The Journal of Green Energy and Environmental Engineering

Review Paper

Research Progress on Preparation and Applications of Transparent Wood/Bamboo-Based Luminescent Materials

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Abstract. Transparent wood- and bamboo-based materials are a novel type of composite material obtained by delignification of wood or bamboo followed by polymer infiltration. They not only possess high transparency and excellent mechanical properties but can also exhibit multiple functionalities such as flame retardancy, UV resistance, conductivity, and color change through appropriate functionalization. They show broad application prospects in fields like green building, flexible electronics, and photonic functional devices. In recent years, with the continuous deepening of research on sustainable functional materials, the introduction of luminescent functions into transparent wood/bamboo structures to prepare composite materials with luminescent characteristics has become a research hotspot in the field of photonic functional materials. This article systematically introduces the preparation methods of transparent wood/bamboo-based luminescent materials. Starting from luminescence mechanisms and functional material types, it elaborates on the composite strategies and typical applications of organic luminescent materials (fluorescent dyes, organic phosphors), inorganic luminescent materials (rare-earth-doped materials, semiconductor quantum dots), and organic-inorganic composite luminescent materials (perovskite materials, metal-organic frameworks) in transparent wood. Finally, it discusses key challenges faced by transparent wood/bamboo-based luminescent materials, such as stability, luminescence efficiency, and scalable preparation, and prospects their future development directions in smart construction, energy, sensing, agriculture, and other fields. The aim is to provide reference and insights for further research and application of transparent wood/bamboo-based luminescent materials.

Keywords: *Transparent wood/bamboo-based material; Delignification; polymer infiltration; Photonic functional device; Sustainable material*

Received on 15 Feb 2023, Accepted on 15 April 2023, Published on 15 May 2023

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1 Introduction

As an emerging green material, transparent wood/bamboo-based materials have garnered widespread attention in recent years[1-4]. Their excellent optical properties, good mechanical strength, and biodegradability make them ideal candidates for applications in transparent building materials, windows, optical instruments, and light-transmitting batteries, among others[5]. By selectively removing lignin from natural wood materials and infiltrating them with transparent polymer materials that have a matching refractive index, wood materials can be made transparent while retaining their porous network structure, providing an ideal platform for the integration of functional materials[6-7].

Luminescent materials are a type of functional material capable of absorbing energy and re-emitting it in the form of light, finding extensive applications in fields such as energy conversion, optoelectronic devices, and biomedicine[8]. Eco-friendly luminescent materials, due to their environmental friendliness, degradability, renewability, and high efficiency, have gradually become a research hotspot in recent years and represent an important direction for the development of modern functional materials[9].

Transparent wood/bamboo-based luminescent materials combine the environmental friendliness of renewable wood/bamboo substrates with the efficient optical properties of luminescent units, breaking through the functional limitations of traditional transparent materials[10]. This "structure-function" integrated design strategy not only provides low-carbon solutions for replacing petroleum-based functional materials but also promotes the high-value utilization of biomass resources through interdisciplinary approaches, demonstrating significant application potential in areas such as smart construction, environmental remediation, and flexible electronic devices[11]. Based on different luminescence mechanisms and material compositions, current transparent wood/bamboo-based luminescent materials can be primarily categorized into three classes: first, organic luminescent materials[12], such as fluorescent dyes and organic phosphors[13]; second, inorganic luminescent materials, such as rare-earth ion-doped materials[14], inorganic crystals, and long-afterglow phosphors[15]; and third, organic-inorganic composite luminescent materials, such as perovskite nanocrystals[16]. This article summarizes the transparent processing techniques for wood/bamboo substrates and the strategies for combining luminescent materials with these substrates, reviews the application progress of transparent wood/bamboo-based luminescent materials in smart construction, energy, sensing, agriculture, and other fields, and concludes with an outlook on future development trends, aiming to provide references for the future research, development, and application of transparent wood/bamboo-based luminescent materials.

2 Transparency Mechanisms and Overview of Luminescent Materials

When light interacts with solid matter, phenomena such as light absorption, scattering, reflection, and refraction may occur. If light can pass through the solid material with minimal scattering or absorption and does not undergo significant directional changes while propagating within the material, the material appears transparent (Figure 1)[17]. Lignin is a strong light-absorbing polymer; its molecular structure contains aromatic rings and chromophores such as phenolic hydroxyl and quinone groups, which confer high absorption capacity for ultraviolet (UV) and visible light. Moreover, the conjugated structures within its molecules further enhance light absorption[18]. Light scattering depends on differences in refractive indices. Wood/bamboo substrates are composed of cellulose (refractive index ~1.52), hemicellulose (refractive index ~1.53), and lignin (refractive index ~1.61). After delignification, the porosity increases, and the natural hierarchical porous structure is filled with air (refractive index ~1.00). The disparity in photon transmission speed between the dense structural polymer matrix (characterized by refractive indices approaching 1.56) and the vacant atmosphere-filled cavities induces significant light ray deviation at the junction separating these distinct phases. Attaining see-through characteristics in plant-derived materials from trees or bamboo demands the elimination of dual opacity contributors: wavelength-selective absorption attributable to complex phenolic lignin networks, and Mie-type scattering arising from mismatched optical densities at air-solid boundaries [19].

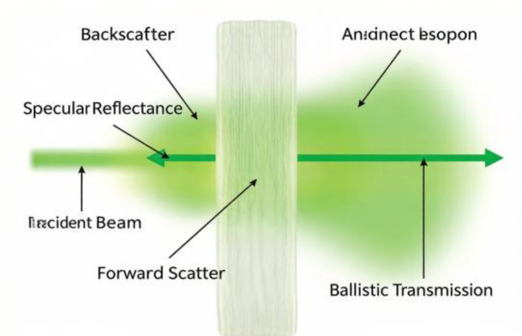

Figure 1 Schematic diagram of material transparency mechanism

Luminescent materials refer to functional materials capable of absorbing external energy (such as light energy, electrical energy, thermal energy, etc.) and converting it into light energy for emission. Based on their material composition and structural characteristics, they can be classified into three main categories: organic luminescent materials, inorganic luminescent materials, and organic-inorganic composite luminescent materials (Table 1).

Organic luminescent materials are composed of carbon-based organic molecules or polymer materials. These organic molecules often contain chromophores, auxochromes, π-conjugated systems, or donor-acceptor (D-A) structures, emitting light through intramolecular π-π* or n-π* transitions. Common organic luminescent materials include fluorescent dyes and organic phosphors[20-23]. Organic luminescent materials offer a wide variety and can be customized through chemical structural adjustments to tune their color and optical properties. Their synthesis is generally relatively simple and cost-effective, making them suitable for large-scale production. However, their photostability and thermal stability are often poor, and they are prone to fluorescence quenching, leading to reduced device lifetime. Xie et al.[24] prepared various polychromatic, efficient, and long-lived persistent mechanoluminescent materials through structural modification-based isomorphic doping. These materials exhibited different phosphorescence lifetimes at room temperature, holding significant importance for promoting the development of efficient organic persistent mechanoluminescent materials. An autonomous investigative unit exploited slender lumber slices as starting materials to construct a photoemissive membrane possessing solar UV-attenuation characteristics and adjustable surface wettability. The manufactured planar assembly exhibited superior mechanical integrity under loading, unhindered visible-light permeability, engineered light scattering, orientation-specific electromagnetic wave redirection, and inherent compostability [13].

Table 1. Advantages, disadvantages and applications of different luminescent materials

Luminescent Material Type	Representative Materials	Advantages	Disadvantages	Application Directions	References
Organic Luminescent Materials	Fluorescent Dyes	High luminescence efficiency, strong tunability, simple preparation	Poor photostability, prone to aggregation quenching	Bioimaging, sensors, cell labeling, etc.	[34]
	Organic Phosphors	Long emission lifetime, high color purity	Low quantum efficiency, high synthesis cost	Safety signage, anti-counterfeiting materials, OLEDs, etc.	[35]
Inorganic Luminescent Materials	Rare-Earth-Doped Materials	High stability, long fluorescence lifetime, narrow-band emission	Complex synthesis, scarcity of rare earth resources	Lighting, lasers, displays, fluorescent probes, etc.	[36]
	Semiconductor Quantum Dots	Tunable emission wavelength, high quantum yield, good stability	Complex synthesis, heavy metal toxicity (Cd/Pb)	Solar cells, bio-labeling, LEDs, etc.	[37]
Organic-Inorganic Composite Luminescent Materials	Perovskite Materials	High luminescence efficiency, tunable bandgap, solution-processable	Poor stability, potential lead toxicity concerns	Photovoltaic cells, light-emitting diodes, lasers, etc.	[33]
	Rare-Earth Complexes	Long luminescence lifetime, narrow emission bands, strong designability	Complex processing technology	Fluorescent sensors, biological probes, anti-counterfeiting labels, etc.	[38]
	Metal-Organic Frameworks (MOFs)	Highly tunable structure, large specific surface area, potential for multifunctional integration	Low luminescence efficiency	Targeted drug delivery, gas detection, photocatalysis, etc.	[39]

Parallel scholarly efforts by Wang et al. [9] similarly employed secondary xylem tissues as architectural frameworks, developing an intensely fluorescent see-through lignocellulosic nanocomposite through strategic incorporation of propeller-shaped tetraphenylethylene chromophores exhibiting emission intensification upon molecular clustering, implemented throughout the consecutive phenolic polymer extraction-thermoset infusion protocol. This methodology enabled direct optical interrogation of the native anisotropic pore channels pervading the botanical substrate via selective chromophore sequestration and radiative efficiency amplification phenomena.

