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Recent advances in sustainable biomass-based aerogels: a review

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Biomass-based aerogels are a new type of porous material obtained from biomass raw materials. Compared with traditional inorganic aerogels such as carbide aerogels, oxide aerogels and sulfide aerogels, they have the outstanding advantages of greenness and sustainability, which have attracted more and more attention from researchers. The characteristics of environmental friendliness, presence of surface multi-functional groups and biocompatibility of biomass make them suitable for improving the eco friendliness of traditional flame retardant materials, adsorption of oily pollutants and medical treatment applications. This review mainly provides an introduction to the preparation methods, properties and applications of pure biomass-based aerogels and functionalized and modified biomass-based aerogels. At the same time, it points out the limitations of biomass-based aerogels according to existing research and compares them with traditional aerogels to finally propose innovative ideas for new research directions and industrialization in this field.

Sustainability spotlight

This review highlights the advancements in sustainable biomass-based aerogels, emphasizing their eco-friendly production, biodegradability, and versatile applications in oil adsorption, thermal insulation, and biomedicine. Derived from renewable sources like cellulose and chitosan, these aerogels reduce the reliance on fossil-based materials and minimize environmental pollution. Their development aligns with multiple UN Sustainable Development Goals (SDGs), including SDG 12 (responsible consumption and production) by promoting green materials, SDG 13 (climate action) through low-carbon manufacturing, and SDG 14 (life below water) by enabling efficient oil spill cleanup. Additionally, their biocompatibility supports SDG 3 (good health and well-being) for medical applications. This work underscores the potential of biomass-based aerogels to drive sustainable innovation across industries.

1. Introduction

Aerogels based on nano-skeleton and nano-porous network structures are the least dense solids in the world. As a new type of material, aerogels have shown great application prospects in many important fields such as flame retardancy and heat insulation,[1–3] sensing,[4,5] and aerospace.[6–8] The development of green environmental protection materials has gradually become a mainstream. Biomass-based aerogels are a kind of material with a wide source of raw materials and are harmless. Their emergence provides a feasible idea for the research of environmental protection materials. Interestingly, due to the

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Table 1 Comparison of some properties between biomass-based aerogels and traditional aerogels

Material	Traditional aerogels (such as inorganic aerogels)	Biomass-based aerogel	Reference
Raw material cost	High	Low	9
Biodegradability	Non degradable	3–12 months	16 and 17
LOI	Up to 59.3%	Up to 63%	18–22
Biological toxicity	Nanoparticles may cause cytotoxicity	Basically non-toxic	23 and 24

unique structure of biomass-based aerogels, with high specific surface areas and surface functional groups, they have shown unique potential in the adsorption of pollutants.

Compared with traditional aerogels, biomass-based aerogels have some outstanding advantages that make them play a unique role in some fields (Table 1). In terms of raw materials, biomass-based aerogels have a wide range of sources, most of which use natural biomass such as cellulose, chitosan, and alginate. They have low cost and biodegradability and cause low pollution in their preparation process, which is in line with the theme of green development. Traditional aerogels are usually prepared from silicon source compounds and metal oxides as raw materials or precursors.[9,10] The cost is high, and pollutants will be produced during the preparation process, which is not friendly to the environment.[11] In terms of the preparation process, biomass-based aerogels can be prepared in a mild way,[12] such as in an aqueous phase. However, the preparation conditions of traditional aerogels usually have high energy consumption and high requirements.[13] In terms of application, biomass-based aerogels have the characteristic of biocompatibility that traditional aerogels lack, so they can be used in the medical field,[14,15] expanding their application in many aspects.

The following analysis charts show the statistical data of the publication time, quantity and proportion of biomass-based aerogel-related literature (data from Science Direct, SCOPUS, ACS and other databases). According to incomplete statistics, the earliest report on biomass-based aerogels appeared in 1971, and cellulose aerogels were prepared by supercritical CO_2 drying. Since then, the number of related literature reports has generally increased year by year. Especially from 2022 to 2025, the number of papers on biomass-based aerogels accounts for 60% of the total number of papers related to biomass-based aerogels (Fig. 1a), which shows that biomass-based aerogels have a broad research prospect. According to statistics, in the research of biomass-based aerogel-related applications, more research is on the adsorption of oily substances (Fig. 1b), which further illustrates that the unique biocompatibility of biomass-based aerogels can make it possible to achieve the role that traditional aerogels cannot achieve in more fields.

