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Wood-derived aerogels: Fabrication strategies, properties, and applications

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Abstract

Aerogels are a unique class of ultralight porous materials characterized by extremely low density, high porosity, and large specific surface area. Traditional aerogels, such as silica- or polymer-based aerogels, often suffer from high production costs, poor mechanical robustness, and limited sustainability. In recent years, wood-derived aerogels have emerged as a promising alternative, leveraging the intrinsic hierarchical structure of wood and the renewability of biomass resources. These aerogels inherit the anisotropic cellular architecture of wood while exhibiting excellent thermal insulation, mechanical resilience, and multifunctionality. This review provides a comprehensive overview of wood-derived aerogels, focusing on their fabrication strategies, structure–property relationships, and diverse applications. Top-down and bottom-up fabrication approaches are discussed in detail, followed by an analysis of key physical, mechanical, thermal, and chemical properties. Current and emerging applications in thermal insulation, water purification, energy storage, environmental remediation, and photothermal systems are summarized. Finally, challenges and future perspectives toward scalable production and advanced functionalization are addressed.

Keywords: Wood aerogel, biomass aerogel, cellulose, thermal insulation, adsorption, sustainable materials

Introduction

Aerogels are solid materials derived from gels in which the liquid phase is replaced by gas without significant collapse of the solid network. Since their first synthesis by Kistler in 1931 [1], aerogels have attracted substantial attention due to their extraordinary properties, including ultralow density, high porosity (>90%), and extremely low thermal conductivity [1]. Conventional aerogels are typically fabricated from inorganic precursors such as silica or alumina, or from synthetic polymers such as polyimides and resorcinol–formaldehyde. Despite their excellent performance, these materials often face limitations including brittleness, complex fabrication processes, high energy consumption, and environmental concerns [2, 3]. In response to the increasing demand for sustainable and environmentally friendly materials, biomass-derived aerogels have gained considerable interest. Among them, wood-derived aerogels stand out as a particularly attractive class of materials. Wood is one of the most abundant, renewable, and carbon-neutral natural resources on Earth. It possesses a unique hierarchical structure ranging from the macroscopic growth ring level to the nanoscale cellulose fibril network [4]. By selectively removing certain components of wood, such as lignin and hemicellulose, and carefully drying the remaining cellulose framework, it is possible to fabricate aerogels that retain the intrinsic anisotropic architecture of wood while achieving extremely high porosity and low density. Wood-derived aerogels combine the advantages of natural wood and aerogel materials. They exhibit excellent thermal insulation performance comparable to or even surpassing that of traditional aerogels, while maintaining improved mechanical robustness due to the continuous cellulose skeleton [5]. Furthermore, the abundant hydroxyl groups on cellulose surfaces enable facile chemical modification, allowing wood aerogels to be functionalized for a wide range of applications, including adsorption, catalysis, energy storage, and photothermal conversion [6]. This review aims to provide a systematic and comprehensive overview of wood-derived aerogels. The fabrication strategies are first classified into top-down and bottom-up approaches, with emphasis on processing methods and structure preservation. Subsequently, the fundamental properties of wood aerogels are discussed, followed by an overview of their current and emerging applications. Finally, the challenges and future research directions in this rapidly evolving field are highlighted.

Structural Characteristics of Wood as a Precursor

1. Hierarchical Architecture of Wood

Wood exhibits a highly ordered hierarchical structure that spans multiple length scales. At the macroscopic level, wood consists of growth rings and oriented fibers aligned along the tree growth direction. At the microscopic level, wood is composed of elongated cells such as tracheids and fibers, forming aligned channels for fluid transport. At the nanoscale, the cell walls are built from cellulose microfibrils embedded in a matrix of hemicellulose and lignin [7]. This multiscale architecture is particularly advantageous for aerogel fabrication. The aligned cellular channels contribute to anisotropic mechanical and thermal properties, while the nanoscale cellulose network provides a high surface area and mechanical integrity. Preserving this hierarchical structure during processing is a key objective in the fabrication of wood-derived aerogels.

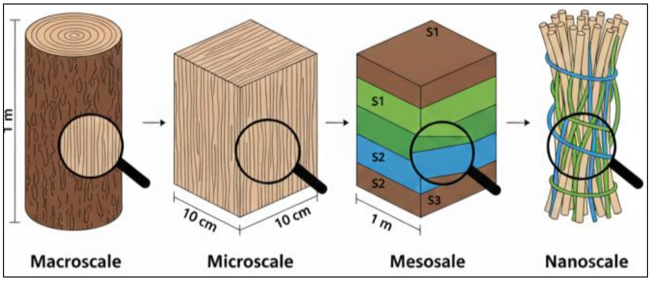

Fig 1: Schematic illustration of the hierarchical structure of wood from macro- to nanoscale [6, 7]

2. Chemical Composition

Wood is primarily composed of three biopolymers: cellulose (40–50%), hemicellulose (20–30%), and lignin (20–30%). Cellulose provides structural strength through crystalline microfibrils, hemicellulose acts as a matrix connecting cellulose fibrils, and lignin serves as a hydrophobic binder that reinforces the cell wall [8]. In the context of aerogel fabrication, cellulose is the most desirable component due to its mechanical strength, flexibility, and abundance of functional hydroxyl groups. Lignin and hemicellulose are often partially or completely removed to increase porosity and accessibility of the cellulose network.