Inorganic luminescent materials are composed of inorganic substances such as alkaline earth metal oxides, sulfides, quantum dots, and rare-earth-doped crystals. They emit light through electronic energy level transitions within the crystal lattice. Common inorganic luminescent materials include rare-earth-doped materials, long-afterglow materials, and semiconductor quantum dots[25-27]. Inorganic luminescent materials possess strong absorption capacity, high conversion efficiency, and stable physicochemical properties. However, their synthesis is complex and costly, and they are often insoluble, which also limits their applications. Fernandes et al.[28] developed a UV-blocking, superhydrophobic semi-transparent wood using epoxy resin and rare-earth-doped aluminate. This phosphorescent wood could glow persistently for extended periods. Under UV irradiation, the phosphorescent wood changed color from colorless to green, and then to yellow-green in the dark, demonstrating potential for smart window applications. Long persistent luminescent materials (LPLMs) hold great potential in optoelectronic applications due to their excellent light storage capacity. Despite progress in exploring novel LPLMs, fabricating transparent LPLMs with customizable shapes, high productivity, multicolor long-afterglow emission, and high chemical stability remains challenging. A specific study reported the construction of partially transparent inorganic-organic assemblies through established melt-processing operations, thus permitting high-throughput production scale-up. The thermoplastic-molded crystal-glass hybrids exhibited prolonged afterglow characteristics across diverse chromatic regions, concomitant with extraordinary resilience against corrosive chemical attack. This work articulates a scalable manufacturing pathway for creating semi-translucent, mechanically stable, and multihued persistent phosphorescent constructs with user-specified morphological configurations [27]. Another study prepared transparent films with persistent luminescence properties via a simple and fast sol-gel method. The film thickness was only a few hundred nanometers and exhibited efficient green emission and yellow afterglow[29].

Organic-inorganic composite luminescent materials combine organic and inorganic components through chemical bonds or physical interactions. Their luminescence relies on interfacial synergistic effects. Such materials primarily include perovskite materials[30], rare-earth complexes[31], and metal-organic frameworks (MOFs)[32]. These materials combine the tunability of organic materials with the high stability of inorganic materials. However, they face prominent issues of interfacial compatibility and synthesis difficulty. Zhang et al.[33] fabricated ultra-thin $CsPbI_3$ perovskite films using a co-evaporation process. These two-dimensional constructs attained photovoltaic conversion efficiencies of 3.6% while preserving optical transparency beyond 50%, pointing toward considerable promise for developing responsive architectural glazing and solid-state lighting applications. In accompanying studies, Yang et al. [31] prepared nanoscale cellulose films coordinated with europium(III) carboxylate functionalities. Under UV irradiation, these specimens generated distinctive red-shifted photoluminescence. Compared to control samples featuring sodium carboxylate attachments, the rare-earth-modified membranes showed substantially enhanced mechanical robustness in both dry and wet states, significantly improved water resistance, greater thermal durability, reduced oxygen barrier permeability, increased dielectric withstand voltage, and higher gravimetric energy density. These high-performance nanocellulosic materials present themselves as promising multifunctional platforms for utilization in fluorescent devices, photon-to-electricity conversion systems, and electrochemical energy storage apparatuses.

3 Preparation Methods for Transparent Wood/Bamboo-Based Luminescent Materials

3.1 Transparent Processing of Wood/Bamboo Substrates

The preparation of transparent wood/bamboo-based materials typically involves two steps: decolorization of the wood/bamboo substrate and polymer infiltration (Figure 2)[40]. Common decolorization methods for wood/bamboo substrates include acidic chlorate oxidation, hydrogen peroxide oxidation, and alkali-hydrogen peroxide modification[41-42].

3.1.1 Acidic Chlorate Oxidation Method

The acidic chlorate oxidation method is an efficient chemical treatment for selectively removing lignin. It utilizes chlorine dioxide (ClO_2) generated from the decomposition of sodium chlorite under acidic conditions to selectively oxidize and degrade the phenylpropane structures in lignin while largely preserving the integrity of the cellulose skeleton. It is a commonly used method for preparing transparent wood/bamboo-based materials. Wang et al.[40] pretreated bamboo with a low-concentration sodium hydroxide solution, then bleached it in a 3% $NaClO_2$ solution at pH 4.6. After impregnating the bleached bamboo with a two-component epoxy resin, they obtained transparent bamboo with a transmittance of up to 80%. In another study, the same method was used to prepare bleached poplar veneer. After resin impregnation and UV curing, transparent poplar veneer was obtained. Further modification with SiO_2 endowed it with self-cleaning functionality, showing broad application prospects in the fields of electronics and optical devices[43].

3.1.2 Hydrogen Peroxide Oxidation Method

The hydrogen peroxide (H_2O_2) alkaline oxidation method is an environmentally friendly wood delignification technology. Its core lies in the selective oxidative degradation of lignin chromophores and cross-linked structures by hydroxyl radicals (•OH) generated from the decomposition of hydrogen peroxide under alkaline conditions. Zhu et al. [44] first immersed wooden blocks in a boiling alkaline solution containing sodium hydroxide and sodium sulfite for 12 hours, then subjected them to bleaching treatment in hydrogen peroxide solution. After epoxy resin impregnation, they obtained transparent wood with over 80% transmittance. Another study adopted the same bleaching method and performed heat treatment on the material after epoxy resin impregnation, obtaining transparent wood with 70% transmittance and 49% haze. This transparent wood exhibited excellent mechanical properties, demonstrating potential for applications in transparent building materials and transparent solar cell windows[45].

3.1.3 Alkali-Hydrogen Peroxide Modification Method

Removing lignin inevitably has a certain negative impact on the mechanical properties of wood/bamboo substrates. Lignin modification achieves decolorization by removing chromophores from lignin while retaining its aromatic skeleton, thereby reducing the impact on the mechanical properties of the substrate. The alkali-hydrogen peroxide modification method uses low-concentration H_2O_2 under mild alkaline conditions to selectively destroy lignin chromophores and some ether bonds through targeted oxidation by radicals, achieving decolorization while preserving the lignin-carbohydrate complex framework. Bisht et al.[46] immersed wood veneer in an aqueous solution containing 3% NaOH, 0.1% EDTA, and 0.1% $MgSO_4$ under weakly alkaline conditions (70°C), then added H_2O_2 and boiled to obtain bleached wood veneer. By impregnating the bleached veneer with epoxy resin and performing multilayer lamination, they obtained multilayer transparent wood with high optical transparency and high mechanical strength. Wang and co-workers [47] applied an identical oxidative pretreatment sequence, subsequently backfilling with epoxy thermoset, to generate see-through bamboo composites. The resultant transparent material displayed outstanding optical clarity at 87% transmission and remarkable axial load-bearing capacity of 118 MPa, coupled with heat transfer coefficients merely 33% those of standard soda-lime glass, establishing its viability for advanced building envelope applications.

The acidic chlorate oxidation method offers high decolorization efficiency and short processing time, but it has harsh reaction conditions, strong oxidizing properties, and environmental pollution risks. The hydrogen peroxide oxidation method has garnered widespread attention due to its mild reaction conditions and relatively good environmental friendliness; however, its decolorization efficiency is relatively lower, and it is more sensitive to process parameters. The alkali-hydrogen peroxide modification method combines effective delignification and bleaching functions through the synergistic action of alkali and hydrogen peroxide, causing less damage to the natural fiber structure. However, it has a longer processing cycle, and the treatment and recycling of high-alkalinity waste liquid are challenging. Future development of wood/bamboo substrate decolorization methods should focus on improving decolorization efficiency and uniformity, reducing damage to the cellulose structure, and achieving green, sustainable processing to meet the preparation requirements for high-performance transparent wood/bamboo materials. After decolorization, wood/bamboo substrates require polymer infiltration to achieve transparency. This process is typically conducted under vacuum or vacuum-pressure conditions, aiming to facilitate the full penetration and filling of low-viscosity polymer monomers or prepolymers into the internal pores, cell lumens, and microfibril interstices within the cell walls of the bamboo. Commonly used polymers include epoxy resin, acrylic resin, polyvinyl alcohol, etc.[48]. The refractive indices of these polymers are close to those of cellulose and hemicellulose, thereby reducing light scattering and making the wood/bamboo substrate transparent.