Although biomass-based aerogels have many outstanding characteristics, there are still deficiencies in practical applications, such as low strength and rigidity, easy collapse under high pressure, insufficient thermal stability, and easy decomposition at high temperatures,[25] which limit their application in extreme environments. At the same time, the large-scale production of biomass-based aerogels still faces challenges such as low drying efficiency. Therefore, starting from the characteristics of biomass-based aerogel raw materials, it is necessary to summarize their preparation methods and application scenarios and put forward the current limitations, so as to provide reference for the development of biomass-based aerogels. The main purpose of this review is to summarize the latest progress in the classification, preparation methods and performance applications of biomass-based aerogels, and to focus on the performance and application of biomass-based aerogels from the aspects of pure biomass-based aerogels and functionalized modified aerogels. It is expected to clarify the

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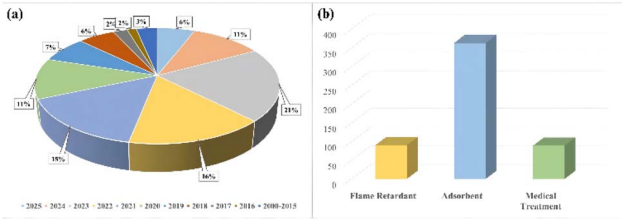

Fig. 1 (a) Proportion of articles on biomass-based aerogel research in different years. (b) Quantitative statistics of articles on different applications of biomass-based aerogels.

development trend and new research fields of biomass-based aerogels through relevant introductions.

2. Classification of biomass-based aerogels

Different types of biomass-based aerogels have their own characteristics in structure, function and application direction. The raw materials of biomass-based aerogels are mainly derived from natural polymers or biomass wastes. According to the different sources of raw materials, they can be divided into cellulose aerogels, chitosan aerogels, alginate aerogels, starch aerogels, konjac glucomannan aerogels, *etc.*

2.1. Cellulose aerogels

As one of the most common substances in nature, cellulose is mainly distributed in the cell wall of plants such as reeds, mulberry bark, wood, and cotton straw. Aerogels prepared using cellulose can be degraded by microorganisms and are a new energy source that is very suitable for sustainable development. Common cellulose aerogels include nanocellulose aerogels and bacterial cellulose aerogels.[26] The general production processes of aerogels and composites are similar. Here, the preparation of Microfibrillated Cellulose Aerogel (MFCA)[27] is shown in Fig. 2. Nanocellulose aerogel is a very light material with a density range of 0.005–0.2 g cm^{-3}. This low density is due to the fact that air or gas occupies most of the volume, the aerogel has a porous structure, and the porosity usually reaches 95%.[28] Bacterial cellulose aerogel is a material with a higher modulus and strength, which is connected by a glucose monomer through a β-1,4-glycosidic bond. In addition, its chemical composition is single and does not contain any other chemical

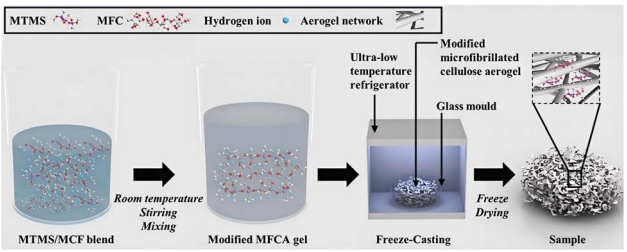

Fig. 2 Schematic of the preparation of the modified MFCA.[27]

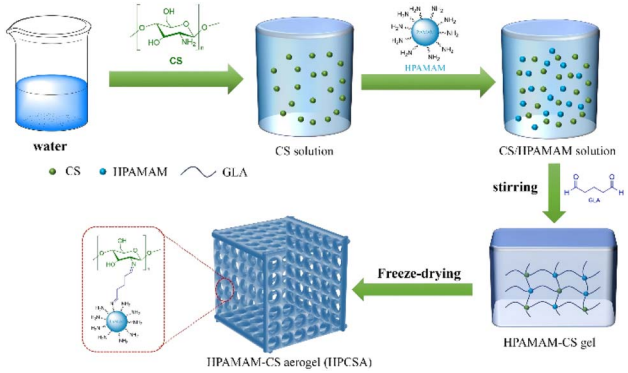

Fig. 3 Synthetic route of HPCSA.[33]

components, that is, impurities such as lignin and hemicellulose can be removed without purification.[29]

2.2. Chitosan aerogels

Chitosan is 2-amino-β-1,4-glucan, which is a natural cationic linear polysaccharide copolymer containing *N*-acetyl-D-glucosamine and D-glucosamine units. It is often obtained by alkaline deacetylation of chitin from various sources. Chitosan aerogel has amino and hydroxyl functional groups that can interact with pollutants,[30] and its preparation process is relatively perfect. Here, the preparation process of chitosan aerogels (HPCSA) is taken as an example (Fig. 3). The chitosan aerogel can be optimized by using metal oxide nanoparticles,[31] SiO_2 (ref. 32) and other nanomaterials, and its application prospect is broad.