Fabrication Strategies of Wood-Derived Aerogels

Wood-derived aerogels are generally fabricated using either top-down or bottom-up approaches. Each strategy has distinct advantages and limitations in terms of structure control, scalability, and material performance.

Top-Down Fabrication Strategies

1. Principle of the Top-Down Approach

The top-down approach involves directly converting natural wood into aerogel by selectively removing non-cellulosic components while preserving the original wood architecture. This strategy is particularly attractive because it exploits the natural hierarchical structure of wood without the need for complex reassembly processes [9].

2. Delignification and Chemical Pretreatment

Delignification is a critical step in top-down fabrication. Chemical treatments using sodium chlorite, sodium hydroxide, or hydrogen peroxide are commonly employed to remove lignin and hemicellulose. This process increases the porosity of the wood and exposes the cellulose nanofibril network [10]. The extent of delignification must be carefully controlled. Excessive removal of lignin can weaken the structural integrity of the cellulose framework, whereas insufficient delignification may limit porosity and aerogel performance.

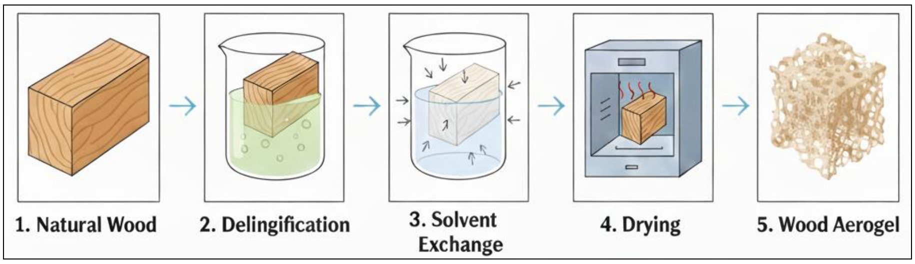

Fig 2: Flowchart of top-down fabrication: natural wood → delignification → solvent exchange → drying → wood aerogel [9-10]

3. Drying Techniques

Drying is one of the most critical steps in aerogel fabrication, as capillary forces during solvent removal can collapse the porous structure.

3.1 Supercritical CO_2 Drying

Supercritical drying is widely regarded as the most effective method for preserving the porous structure. By avoiding the liquid–gas interface, capillary stresses are eliminated, resulting in minimal shrinkage and high porosity [11].

3.2 Freeze-Drying

Freeze-drying involves freezing the solvent and sublimating it under vacuum. This method is more accessible and cost-effective than supercritical drying but may introduce ice-templated macropores and structural anisotropy [12].

3.3 Ambient and Vacuum Drying

Although simpler and more scalable, ambient or vacuum drying often leads to partial collapse of the pore structure, resulting in higher density and reduced performance [13].

Bottom-Up Fabrication Strategies

1. Concept of the Bottom-Up Approach

In the bottom-up approach, wood components—primarily cellulose—are first extracted and processed into nanocellulose suspensions. These building blocks are then reassembled into a three-dimensional gel network, followed by drying to form aerogels [14].

2. Nanocellulose Extraction

Nanocellulose can be obtained through mechanical fibrillation, acid hydrolysis, or TEMPO-mediated oxidation. These processes yield cellulose nanofibrils (CNFs) or cellulose nanocrystals (CNCs) with high aspect ratios and surface functionality [15].

3. Gelation and Network Formation

The nanocellulose suspension is induced to form a gel through physical entanglement, hydrogen bonding, or chemical cross-linking. The resulting gel network can be tailored to achieve specific pore structures and mechanical properties.

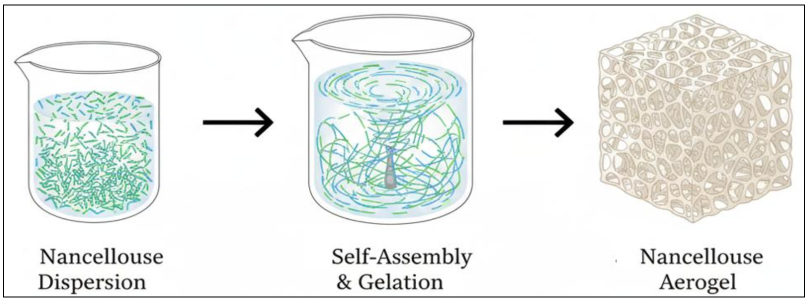

Fig 3: Schematic illustration of bottom-up assembly of nanocellulose aerogels [14, 15]

Properties of Wood-Derived Aerogels

1. Density and Porosity

Wood-derived aerogels typically exhibit densities ranging from 0.01 to 0.1 g/cm³ and porosities exceeding 90%. The density can be tuned by adjusting the degree of delignification, drying method, and processing conditions [16].