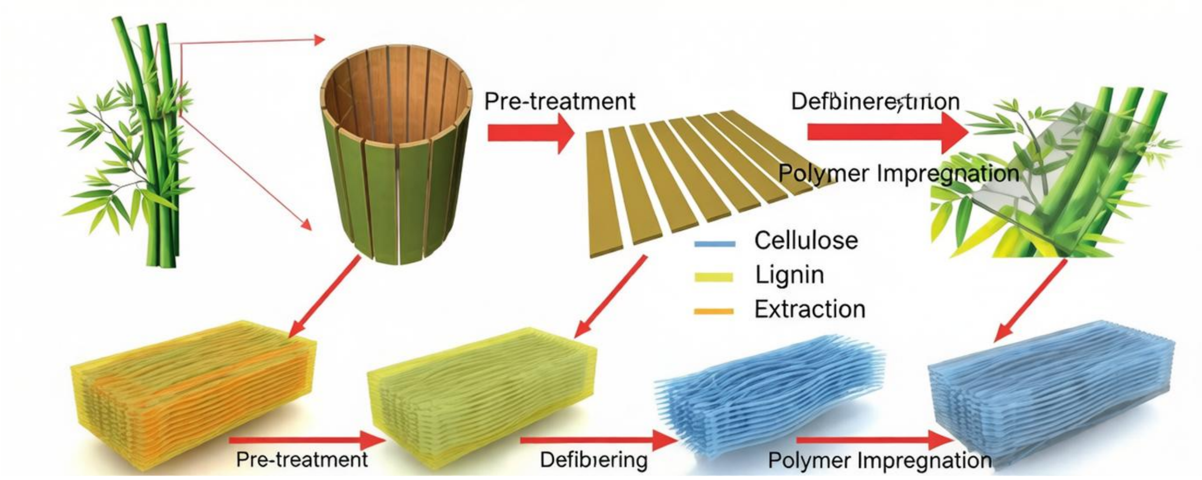

Figure 2 Fabrication process of transparent bamboo

3.2 Composite Mechanisms of Luminescent Materials with Wood/Bamboo Substrates

3.2.1 Physical Impregnation Method

Physical impregnation is currently the most widely used method for introducing luminescent materials. This method relies on the porous network structure formed in the wood/bamboo substrate after delignification. A dispersion of luminescent substances (such as dyes, quantum dots, or rare-earth complexes) is impregnated via vacuum-pressure technology, followed by in-situ polymerization and curing of a refractive-index-matching polymer monomer. This method is simple, versatile, and can effectively preserve the structural integrity of the wood/bamboo substrate. However, issues such as migration of luminescent agents or uneven distribution of luminescent materials may occur. Liu et al. [49] successfully fabricated photochromic transparent wood (PTW) capable of responding to UV and visible light by impregnating delignified wood with a mixture of poly(methyl methacrylate) (PMMA) and the photochromic dye 1,2-bis(5-chloro-2-methylthiophen-3-yl)cyclopentene (DTE).This PTW, integrating light modulation properties, UV-blocking functionality, and reversible yellow-colorless switching capability, shows application potential in the field of intelligent packaging materials, particularly suitable for QR code scanning and anti-counterfeiting materials. Another study prepared magnetic and fluorescent transparent bamboo (MFTB) by vacuum impregnating bleached bamboo with epoxy resin containing rare-earth long-afterglow materials and magnetic nano-Fe_3O_4. The MFTB prepared by this technique shows great application prospects in fields such as information storage, magneto-optical switches, and bioanalytical applications[50].

3.2.2 In-Situ Synthesis Method

The in-situ synthesis method involves impregnating the pores of the wood/bamboo substrate with precursor solutions of luminescent materials, followed by the in-situ generation of the luminophores within the wood/bamboo body via heat, light, or chemical reactions. This strategy can achieve uniform dispersion and strong interfacial bonding of the luminophores, significantly enhancing stability. However, it has stringent requirements regarding reaction conditions and compatibility with the wood matrix. Chen and colleagues [51] engineered luminescent transparent woody membranes through the direct formation of fluorescent nitrogen-doped carbon quantum dots (NCDs) within the porous architecture of a transparent lignocellulosic scaffold.The resulting wood films exhibited excellent tensile strength ((310.00±15.57) MPa), high transmittance (76.2%), UV-blocking properties, and tunable fluorescence. Fluorescent patterning could be easily achieved by adjusting the region of in-situ NCD synthesis. These fluorescent structured timber membranes enabled efficient data encoding, secure information safeguarding, and bidirectional communication with external stimuli through the optically transparent substrate. This scholarly work presents a sustainable and economically viable manufacturing approach for generating luminescent archival and cryptographic materials. In parallel research, Wang and co-workers [52] exploited a photopolymerizable deep eutectic solvent (PDES) formulation—specifically an acrylic acid/choline chloride complex—as a void-filling precursor, effecting in-situ radical polymerization within lignin-extracted wood to produce a biocomposite exhibiting exceptional optical clarity (90% transmittance), considerable mechanical compliance (tensile strain reaching 80%), and moderate electronic charge transport (0.16 S/m).

3.2.3 Surface Modification Method

Surface modification refers to the stable loading of luminescent materials onto the surface or interfacial regions of wood/bamboo substrates through chemical grafting, molecular self-assembly, or coating, imparting specific optical functionalities (Figure 3). This method is suitable for constructing functional layers, regulating luminescent responses, and integrating multiple functions. However, the process is complex, loading capacity is limited, and it may affect the substrate's light transmittance. Yang et al.[53] applied rare-earth upconversion fluorescent ink onto transparent wood via spin coating and combined it with laser etching to prepare photo-responsive transparent wood (PTW) with customizable patterns. This PTW can act as an invisible security label applied to various products and their packaging, enabling information storage and concealment under visible light while allowing information decoding under UV light, thus achieving covert anti-counterfeiting functionality. Another study prepared luminescent transparent wood films with UV resistance and tunable surface energy by modifying delignified wood surfaces through esterification to introduce β-ketoester groups, followed by in-situ construction of 1,4-dihydropyridine (DHP) luminophores with aggregation-induced emission characteristics via the Hantzsch reaction [13].

Table 2. Compositing methods for luminescent materials and wood substrates: comparison of advantages and disadvantages

Composite Method	Advantages	Disadvantages	Applicable Luminescent Material Types	References
Physical Impregnation	Simple operation, does not damage wood/bamboo substrate structure	Limited loading capacity, poor uniformity	Fluorescent dyes, quantum dots, rare-earth complexes	[50]
In-Situ Synthesis	Strong bonding with material, high loading capacity, good luminescence stability	Complex synthesis conditions, may damage wood/bamboo substrate structure	Perovskites, MOFs, inorganic nanoparticles	[51]
Surface Modification	High tunability, precise control of luminescent layer thickness	Weak interfacial bonding, low environmental stability, insufficient internal functionality	MOFs, inorganic nanoparticles	[52]

Different composite methods significantly impact the construction of specific types of luminescent functional materials. The physical impregnation method is suitable for introducing environmentally less sensitive luminescent materials with small molecular sizes, such as fluorescent dyes, quantum dots, and rare-earth complexes. It is simple to operate and suitable for application scenarios requiring high structural integrity of the wood/bamboo. The in-situ synthesis method is more suitable for materials requiring strong structural bonding and dispersion stability, such as perovskites, metal-organic frameworks (MOFs), and inorganic nanoparticles, enabling high loading capacity and excellent luminescence stability. The surface modification method is often used to construct organic phosphors or functionalized fluorescent layers with high controllability and fine structure, suitable for complex devices requiring precise control over luminescent layer thickness and functional layer interfaces. Therefore, selecting appropriate composite methods to construct corresponding types of luminescent systems based on different application requirements will be a key strategy for preparing high-performance wood/bamboo-based luminescent functional materials (Table 2).