2.3. Alginate aerogels

An alginate aqueous solution has high viscosity, mild gel formation conditions and fast formation speed. Alginate aerogels feature abundant hydroxyl/carboxyl groups. The pore structure of alginate aerogels can be regulated by the

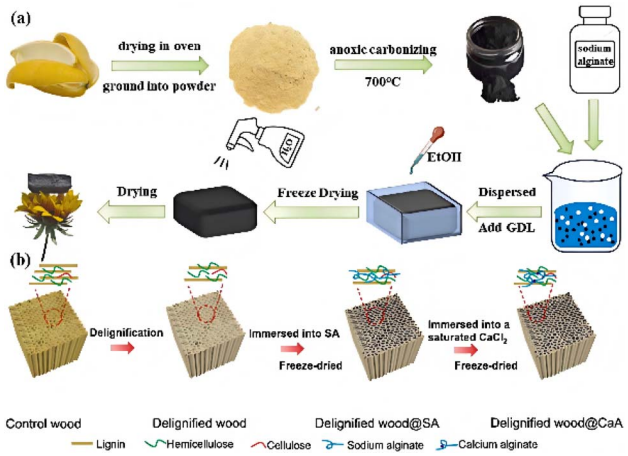

Fig. 4 (a) Schematic of the preparation process of the SA-CA aerogel.[34] (b) Diagram of the preparation of the delignified wood@CaA aerogel.[35]

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preparation process to form nano-micron gradient hierarchical pores, which has received extensive attention. Jing *et al.*[34] proposed the cross-linking of sodium alginate (SA) and ethanol to form aerogels (Fig. 4a), and Meng *et al.*[35] proposed the preparation of a bio-based calcium alginate (CaA) and delignification wood composite aerogel material (Fig. 4b). These materials have optimized and expanded the use of alginate aerogels.

2.4. Other biomass aerogels

Starch aerogels have low density (0.05–0.25 g cm^{-3}), high porosity (82–95%) and hierarchical pore structures (micropores, mesopores and macropores). The porosity of corn starch aerogel was the highest (85.8%), and Young's modulus was 6.23 MPa. Potato starch aerogels have dense pore structures, high hardness but low porosity. Ultrahigh-strength (>80 MPa) starch aerogels can be obtained by thermoplastic processing (such as extrusion and mixing) combined with salt bridge and dynamic bond crosslinking. Shao *et al.*[36] innovatively proposed to graft acrylic acid (AA) and sodium allylsulfonate (AS) onto the main chain of sodium carboxymethyl starch (CMS) to prepare sulfonated activated carbon-reinforced starch-based aerogels, achieving low density (0.29 g cm^{-3}), high porosity (86.48%) and strong swelling capacity (60.78 g g^{-1}).

Konjac glucomannan (KGM) is a natural polysaccharide present in konjac tubers (Fig. 5). It is a type of high-molecular-weight neutral polysaccharide with rich content, non-toxicity and water solubility. It is mainly composed of β-(1–4)-linked D-mannose and D-glucose. It has a large specific surface area, high porosity, low density and low thermal conductivity. Its skeleton unit is rich in free hydroxyl groups and forms a cross-linked structure, which is considered to be an ideal skeleton material for preparing aerogels.[37] Deng's team[38] introduced polyimide (PI)-conjugated structural molecules into konjac glucomannan aerogels, broadening the application scenarios of KGM-based aerogels.

3. Preparation method and process

After introducing different types of biomass-based aerogels and their basic characteristics, below we will introduce the preparation methods and processes of different biomass-based aerogels. The main preparation process of biomass-based aerogels typically involves two steps: sol–gel conversion and drying. The drying methods mainly include supercritical drying, freeze-drying, and atmospheric drying. The drying method directly affects the pore structure and mechanical properties of the aerogels. Therefore, this article mainly introduces three drying methods and compares the advantages and disadvantages of different methods. It is planned to divide different preparation methods into two aspects: pure biomass-based aerogels and functionalized modified biomass-based aerogels, which will pave the way for the introduction of biomass-based properties.