2. Mechanical Properties

Unlike traditional silica aerogels, wood-derived aerogels often display remarkable mechanical resilience. The continuous cellulose framework allows them to withstand compression and recover their shape after deformation [17].

3. Thermal Insulation Performance

The high porosity and nanoscale pore structure of wood aerogels significantly suppress heat transfer through conduction and convection. Thermal conductivity values as low as 0.018 $W \cdot m^{-1} \cdot K^{-1}$ have been reported, making them competitive with commercial insulation materials [18].

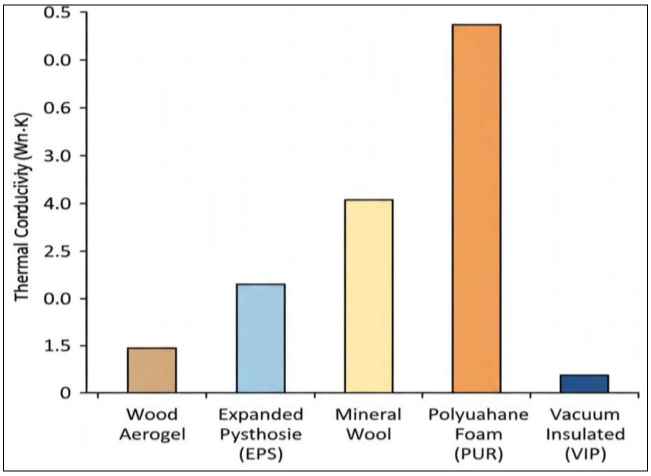

Fig 4: Comparison of thermal conductivity of wood aerogels with conventional insulation materials [10, 16]

4. Surface Chemistry and Functionalization

The abundant hydroxyl groups on cellulose surfaces enable diverse chemical modifications. Functionalization with inorganic nanoparticles, carbon materials, or polymers can impart additional functionalities such as conductivity, flame retardancy, or selective adsorption [19].

Applications of Wood-Derived Aerogels

1. Thermal Insulation in Buildings

Due to their low thermal conductivity and renewable origin, wood-derived aerogels are promising candidates for sustainable building insulation materials [20].

2. Water Purification and Adsorption

Functionalized wood aerogels exhibit excellent adsorption capacity for heavy metal ions, dyes, and organic pollutants. Their interconnected pore networks facilitate rapid mass transport and high adsorption efficiency [21].

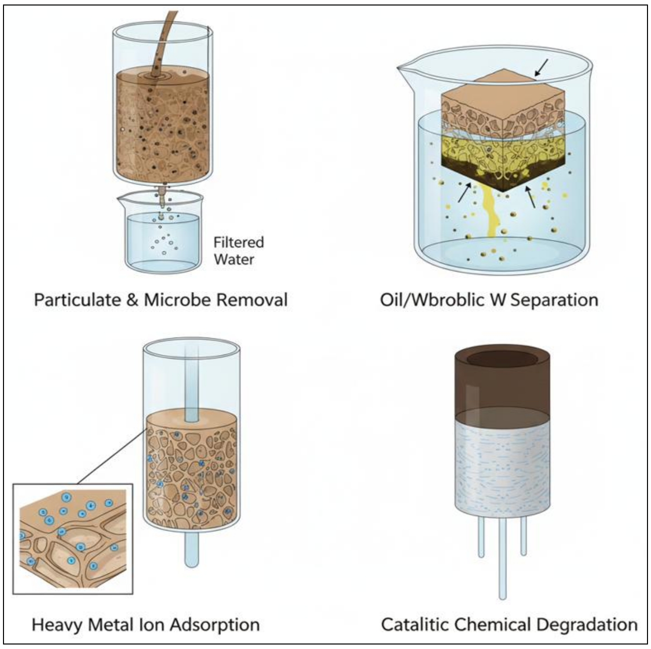

Fig 5: Application of wood aerogels in water filtration systems [20, 21]

3. Energy Storage and Conversion

After carbonization, wood aerogels can be transformed into lightweight carbon aerogels with high electrical conductivity and surface area, suitable for electrodes in supercapacitors and batteries [22].

4. Photothermal and Solar Steam Generation

Wood-derived aerogels with photothermal coatings have been employed in interfacial solar steam generation systems, achieving high evaporation efficiency and water purification performance [23].

Challenges and Future Perspectives

Despite significant progress, several challenges remain. These include scalable manufacturing, cost reduction of drying processes, long-term durability, and standardization of material performance. Future research is expected to focus on hybrid structures, multifunctional composites, and integration into real-world systems [24].

Conclusions

Wood-derived aerogels represent a rapidly emerging class of sustainable materials that combine the unique hierarchical structure of wood with the exceptional properties of aerogels. Through appropriate fabrication strategies, these materials can achieve outstanding thermal, mechanical, and functional performance. Continued research and development are expected to unlock their full potential in energy, environmental, and construction applications.

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