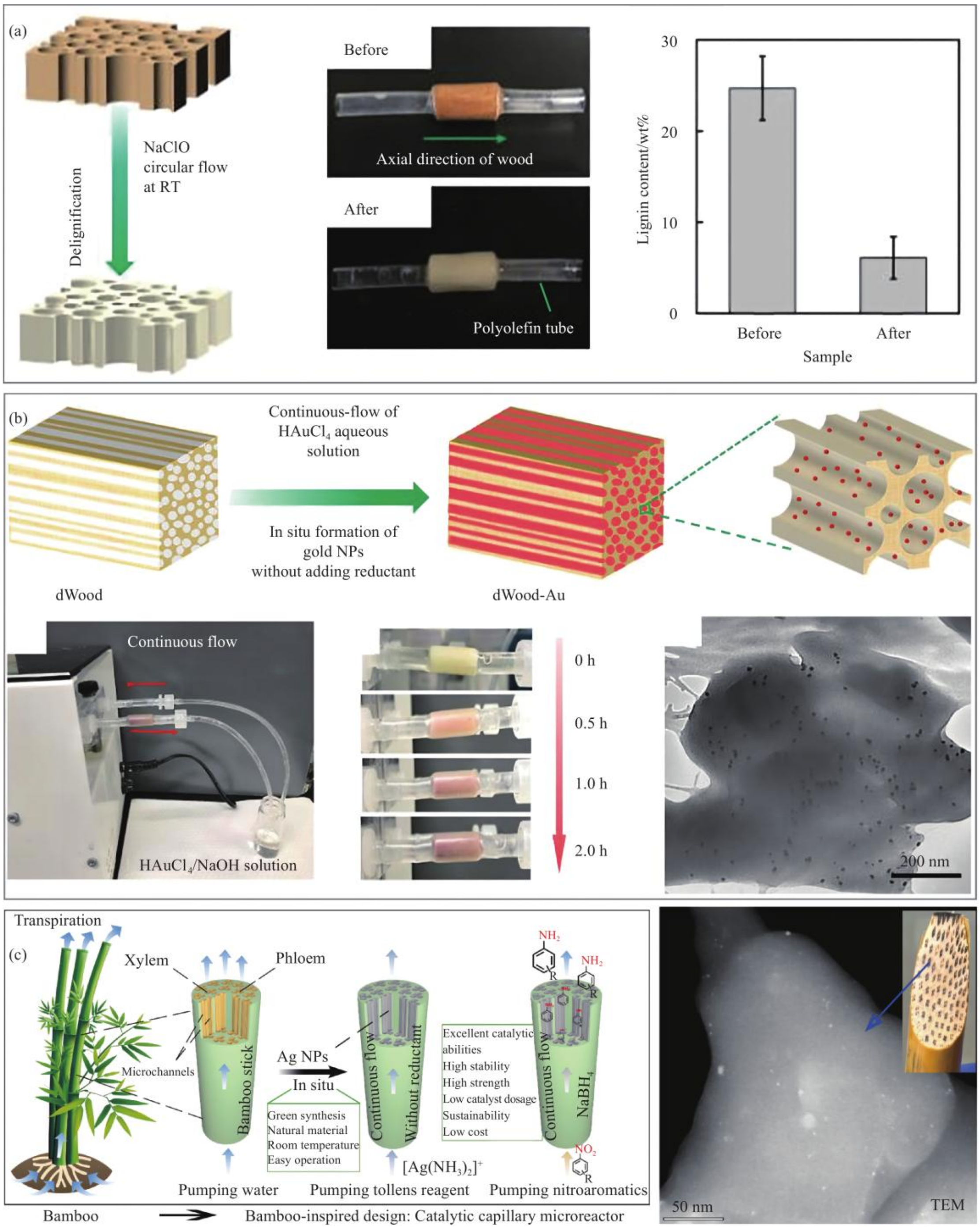

Figure 3 Fabrication process of transparent bamboo by surface modification

4 Applications of Transparent Wood/Bamboo-Based Luminescent Materials

4.1 Smart Construction Field

In recent years, with the continuous advancement of green building and intelligent development concepts, transparent wood/bamboo-based luminescent materials with good optical regulation capabilities and environmentally friendly characteristics have shown broad application prospects in the field of smart construction. Their combination of high light transmittance, mechanical strength, and functional integration enables applications in light regulation, privacy protection, and visual comfort enhancement, among others, providing a sustainable development path for constructing a new generation of energy-saving intelligent building materials[54-55].

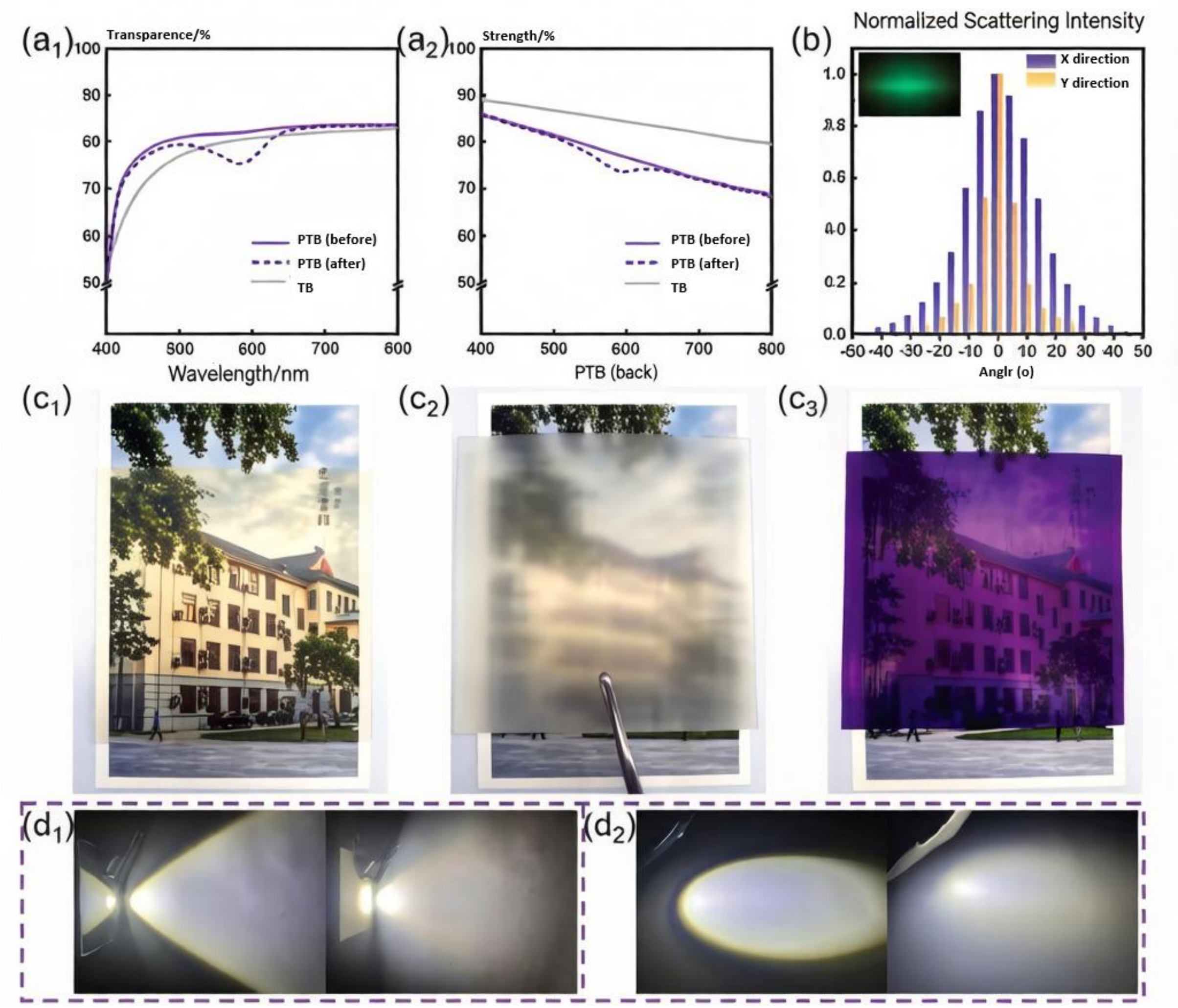

Figure 4 Optical properties of TB and PTB

a1) Transmittance of TB and PTB (comparison before and after UV irradiation); a2) Haze of TB and PTB (comparison before and after UV irradiation); b) Normalized intensity of scattered light through PTB along x/y directions; c1) Imaging when PT is attached to a background pattern; c2) Imaging when PTB is not in contact with the background pattern; c3) Imaging when PTB is attached to the background pattern after UV irradiation; d1) Comparison of light distribution through glass and PTB under vertical spotlight incidence; d2) Comparison of light distribution through glass and PTB under oblique spotlight incidence.