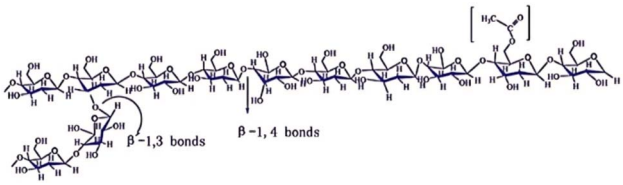

Fig. 5 Molecular structure of konjac glucomannan.[39]

3.1. Supercritical drying method

Under normal drying conditions, due to the tension of the solvent inside the aerogel, the pore size of the aerogel is prone to collapse. Under supercritical conditions, the interface between gas and liquid no longer exists, so when the fluid is discharged from the gel, there is no capillary force, which will not cause the destruction of the gel structure, thus obtaining a porous structure. At the same time, the aerogels prepared by a supercritical drying method have advantages such as lower density, higher specific surface area and smaller pore size,[24,40–44] which can effectively improve the performance of aerogels. The commonly used supercritical drying medium is CO_2, and the processing of aerogels in this medium has the advantages of non-oxidation environment and environmental protection, which is in line with the sustainable development strategy. Supercritical drying is the preferred drying method for traditional aerogels, but it also has certain applications in the preparation of biomass-based aerogels.

The hemp cellulose aerogel prepared by a supercritical drying method by Cabrera-Villamizar[40] *et al.* has a smaller pore width, and the use of supercritical drying method may remove lignin compounds and their derivatives in the aerogel to improve the stability of the aerogel, but it produces more obvious cellulose shrinkage, which limits the use of the aerogel as absorbent pads. The use of supercritical CO_2 drying method is a key step in the preparation of aerogels. Liu *et al.*[41] prepared cellulose nanofiber aerogels at 40 °C and 100 bar for 4 h, Dhua *et al.*[43] prepared corn starch-based aerogels at 40 °C and 150 bar by a supercritical drying method, and Chen *et al.*[45] prepared bio-based polyimide aerogels at 40 °C and 150 bar and obtained aerogels with low density, large porosity and a uniform porous structure.

The preparation of biomass-based aerogels by a supercritical drying method has many outstanding advantages. The obtained aerogels have the characteristics of high porosity, very low density and high specific surface area. At the same time, the aerogels prepared by using CO_2 as the medium also have the outstanding characteristics of non-toxicity and mild critical conditions. This provides an innovative and feasible way to realize the application of biomass-based aerogels in the field of medical treatment.

3.2. Freeze-drying method

The freeze-drying method refers to the preparation of aerogels by sublimating the biomass solution under vacuum conditions to remove the ice crystals and leave the porous structure. This method can preserve the pore structure of the aerogels well and the operation is simple.

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Table 2 Summary of material, freezing method, property and oil–water separation performance of cellulose aerogels[46]

Material	Freezing method	Property	Oil	Oil–water separation performance	References
α-Cellulose	Conventional	Double-layer pore structure, oil contact angles of 158°	Toluene	Separation efficiency of 99.97%, permeate flux of 0.025 L m^{-2} s^{-1}, cycle number of 6	48
Sulfonated cellulose	Conventional	Five different oils contact angles of 160.9°–173.9°	5 Kinds of organic solvents and oils	Permeate flux of 0.100 L m^{-2} s^{-1}, cycle number of 20	49
Epichlorohydrin-CS/cellulose	Conventional	Oil contact angle of 156.2°	5 Kinds of organic solvents and oils	Separation efficiency of 96%, permeate flux of 0.313 L m^{-2} s^{-1}, cycle number of 5	50
MBA/GO/cellulose	Conventional	Oil contact angle of 140°, density of 10 mg cm^{-3}, high porosity of 97%	7 Kinds of organic solvents and oils	Separation efficiency of 98.5%, permeate flux of 6.36 L m^{-2} s^{-1}, cycle number of 10	51

3.2.1. Pure biomass-based aerogels. Freezing technology is a basic and widely used method for preparing aerogels. This technology usually directly affects the pore structure of aerogels and further determines the structure of aerogels. The review of Zhang *et al.*[46] first summarized various methods to optimize the freezing stage in the process of preparing aerogels by freeze-drying (Table 2). The optimization method of auxiliary solvent addition mainly discussed the effect of *Tert*-Butyl Alcohol (TBA) on the pore structure of aerogels. The addition of appropriate amount of TBA is beneficial to improve the structural stability of aerogels, but at the same time, excessive addition will adversely affect the performance of aerogels. The article also introduces the effects of other improvement methods such as directional freezing and soft ice freezing on the pore structure of cellulose aerogels. Different from the freeze-drying method of biomass-based aerogels, high-temperature carbonized biomass (such as corn cobs) can generate graded porous carbon materials (such as N-CNTs@MC), and its mesoporous-microporous synergistic effect significantly improves the specific surface area (1806.3 m^2 g^{-1}) and ion accessibility,[47] providing a new idea for the optimization of the pore structure of aerogels.

