials are prone to water absorption, swelling, deformation, and even rotting, affecting their structural stability and service life; prolonged exposure to sunlight can cause material degradation, discoloration, and embrittlement due to ultraviolet radiation, leading to cracks and deformation, impacting overall performance; in chemically corrosive media, materials are susceptible to corrosion, limiting their application in harsh outdoor environments and complex, variable scenarios like marine settings.

5.4 Insufficient Functional Integration

Multifunctionality and structure-function integration are mainstream trends in the current development of composite materials. However, existing designs of flexible wood composites are often limited to providing a specific isolated performance, failing to effectively integrate or derive other practically valuable additional functions, making it difficult to meet increasingly complex application needs and high-performance integration requirements. Therefore, it is necessary to promote functional diversification through sophisticated structural design and the combination of multiple basic materials.

6 Future Research Outlook

Currently, researchers have achieved significant fundamental scientific results in the study of flexible wood composites in fields like construction, information, and energy. Future efforts should continue to focus on the research and development of key core technologies, promoting the large-scale application demonstration of new technologies and products. Simultaneously, emerging industries represent new directions for future technological development and are important pathways for cultivating new development momentum and gaining competitive advantages. On this basis, disciplinary barriers should be broken, new quality productive forces should be focused on, and the application of flexible wood composites in high-end fields should be actively expanded to fully leverage their unique advantages. Therefore, future development suggestions should focus on the following aspects.

6.1 Bio-tissue Compatible Materials

In the future development of flexible wood composites, the field of biological tissues shows important

application potential. For example, how to construct an excellent cell adhesion and proliferation environment while maintaining mechanical flexibility; how to endow materials with more biological activity through surface modification or functionalization. In the future, through multi-scale regulation methods, flexible wood composites can better match the natural extracellular matrix at the micro-nano structural level, thereby promoting their further development in the field of biological tissue materials.

6.2 Flexible Shape Memory Materials

Wood cellulose, due to its abundant sources, renewability, and multi-scale pore characteristics, provides new ideas for constructing green shape memory materials. Through multi-scale interfacial engineering, crosslinking design at the molecular level, and compounding with functional polymers, the shape fixity and recovery efficiency of materials can be improved, achieving intelligent shape memory effects in flexible wood composites under multiple external field conditions such as light, electricity, and humidity.

6.3 Embodied Intelligent Materials

In the context of the rapid development of embodied intelligence, flexible wood composites not only possess good mechanical flexibility and processability but also combine sustainable characteristics like renewability and degradability, providing a green development path for intelligent systems. By expanding the "self-sensing - self-adaptation" function at the material level, flexible wood composites can enable the "body" of robots or intelligent devices to dynamically interact with the environment, thus playing an important role in fields like soft robotics, artificial skin, intelligent wearable devices, and human-computer interaction interfaces, promoting embodied intelligent systems towards sustainability and high integration.

7 Conclusion

Flexible wood composites, as an environmentally friendly and high-performance new material, hold significant strategic importance in the context of green and low-carbon development. Based on the multi-scale structure of wood, this article systematically summarizes the preparation strategies and their advantages and disadvantages for flexible wood composites, and reviews the research progress in the multidisciplinary application of multifunctional flexible wood composites in fields such as construction and decoration, information, energy, and biomedicine. Finally, the main challenges currently faced by flexible wood composites in science and technology are outlined, including unclear structure-property relationships between microstructure characteristics and macroscopic performance, difficulty balancing efficiency and environmental friendliness in large-scale manufacturing, insufficient long-term durability, and singular product functionality. Meanwhile, the application prospects of flexible wood composites in future fields like biological tissue materials, flexible shape memory materials, and embodied intelligent materials are foreseen. Although flexible wood composites still face technical challenges in aspects like material structure-property relationships, process optimization, and large-scale application, with the deepening of basic research, breakthroughs in industrial technology, and the establishment of a full lifecycle green evaluation system, flexible wood composites are expected to achieve the leap from laboratory to industrialization, providing innovative ideas for the development of green industry, circular economy, and the realization of global "dual carbon" goals.

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