Mehrez et al.[14] developed a UV-blocking, superhydrophobic semi-transparent wood using epoxy resin and rare-earth-doped aluminate. This phosphorescent wood could glow persistently for long periods. Under UV irradiation, the phosphorescent wood's color could change from colorless to green, and then to yellow-green in the dark, demonstrating potential for smart window applications. Zhang et al.[56] synthesized macroscale, geometrically stable photochromic translucent lignocellulose (PTL) via tandem pre-crosslinking-mediated lignin extraction from Phyllostachys pubescens laminae and ensuing impregnation with chromophore-modified thermosetting polymers. The derived biohybrid manifested elevated luminous permeability, switchable photochromic kinetics, marked thermal insulation efficacy, and considerable load-bearing capacity. Recording

81.6% spectral transmission alongside 79.0% light diffusion metrics, this architected substance optimized diurnal radiance admission while safeguarding concealed observation for privacy assurance.Its photochromic properties allow it to automatically adjust color and transmittance according to external environmental conditions, showing broad application prospects in intelligent decorative materials and energy-saving buildings (Figure 4). Binyaseen et al.[57] prepared a long-afterglow photoluminescent transparent wood with color-changing ability and light-switchable transmittance by infiltrating lignin-modified wood with methyl acrylate (MA) and a solution of rare-earth strontium aluminate oxide ($SrAl_2O_4:Eu^{2+}, Dy^{3+}$). This radiolucent, phosphorescent wooden medium exhibited marked ultraviolet-attenuating capabilities and striking non-wetting surface behavior. Under UV-triggered activation, the processed ligneous framework experienced prompt, bidirectional chromatic shifts, establishing its suitability as an emerging solution for sophisticated responsive window technologies.Wang et al.[58] developed a high-transparency cellulose composite material retaining the natural morphology and fiber structure of bamboo. They laminated transparent whole bamboo, transparent bamboo veneer, and electromagnetic shielding films to prepare a multilayer composite device. This composite material not only exhibited excellent thermal insulation properties but also achieved an electromagnetic shielding effectiveness of 46.3 dB. This engineered composite, converging high luminous transmittance, exceptional structural integrity, desirable thermal behavior, and robust electromagnetic interference suppression, serves applicability within eco-conscious architectural frameworks and automated dwelling ecosystems.

4.2 Energy Field

Against the backdrop of the rapid development of clean energy and green energy storage technologies, transparent wood/bamboo-based luminescent materials, due to their unique light regulation and energy conversion capabilities, are gradually being applied in photovoltaic module encapsulation, photoelectric power generation windows, and light energy harvesting systems. Their high transparency, flexible structure, and good environmental adaptability provide new material solutions for building-integrated energy devices and sustainable energy utilization[59-62].

Yin et al.[63] prepared blue and green graphitic carbon nitride through precursor structure regulation and thermal polymerization. Lignin-stripped balsa cellular frameworks underwent saturation with polymerizable epoxy blends incorporating tricolor (RGB) photoemissive dopants, generating luminescent see-through woody nanohybrids displaying simultaneous heightened axial transmittance and marked diffuse scattering behavior. The resulting biogenic composite retained fundamental properties of canonical transparent lumber while prospecting utility within integrated photonic device infrastructures. In parallel breakthroughs, investigators realized premier assembly of hybrid organic-inorganic perovskite photovoltaic cells upon clarified lignocellulosic templates employing low-thermal-budget fabrication protocols (<150°C), achieving 16.8% solar-to-electrical conversion efficiency. These monolithic constructs preserved considerable luminous permeability alongside validated extended-duration stability (Figure 5)[16]. Experimental corroborations substantiate the viability of transparent plant-derived substrates as environmentally benign, embodied-carbon-reducing alternatives to conventional silica-based foundations in light-harvesting technologies. Systematic optimization of interfacial energetics and pore network topologies at molecular and nanometer-length scales within the transparent wooden scaffold may progressively enhance radiative transport characteristics, potentially catalyzing improved internal quantum efficiencies in next-generation photovoltaic energy conversion systems[16].

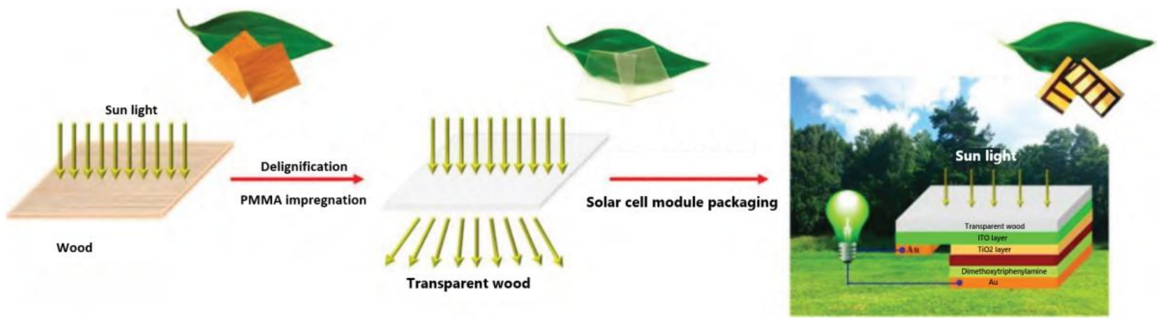

Figure 5 Schematic sketch showing the process of transparent wood preparation and assembling of a

solar cell on the transparent wood substrate. Solar cell structure: Transparent wood substrate / ITO (indium tin oxide) layer / compact TiO2 layer / perovskite layer / Spiro-OMeTAD layer / Au electrode (yellow arrows indicate light path).

4.3 Sensing Field

Transparent wood/bamboo-based luminescent materials, due to their natural porous structure, biocompatibility, and excellent optical response characteristics, are gradually becoming an important material foundation for the design of new sensors. By integrating various sensing elements or utilizing their inherent optical response properties, they can achieve sensitive responses to environmental variables such as temperature, humidity, pH, and gases. They offer advantages such as rapid response, visual output, and green degradability, holding significant application potential in environmental monitoring and intelligent response systems.

Chen et al.[64] permeated delignified timber matrices with vinyl alcohol polymer systems incorporating Eu^{2+}-activated nitridosilicate phosphors, generating renewable luminescent see-through lignocellulosic sheets. Capitalizing on mutual photonic interactions between hemicellulosic scaffolds and radiant dopants, the fabricated biofilm's emission signature exhibited targeted overlap with spectral absorption windows of botanical photosensitizers—encompassing chlorophyll macrocycles, xanthophyll carotenoids, and red/far-red photoreversible phytochromes—implying suitability for greenhouse photoperiod optimization. Furthermore, the clarified wooden laminate displayed thermoresponsive optical modulation, permitting non-destructive thermal imaging of plant physiological status. This luminescent transparent wood film, integrating flexibility, high transparency, optical tunability, recyclability, and biodegradability, possesses dual functionality for plant growth lighting and optical thermal sensing, providing an innovative strategy for the sustainable development of smart agriculture. Drawing upon the light-producing biological mechanisms of *Noctiluca scintillans*, Tang et al.[65] developed a hierarchically structured, deformable lignocellulose-based artificial skin. The configuration utilized delignified woody substrates as mechanical supports, silver nanowire-reinforced ultra-flexible transparent timber membranes as electrical conductors, and pyramid-microstructured polydimethylsiloxane layers doped with Cu-activated ZnS phosphors as mechano-optical responsive interfaces. By integrating parallel capacitive and luminescent sensing architectures, this bio-inspired platform achieved numerical determination and spatial distribution mapping of stationary and time-dependent pressure loads, concurrently enabling detection of injurious mechanical stimuli. It opens new pathways for the innovative application of natural wood in human-machine interfaces and intelligent robotics (Figure 6)[65].

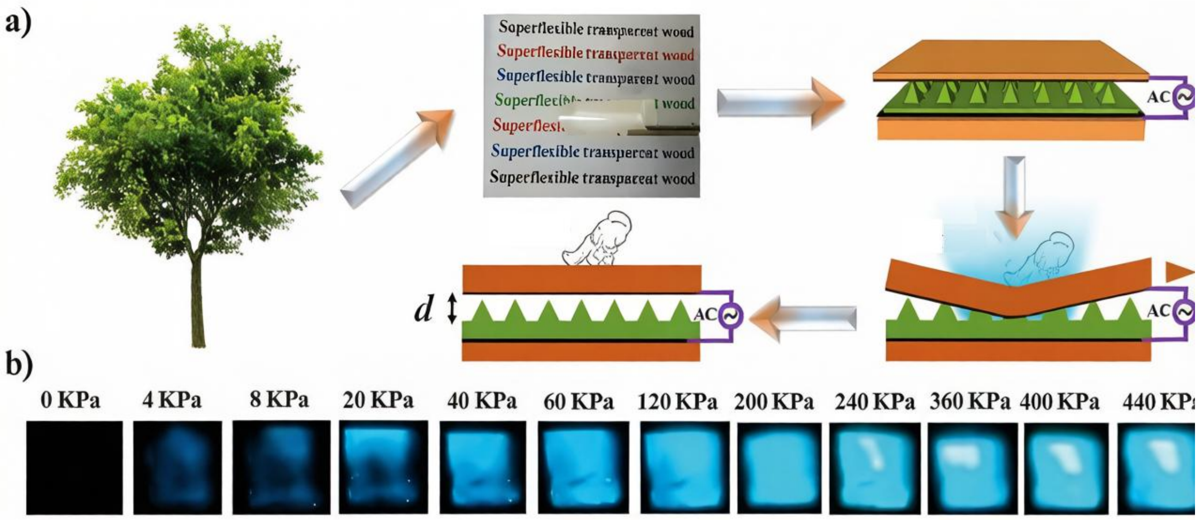

Figure 6 Sensing mechanism of the wood-based electronic skin (a) and images of the instantaneous luminescent response under increasing pressure (b)