Duan *et al.*[52] prepared aerogels using different starch raw materials by a sol–gel freeze-drying technology, and mainly studied the effects of different types of starch on the properties of the prepared aerogels. The larger the particle diameter of starch, the more fully it dissolved, and the higher the transparency. The higher the content of amylopectin, the stronger and denser the grid structure of the aerogel, and the lower the shrinkage rate. The article also studied the effects of different starch raw materials on the density, porosity, and thermal conductivity of the prepared aerogel.

The preparation of biomass-based aerogels by a freeze-drying method has the characteristics of simple process and flexible solvent selection. Therefore, it is a commonly used method for preparing aerogels. Through the adjustment and control of different link conditions, aerogels with high porosity can be easily obtained.

3.2.2. Functional modification of biomass-based aerogels. In the preparation process of functionalized modified biomass-based aerogels, freeze-drying technology is a commonly used preparation technology, and it is often combined with other preparation technologies to obtain aerogels with better performance.

For example, Liu *et al.*[53] used freeze-drying technology to prepare cellulose-derived carbon aerogels from hemp stems by carbonization at different temperatures. This treatment method is combined with appropriate alkali concentration and carbonization temperature. The resulting aerogel has a more complete three-site mesh layer and a thicker layered structure; the composite aerogel prepared by the combination of atmospheric pressure drying and freeze-drying technology proposed by Hou *et al.*[54] has both high mechanical strength and excellent flame retardancy. The freeze-dried surface-modified basalt fiber (Z@BF) and the aerogel form a double grid structure (Fig. 6), which increases the compressive strength of the composite aerogel by 55.43% and reduces the total heat release by 36.9%. Benito González *et al.*[55] used freeze-drying and polylactic acid (PLA) to prepare aerogels with hydrophobic properties and improved the mechanical properties of aerogels.

Freeze-drying technology is a relatively simple and commonly used technology for preparing aerogels, but there are problems of high energy consumption and high cost, which is not conducive to the development of green environmental protection experiments. This is also one of the aspects that can be improved after aerogel preparation.

3.3. Ambient pressure drying method

Ambient pressure drying refers to a method where solvent displacement is used to reduce surface tension, followed by

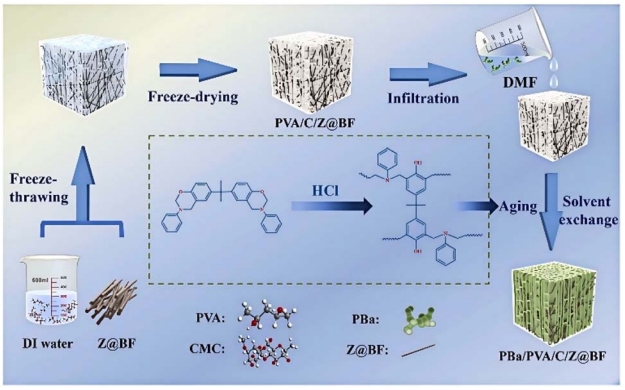

Fig. 6 Schematic of the synthesis of PBa/PVA/C/Z@BF.[54]

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evaporation at room temperature to obtain aerogels. Compared to supercritical drying and freeze drying, there is currently less research on obtaining biomass-based aerogels through ambient pressure drying.

3.3.1. Pure biomass-based aerogel. Direct atmospheric drying of biomass-based aerogels often leads to issues such as pore structure collapse, high shrinkage rates, structural cracking, and loss of functionality. To mitigate these problems in pure biomass-based aerogels, the drying process is often optimized through methods such as solvent replacement and surface tension regulation.

Toivonen *et al.*[56] prepared a breathable and transparent CNF (cell nanofibers) aerogel membrane by drying at room temperature after solvent exchange. These membranes have outstanding characteristics such as high strength (tensile strength of 97 MPa and specific strength of 161 MPa m^3 kg^{-1}), a porosity of 10–30 nm, a specific surface area of 208 m^2 g^{-1} and high stiffness (Young's modulus of 6 GPa and specific modulus of 10 GPa cm^3 g^{-1}). This method is obtained by vacuum filtering and solvent exchange of aqueous compressed naphthalene fiber dispersion into 2-propanol, which is then exchanged into octane, and then dried at room temperature. Sankhla *et al.*[57] freeze-thawed the aqueous suspension of CNF and urea, and then dried it at ambient temperature to obtain the CNF aerogel, which has an elastic modulus of 1345 kPa and a porosity of 96.9%. Then, the surface of the aerogel was modified with polycaprolactone (PCL) to realize the oil absorption function of the CNF aerogel.