4.4 Agriculture Field

The development of light conversion materials is of great significance for precisely regulating plant photosynthesis and promoting sustainable agricultural development. However, current research on luminescent materials based on transparent wood/bamboo in agricultural applications is still limited. To promote the agricultural application of light-converting transparent bamboo, the authors successfully prepared flexible light-converting transparent bamboo (PTB) films with both light conversion functionality and mechanical reinforcement properties, using transparent bamboo as a flexible substrate and compounding it with the efficient wavelength converter Eu(hfa)3(TPPO)2. Experiments showed that PTB transparency could reach 86.3%, and it exhibited strong emission in the red region upon excitation in the ultraviolet region. This indicates that PTB can effectively absorb UV light, which is unnecessary for plant growth, and convert it into red light that promotes plant growth, effectively expanding the photosynthetically active radiation range. Simultaneously, PTB demonstrated excellent thermal stability and mechanical strength (tensile strength 100.5 MPa), significantly superior to conventional polymer agricultural films. The promoting effect of PTB on plant growth was verified through Arabidopsis thalianagrowth experiments. Chlorophyll fluorescence imaging showed that Arabidopsiscovered with PTB had higher maximum photochemical efficiency, and biomass indicators (leaf count, fresh/dry weight) were significantly higher than the control group (leaf count increased by 28.6%, fresh/dry weight increased by 108.6% and 118.2%, respectively, compared to the control). This research provides a new strategy for developing high-performance, eco-friendly agricultural light regulation materials, showing broad application potential in smart greenhouses and low-carbon agriculture. However, the synthesis cost of PTB is relatively high. For practical agricultural applications, issues such as cost, long-term stability, and environmental behavior still need to be addressed. Future research will focus on cost reduction, in-depth assessment of long-term environmental stability, optimization of spectral matching, and preliminary field effect validation, aiming to promote the practical application of this green, intelligent agricultural material (Figure 7).

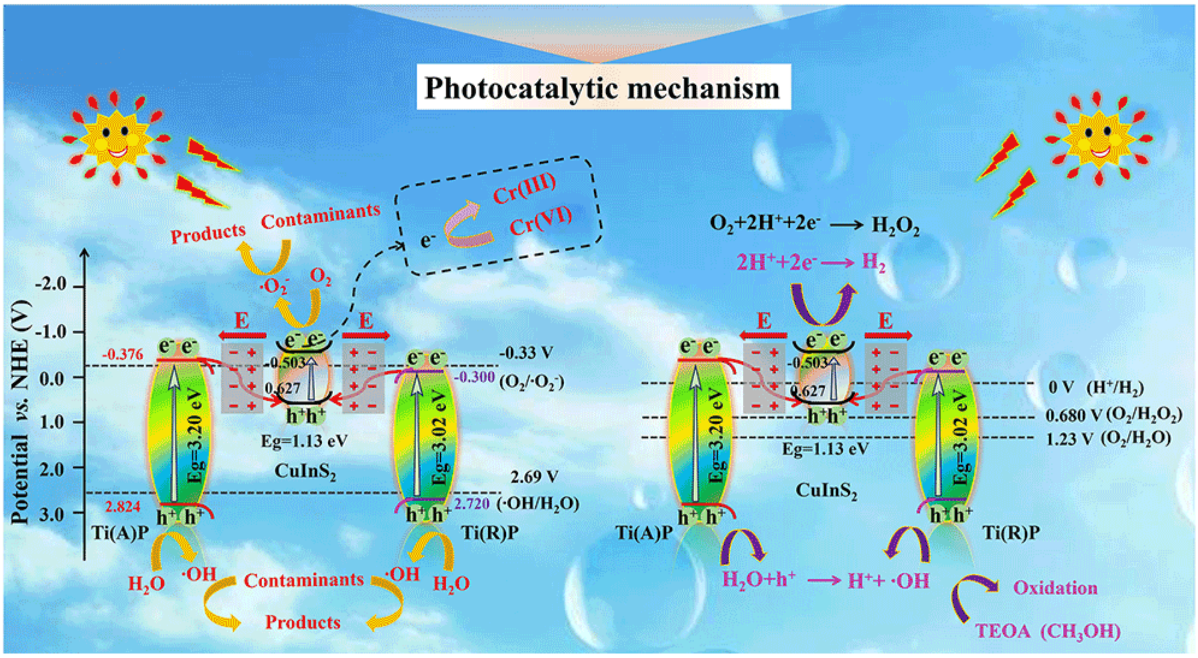

Figure 7 Application of transparent wood in Agriculture Field

Supplementing their broad utilization across smart architectural systems, energy harvesting platforms, sensory apparatus, and crop cultivation technologies, photoluminescent transparent woody/bamboo substrates have progressively revealed considerable applicability within specialized sectors such as clinical therapeutics, decorative arts, and data visualization displays.For example, their good biocompatibility and optical properties make them promising for applications in fluorescent labeling, bioimaging, and degradable optical devices[9, 66]; their excellent light transmittance and luminescent characteristics enable their use in flexible displays, safety signage, and personalized lighting systems[67-69]; furthermore, the combination of their natural texture and functionality provides novel visual expression avenues for creative furniture, decorative materials, and artwork design[70].

5 Outlook

Transparent wood/bamboo-based luminescent materials not only possess good transparency and mechanical strength but can also achieve multifunctional integration by regulating luminescent components, providing new ideas for constructing intelligent, sustainable next-generation green materials. Although current research has made certain progress, many challenges remain to be addressed. On one hand, the distribution uniformity, loading capacity, and long-term stability of luminescent materials within wood/bamboo substrates under complex environments still need optimization. On the other hand, most current preparation processes suffer from issues such as high energy consumption, significant environmental burden, and poor scalability feasibility. Furthermore, the lack of in-depth mechanistic research on the relationships between material structure, performance, and application also limits their widespread use in practical engineering scenarios. Therefore, how to achieve high performance while also considering environmental friendliness and process controllability is a key challenge in the current development of this field. To address the above series of issues, future research can focus on the following five directions:

Introduce low-temperature, low-energy composite technologies and environmentally friendly luminescent materials to reduce the energy consumption and environmental burden of traditional preparation processes, achieve green and sustainable preparation while ensuring functional performance, and simultaneously enhance the scalability potential of the material system.

Improve the compatibility between wood/bamboo substrates and luminescent components, enhance the interfacial bonding strength of composites, and improve the stability and long-term service performance of luminescent functional materials in complex environments through strategies such as interfacial functionalization treatment and intermediate layer introduction.

Achieve precise multi-scale spatial distribution of luminescent materials within wood/bamboo substrates by leveraging patterned construction, self-assembly, and advanced digital manufacturing methods. Promote the deep coupling between material structural design and functional performance to achieve overall optimization of composite material properties.

Intensify investigation into deployment opportunities within nascent technological domains encompassing radiant energy reservoirs, pliable visualization panels, and body-adherent electronic apparatus. Promote the effective integration of luminescent functions with practical application scenarios, enhance the application breadth and engineering adaptability of materials. Moreover, intensify investigative scrutiny regarding their prospective deployment within highly specialized operational contexts, specifically encompassing bathypelagic illumination infrastructure, stratified earth-crust resource identification, and ultra-capacity photonic data transmission modalities, thereby systematically expanding the operational parameter boundaries of these substances when subjected to crushing hydrostatic forces, oxygen-deficient or toxic gaseous milieus, and rigorously demanding technical benchmarks.

Strengthen the integrated application of disciplines such as polymer chemistry, interfacial engineering, biomimetic design, and artificial intelligence-assisted optimization. Enhance the understanding of structure-property relationships in luminescent composite systems, promote intelligent material design and efficient device integration, and accelerate the translation of scientific research achievements into practical applications.

References

[1] YANG L C, WU Y, YANG F, et al. Study on the preparation process and performance of a conductive, flexible, and transparent wood[J]. Journal of Materials Research and Technology,2021,15:5396-5404. DOI:10.1016/j.jmrt.2021.11.021.
[2] WAN C C, LIU X Y, HUANG Q T, et al. A brief review of transparent wood: synthetic strategy, functionalization and applications[J]. Current Organic Synthesis,2021,18(7):615-623. DOI:10.2174/1570179418666210614141032.
[3] WANG J, WANG Y J, WU Y, et al. A multilayer transparent bamboo with good optical properties and UV shielding prepared by different lamination methods[J]. ACS Sustainable Chemistry & Engineering, 2022,

10(18): 6106-6116. DOI:10.1021/acssuschemeng.2c01719.
[4] ZHANG W Z, LI X L, ZHANG M H, et al. Transparent bamboo with multiple light transmittance levels, fiber textures, and colors based on the gradient structure of bamboo[J]. Advanced Engineering Materials, 2024, 26(3): 2301113. DOI:10.1002/adem.202301113.
[5] DAI Shuxia, XU Jin, TAN Bin. Study on transparency and properties of transparent wood, a new building material[J]. Industrial Innovation,2024(22):82-84.
[6] YANG Weijun, ZHANG Mingtong, GAO Mengying, et al. Research progress on wood delignification and its applications[J]. Chemistry and Industry of Forest Products, 2024, 44(5): 52-64. DOI:10.3969/j.issn.0253-2417.2024.05.004.
[7] XU Caijuan, LAN Yujiao, CEN Lifang, et al. Study on the preparation mechanism of natural bamboo-based transparent materials[J]. Guangdong Forestry Science and Technology,2024,40(3):49-56. DOI:10.3969/j.issn.1006-4427.2024.03.007.
[8] CAI Xinjie, XU Yidong, WANG Yuquan, et al. A state-of-the-art review on photocatalytic composite materials using persistent luminescent materials as internal light sources[J]. Materials Reports, 2024, 38(15): 100-109. DOI:10.11896/cldb.23030157.
[9] WANG S D, HE J Z, TAO X M, et al. Design and construction of highly luminescent transparent woody materials exhibiting unique fluorescence-enhanced staining effects for visualization of intrinsic microporous networks[J]. ACS Applied Materials & Interfaces,2024,16(34):45447-45458. DOI:10.1021/acsami.4c08138.
[10] JIA Litong, GUO Minghui, DU Wenxin, et al. Research progress in photo-responsive luminescent transparent wood[J]. World Forestry Research,2023,36(3):51-57. DOI:10.13348/j.cnki.sjlyyj.2023.0023.y.
[11] LI Y Y, YU S, VEINOT J G C, et al. Luminescent transparent wood[J]. ACS Nano, 2020, 14(10): 13775-13783. DOI:10.1021/acsnano.0c06110.
[12] BI Z H, LI T W, SU H, et al. Transparent wood film incorporating carbon dots as encapsulating material for white light-emitting diodes[J]. ACS Sustainable Chemistry & Engineering,2018,6(7):9314-9323. DOI:10.1021/acssuschemeng.8b01618.
[13] WANG M, LIU H C, FENG X, et al. State-of-the-art luminescent materials based on wood veneer with superior strength, transparency, and water resistance[J]. Chemical Engineering Journal,2023,454:140225. DOI:10.1016/j.cej.2022.140225.
[14] EL-NAGGAR M E, ULLAH S, WAGEH S, et al. Preparation of epoxy resin/rare earth doped aluminate nanocomposite toward photoluminescent and superhydrophobic transparent woods[J]. Journal of Rare Earths, 2023, 41(3): 397-405. DOI:10.1016/j.jre.2022.04.018.
[15] ZHOU N Y, LONG S F, SONG D S, et al. Fabrication of carbon dots-embedded luminescent transparent wood with ultraviolet blocking and thermal insulating capacities towards smart window application[J]. International Journal of Biological Macromolecules,2024,259:129358. DOI:10.1016/j.ijbiomac.2024.129358.
[16] LI Y Y, CHENG M, JUNGSTEDT E, et al. Optically transparent wood substrate for perovskite solar cells[J]. ACS Sustainable Chemistry & Engineering, 2019, 7(6): 6061-6067. DOI:10.1021/acssuschemeng.8b06248.
[17] CHEN H, MONTANARI C, SHANKER R, et al. Photon walk in transparent wood: scattering and absorption in hierarchically structured materials[J]. Advanced Optical Materials, 2022, 10(8): 2102732. DOI:10.1002/adom.202102732.
[18] CHEN H, MONTANARI C, YAN M, et al. Refractive index of delignified wood for transparent biocomposites[J]. RSC Advances, 2020,10(67):40719-40724. DOI:10.1039/D0RA07409H.
[19] JELE T B, ANDREW J, JOHN M, et al. Engineered transparent wood composites: a review[J]. Cellulose, 2023, 30(9): 5447-5471. DOI:10.1007/s10570-023-05239-z.
[20] TAO P, MIAO Y Q, WANG H, et al. High-performance organic electroluminescence: design from organic light-emitting materials to devices[J]. The Chemical Record,2019,19(8):1531-1561. DOI:10.1002/tcr.201800139.
[21] JIANG G Y, YU J, WANG J G, et al. Ion-π interactions for constructing organic luminescent materials[J]. Aggregate, 2022, 3(6):e285. DOI:10.1002/agt2.285.
[22] CHEN S, WANG X D, ZHUO M P, et al. Organic white-light sources: multiscale construction of organic luminescent materials from molecular to macroscopic level[J]. Science China Chemistry, 2022, 65(4): 740-745. DOI:10.1007/s[Note: The DOI appears to be incomplete in the original text.]
[23] MUKHERJEE S, THILAGAR P. Renaissance of organic triboluminescent materials[J]. Angewandte Chemie International Edition,2019,58(24):7922-7932. DOI:10.1002/anie.201811542.
[24] XIE Z L, XUE Y F, ZHANG X H, et al. Isostructural doping for organic persistent mechanoluminescence[J].

Nature Communications,2024,15:3668. DOI:10.1038/s41467-024-47962-6.
[25] SU L M, FAN X, YIN T, et al. Inorganic 2D luminescent materials: structure, luminescence modulation, and applications[J]. Advanced Optical Materials, 2020, 8(1): 1900978. DOI:10.1002/adom.201900978.
[26] KIM J, ROH J, PARK M, et al. Recent advances and challenges of colloidal quantum dot light-emitting diodes for display applications[J]. Advanced Materials, 2024, 36(20): 2212220. DOI:10.1002/adma.202212220.
[27] MOHAMED M A, ALI M A, GUO S R, et al. Fabrication of translucent and chemically durable crystal-glass composite with multicolor persistent luminescence[J]. Advanced Optical Materials, 2024, 12(21): 2400576.
[28] FERNANDES R G, DE ANDRADE MATTOS E, DA SILVA V M P, et al. Translucent persistent luminescence glass matrix composite obtained by pressureless viscous sintering[J]. Materialia, 2024,38:102222. DOI:10.1016/j.mtla.2024.102222.
[29] CASTAING V, LOZANO G, MGUEZ H. Transparent phosphor thin films based on rare-earth-doped garnets: building blocks for versatile persistent luminescence materials[J]. Advanced Photonics Research, 2022,3(7): 2100367. DOI:10.1002/adpr.202100367.
[30] XIAO Z W, SONG Z N, YAN Y F. From lead halide perovskites to lead-free metal halide perovskites and perovskite derivatives[J]. Advanced Materials,2019,31(47):1803792. DOI:10.1002/adma.201803792.
[31] YANG Q L, ZHANG C G, SHI Z Q, et al. Luminescent and transparent nanocellulose films containing europium carboxylate groups as flexible dielectric materials[J]. ACS Applied Nano Materials, 2018, 1(9): 4972-4979. DOI:10.1021/acsanm.8b01112.
[32] SUN D R, JANG S, YIM S J, et al. Metal doped core-shell metal-organic Frameworks@Covalent organic frameworks (MOFs@COFs) hybrids as a novel photocatalytic platform[J]. Advanced Functional Materials, 2018, 28(13): 1707110. DOI:10.1002/adfm.201707110.
[33] ZHANG Z B, JI R, JIA X K, et al. Semitransparent perovskite solar cells with an evaporated ultra-thin perovskite absorber[J]. Advanced Functional Materials, 2024, 34(50): 2307471. DOI:10.1002/adfm.202307471.
[34] HE Y J, WANG Y T, GUO Y J, et al. Fine adjustment of emission wavelength, light-conversion quality, photostability of blue-violet light conversion agents based on FRET effect[J]. Dyes and Pigments, 2023, 217: 111429. DOI:10.1016/j.dyepig.2023.111429.
[35] GU L, WU H W, MA H L, et al. Color-tunable ultralong organic room temperature phosphorescence from a multicomponent copolymer[J]. Nature Communications, 2020, 11: 944. DOI:10.1038/s41467-020-14792-1.
[36] LIU J, KACZMAREK A M, VAN DEUN R. Advances in tailoring luminescent rare-earth mixed inorganic materials[J]. Chemical Society Reviews, 2018, 47(19): 7225-7238. DOI:10.1039/C7CS00893G.
[37] YOUSEFI H, SAGAR L K, GERAILI A, et al. Highly stable biotemplated InP/ZnSe/ZnS quantum dots for in situ bacterial monitoring[J]. ACS Applied Materials & Interfaces, 2024, 16(41): 55086-55096. DOI:10.1021/acsami.4c09968.
[38] YAO H, KAN X T, ZHOU Q, et al. Lanthanide-mediated cyclodextrin-based supramolecular assembly-induced emission xerogel films: a transparent multicolor photoluminescent material[J]. ACS Sustainable Chemistry & Engineering, 2020, 8(34): 13048-13055. DOI:10.1021/acssuschemeng.0c04490.
[39] MOSCOSO F G, ROMERO-GUERRERO J J, RODRIGUEZ-LUCENA D, et al. Nanosized porphyrinic metal-organic frameworks for the construction of transparent membranes as a multiresponsive optical gas sensor[J]. Small Science, 2024: 2400210. DOI:10.1002/smsc.202400210.
[40] WANG X, SHAN S Y, SHI S Q, et al. Optically transparent bamboo with high strength and low thermal conductivity[J]. ACS Applied Materials & Interfaces, 2021, 13(1): 1662-1669. DOI:10.1021/acsami.0c21245.
[41] QIU He. Preparation and properties of large-format transparent wood veneer[J]. China Wood-Based Panels, 2024, 31(6): 48. DOI:10.12326/j.2096-9694.2023039.
[42] WANG Quanliang, YANG Pengling, GUO Zhengshen, et al. Preparation technology and frontier application of transparent plant fiber-based composites[J]. Acta Materiae Compositae Sinica, 2025, 42(2): 704-722. DOI:10.13801/j.cnki.fhclxb.20240716.001.
[43] WU X Y, KONG Z Q, YAO X Z, et al. Transparent wood with self-cleaning properties for next-generation smart photovoltaic panels[J]. Applied Surface Science, 2023, 613: 155927. DOI:10.1016/j.apsusc.2022.155927.
[44] ZHU M W, SONG J W, LI T, et al. Highly anisotropic, highly transparent wood composites[J]. Advanced Materials, 2016, 28(26):5181-5187. DOI:10.1002/adma.201600427.
[45] YADDANAPUDI H S, HICKERSON N, SAINI S, et al. Fabrication and characterization of transparent wood for next generation smart building applications[J]. Vacuum, 2017, 146: 649-654. DOI:10.1016/j.vacuum.2017.01.016.
[46] BISHT P, PANDEY K K. Optical and mechanical properties of multilayered transparent wood[J]. Materials