In a word, in the ambient pressure drying of pure biomass-based aerogels, solvent replacement is mostly used to prevent the deformation of pore structures and optimize the process.

3.3.2. Functionalized modified biomass-based aerogel. It is found that most aerogels made from cross-linked biomass have good mechanical properties, relatively stable characteristics and adjustable structure, which can effectively prevent the collapse of pore structure. An *et al.*[58] team used chitosan, citric acid, pectin and phytic acid as raw materials to prepare aerogel through the triple strategy of ion crosslinking, physical cross-linking and chemical crosslinking (Fig. 7); Menshutina *et al.*[59] used 53% mixed cellulose solution and crosslinking agent epichlorohydrin to prepare aerogel; Ye *et al.*[60] used natural animal gelatin and water-soluble chitosan as raw materials and prepared aerogels by cross-linking between aldehyde groups and amino groups, which all have denser structures, better mechanical properties and stronger structures. This shows that the use conditions of aerogels can be broken by cross-linking modification technology, so as to broaden their application field.

Therefore, in order to alleviate the problems that may occur during ambient pressure drying, in addition to the above-mentioned solvent displacement method, cross-linking is usually used to enhance the network strength, prevent pore structure collapse, and make ambient pressure drying possible.

The urea-modified chitosan aerogel researched by Guerrero Albuquerque[61] and others was also prepared by drying under ambient pressure. Urea is a possible amino crosslinking agent. The addition of urea may result in the grafting of urea group and crosslinking with a urea benzene group, which to some extent reduces the collapse of pore structure after drying under ambient pressure. The thermal conductivity of this type of aerogel material is as low as 30.9 mW (m K)$^{-1}$. Although some properties are still lower than the biomass-based aerogel produced by supercritical CO_2 drying (Fig. 8), this study proves the possibility of producing high-performance biopolymer aerogels by ambient pressure drying.

In the research of Hu *et al.*,[62] the amino silane coupling agent 3-aminopropyltriethoxysilane (APTES) was used to form an

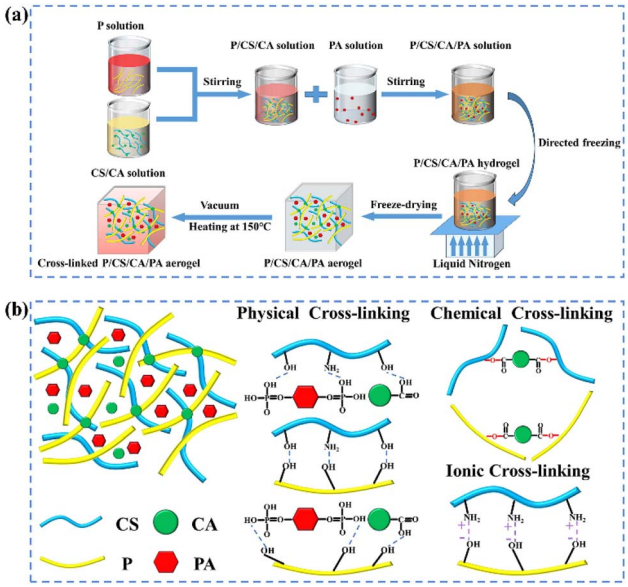

Fig. 7 Schematic of the synthesis process (a). Structural composition of aerogel with a triple cross-linking network (b).[58]

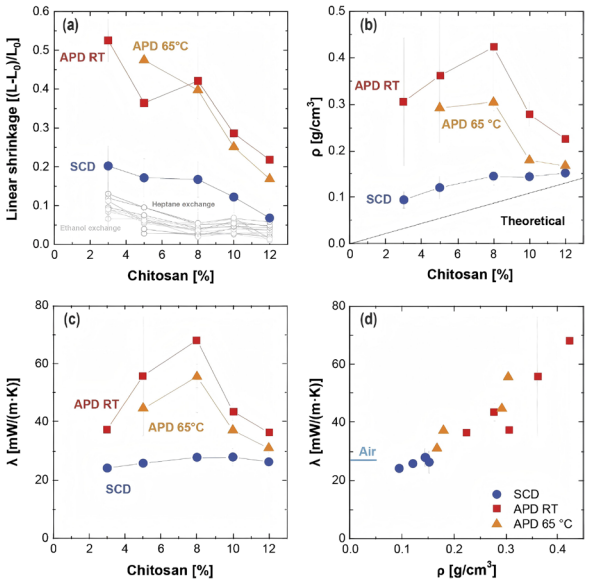

Fig. 8 (a) Linear shrinkage as a function of chitosan concentration. (b) Density dependence on the chitosan concentration. (c) Thermal conductivity *versus* chitosan concentration. (d) Thermal conductivity *versus* density.[61]