Today Communications,2024,38:107871. DOI:10.1016/j.mtcomm.2023.107871.

[47] WANG Y Y, GUO F L, LI Y Q, et al. High overall performance transparent bamboo composite via a lignin-modification strategy[J]. Composites Part B: Engineering, 2022, 235: 109798. DOI:10.1016/j.compositesb.2022.109798.

[48] HU X, YU R J, WANG F M, et al. Fabrication, functionalities and applications of transparent wood: a review[J]. Advanced Functional Materials, 2023, 33(37): 2303278. DOI:10.1002/adfm.202303278.

[49] LIU L, ZHU G Y, CHEN Y J, et al. Switchable photochromic transparent wood as smart packaging materials[J]. Industrial Crops and Products,2022,184:115050. DOI:10.1016/j.indcrop.2022.115050.

[50] QIU X S, WANG Z H, ZHANG Y L, et al. Preparation and performance on fluorescent magnetic transparent bamboo[J]. Industrial Crops and Products,2024,208:117881. DOI:10.1016/j.indcrop.2023.117881.

[51] CHEN X Q, ZHANG J, ZHANG L, et al. In-situ controllable synthesis of carbon dots for patterned fluorescent wood films rapid fabrication strategy[J]. Aggregate, 2024, 5(3):e519. DOI:10.1002/agt2.519.

[52] WANG M, LI R N, CHEN G X, et al. Highly stretchable, transparent, and conductive wood fabricated by in situ photopolymerization with polymerizable deep eutectic solvents[J]. ACS Applied Materials & Interfaces, 2019, 11(15): 14313-14321. DOI:10.1021/acsami.9b00728.

[53] YANG X L, TIAN Z W, DUAN G G, et al. Light-responsive multimode luminescence in photochromism transparent wood for anti-counterfeiting application[J]. Industrial Crops and Products, 2024, 219: 119098. DOI:10.1016/j.indcrop.2024.119098.

[54] WANG Z H, TONG J W, KUAI B B, et al. Preparation and performance of fluorescent transparent bamboo[J]. Industrial Crops and Products, 2022, 186: 115222. DOI:10.1016/j.indcrop.2022.115222.

[55] AL-QAHTANI S D, ATTIA Y A, AL-SENANI G M. Photoluminescence of polysiloxane-immobilized lignin-toward color-tunable and ultraviolet protective smart window[J]. Ceramics International, 2024, 50(20): 39687-39697. DOI:10.1016/j.ceramint.2024.07.348.

[56] ZHANG T, ZHENG M, LI H J, et al. Photochromic transparent bamboo composite with excellent optical and thermal management for smart window applications[J]. Industrial Crops and Products, 2023, 205: 117532. DOI:10.1016/j.indcrop.2023.117532.

[57] BINYASEEN A M, ALAYSUY O, ALHASANI M, et al. Novel strategy toward color-tunable and glow-in-the-dark colorless smart natural wooden window[J]. Journal of Photochemistry and Photobiology A: Chemistry, 2024, 448: 115321. DOI:10.1016/j.jphotochem.2023.115321.

[58] WANG J, WU X Y, WANG Y J, et al. Green, sustainable architectural bamboo with high light transmission and excellent electromagnetic shielding as a candidate for energy-saving buildings[J]. Nano-Micro Letters, 2022, 15(1): 11. DOI:10.1007/s40820-022-00982-7.

[59] YANG H Y, LIU Y S, LI J, et al. Full-wood photoluminescent and photothermic materials for thermal energy storage[J]. Chemical Engineering Journal,2021,403:126406. DOI:10.1016/j.cej.2020.126406.

[60] GAN W T, GAO L K, XIAO S L, et al. Transparent magnetic wood composites based on immobilizing Fe3O4 nanoparticles into a delignified wood template[J]. Journal of Materials Science, 2017, 52(6): 3321-3329. DOI:10.1007/s10853-016-0619-8.

[61] FU Q L, TU K K, GOLDHAHN C, et al. Luminescent and hydrophobic wood films as optical lighting materials[J]. ACS Nano,2020,14(10):13775-13783. DOI:10.1021/acsnano.0c06110.

[62] ALDALBAHI A, EL-NAGGAR M E, KHATTAB T A, et al. Preparation of flame-retardant, hydrophobic, ultraviolet protective, and luminescent transparent wood[J]. Luminescence,2021,36(8):1922-1932. DOI:10.1002/bio.4126.

[63] YIN X F, ZHANG Y Q, XU Y J. Luminescent transparent wood from balsa wood loaded by graphite carbon nitride for application in photoelectric device[J]. Wood Science and Technology,2023,57(2):467-481. DOI:10.1007/s00226-023-01459-5.

[64] CHEN H, CHEN J Q, MI R Y, et al. Toward recyclable, luminescent transparent wood film via synergistic light responses of lignocellulose and phosphors for plant growth lighting and optical thermometer[J]. Advanced Functional Materials, 2025, 35(36):2423874. DOI:10.1002/adfm.202423874.

[65] TANG Q H, ZOU M, CHANG L, et al. A super-flexible and transparent wood film/silver nanowire electrode for optical and capacitive dual-mode sensing wood-based electronic skin[J]. Chemical Engineering Journal, 2022, 430: 132152. DOI:10.1016/j.cej.2021.132152.

[66] HOGLUND M, BAITENOV A, BERGLUND L A, et al. Transparent wood biocomposite of well-dispersed dye content for fluorescence and lasing applications[J]. ACS Applied Optical Materials, 2023, 1(5): 1043-1051. DOI:10.1021/acsaom.3c00100.

[67] WANG X, MENG X, CUI T T, et al. Highly transparent cellulose-based phosphorescent materials with tunable

afterglow colors and white emission[J]. Carbohydrate Polymers,2024,341:122309. DOI:10.1016/j.carbpol.2024.122309.

[68] PIAO X X, NING Z W, HE Q X, et al. Organic long persistent luminescence wood-based materials[J]. Chemical Engineering Journal,2025,507:160718. DOI:10.1016/j.cej.2025.160718.

[69] PIAO X X, WANG T Y, CHEN X F, et al. Room-temperature phosphorescent transparent wood[J]. Nature Communications,2025,16:868. DOI:10.1038/s41467-025-55990-z.

[70] WU T T, XU Y N, CUI Z W, et al. Shape-editable transparent wood based on in situ polymerization of epoxy vitrimers embedded with luminescent BODIPY molecules for smart decoration materials[J]. ChemPhotoChem, 2024, 8(5): e202300148. DOI:10.1002/cptc.202300148.