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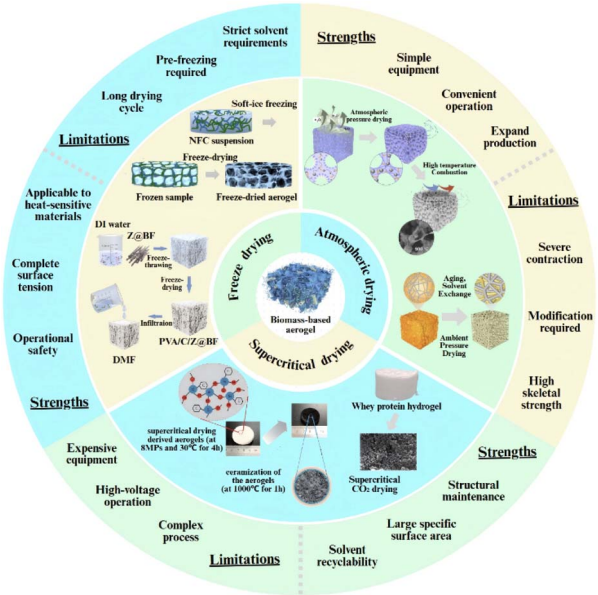

Fig. 9 Comparison of the preparation characteristics of biomass-based aerogels.

amino-rich polymer layer on the surface of bacterial cellulose during the freezing process, and then the gel was immersed in the ethanol solution containing glutaraldehyde, and solvent exchange and cross-linking were carried out through the freezing connection technology to strengthen the fiber skeleton. At the same time, combined with solvent exchange, the preparation of aerogel was achieved. The volume shrinkage of the biomass-based aerogel can be as low as 3.3% ± 1.4%, and the water resistance, thermal performance and dye adsorption performance have been improved. Tang *et al.*[63] used a triazine derivative, 4-(4,6-dimethoxy [1.3.5]triazin-2-yl)-4-methylmorpholine chloride hydrate, to form an amide bond, triggering the crosslinking and gel formation of CNF and carboxymethyl cellulose (CMC) solutions. Franon *et al.*[64] used cellulose nanofibers (CNFs) and alginate as raw materials in non-covalent chemical methods to achieve cross-linking and then combined them with a solvent exchange strategy to achieve the preparation of biomass-based aerogels at normal pressure.

Fig. 9 summarizes the advantages and disadvantages of the three main preparation methods. Supercritical drying and freeze-drying have limited the large-scale production of biomass-based aerogels due to their extreme conditions, long processing time and high energy consumption.[65] The ambient pressure drying requires mild conditions, which provides a low-cost and efficient solution for the manufacturing of cellulose aerogels, promotes the large-scale production and wide-ranging application of biomass-based aerogels, and is an important direction in current research.

4. Performance and applications

The ultimate goal of new materials is the practical application in specific fields. Therefore, after introducing the classification and preparation methods of biomass-based aerogels, this review will focus on the performance and application of biomass-based aerogels. Biomass-based aerogels have the characteristics of high porosity, good biocompatibility, and non-toxic raw materials, so they have great application potential in many aspects. The properties of pure biomass-based aerogels and functionalized modified biomass-based aerogels are different. Therefore, the following will be divided into two parts to mainly introduce the application of biomass-based aerogels in oil pollutant adsorption, heat insulation, flame retardancy and medical treatment.

It should be noted that when exploring the performance optimization strategies of biomass aerogels, it is necessary to balance the synergistic effects of surface functionalization and bulk compositional tuning. Surface functionalization (such as hydrophobic coating and plasma treatment) rapidly achieves specific functions (such as superhydrophobicity) by modifying the chemical groups on the surface of aerogels (such as –OH and –COOH), but it may sacrifice porosity or mechanical strength (for example, paraffin coating leads to a decrease in degradability). Bulk compositional tuning (such as raw material selection and crosslinking agent design) optimizes the network structure at the molecular level (for example, the amino groups of chitosan aerogel enhance the adsorption of pollutants), providing more stable performance but complex synthesis. In the field of oil stain adsorption, hydrophobic modification (surface) needs to be matched with high porosity (bulk phase) to enhance the adsorption capacity (for example, SiO_2-modified starch aerogel). In flame retardant applications, phosphorus-based flame retardants (bulk phase) and graphene coatings (surface) work in synergy to enhance the stability of the carbon layer. In this section, we will elaborate on the discussion.

4.1. Biomass-based aerogels have adsorption effects on oily pollutants

Functional groups such as –OH and –COOH on the surface of biomass-based aerogels can form hydrogen bonds with water molecules to form hydrophilic surfaces, thus enhancing the hydrophilicity of aerogels. However, to achieve the adsorption of oily pollutants, the surface wettability should be reversed, and these groups should be masked to achieve the lipophilic characteristics. Therefore, in order to achieve the adsorption of oily contaminants, biomass-based aerogels are usually hydrophobic modified by reducing surface energy and improving surface roughness.[66] Common modification methods include *in situ* method, plasma modification, and vapor deposition.[67] While –OH and –COOH are usually the main reaction groups for chemical modification methods.

Cao *et al.*[68] proposed the hydrophobic modification of aerogels with hexadecyltrimethoxysilane (HDTMS) combined with a chemical vapor deposition (CVD) method to prepare a superhydrophobic biomass-based aerogel (SBA) that can be reused for many times and has outstanding adsorption capacity in the range of 8–37.8 g g^{-1} of oil/SBAs (Fig. 10), which is a more environmentally friendly oil adsorbent. The adsorption capacity surpasses conventional polyurethane foams (3–15 g g^{-1}) yet requires solvent-intensive modification. Zhang 's team[69]

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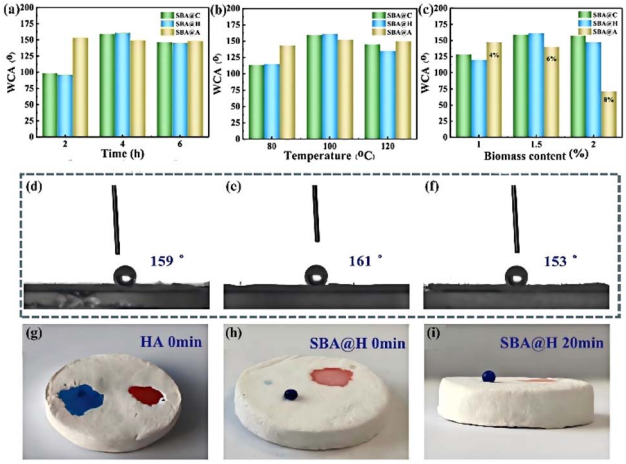

Fig. 10 (a) Effect of reaction time, (b) temperature, and (c) biomass content on the WCA of SBAs. Maximum water contact angle images of SBA@C (d), SBA@H (e) and SBA@A (f). (g–i) Permeating behavior of water and oil droplet on the material surface.[68]

proposed to combine collagen and dialdehyde carboxymethyl cellulose (DCMC) to prepare a new hydrophobic aerogel for oil/water separation. The freeze-drying method was used to modify the hydrophobicity of DCMC collagen by dip coating with mixed wax to maintain the structural porosity of DCMC-collagen and the conversion of amphiphilicity to hydrophobicity. Lin *et al.*[70] proposed a biomass-based carbon aerogel that can adsorb high-viscosity crude oil on the water surface, and then can achieve demulsification separation in an oil-in-water emulsion with the help of solar radiation, and the carbon emission of this treatment method is reduced by about 100 times compared to the traditional method.

Interestingly, Ye *et al.*[60] prepared a highly hydrophobic biomass-based aerogel by wax impregnation and coating methods and achieved hydrophobic modification of the aerogel. The aerogel with a smaller pore size and a larger specific surface area has the highest adsorption capacity, showing a high oil absorption capacity of about 27–46 times its own weight. It was found that the pore size of the aerogel could be controlled by adjusting the content of DCMC and carboxymethyl chitosan (CMCS) to promote the adsorption of different oils/organic solvents. It is an effective method to achieve large-scale and selective cleaning of marine oil pollution.

From the above, we can know that the hydrophobic modification of biomass-based aerogels is easier to achieve, and oil–water selective adsorption can be achieved through pore size design. At the same time, it can achieve biodegradability and has good elasticity. The main difference of cellulose aerogels, chitosan aerogels and alginate aerogels in terms of adsorption function lies in the difference of surface functional groups, so the adsorption mechanism and adsorption capacity for different pollutants are also different. Table 3 compares the adsorption mechanism of three aerogels. By selecting different materials based on specific application scenarios, the maximum adsorption capacity can be achieved. As summarized in Table 3, charge-specific interactions (*e.g.*, electrostatic attraction for chitosan) enable targeted pollutant removal, addressing selectivity limitations of carbon-based aerogels.

However, traditional aerogels are difficult to achieve the characteristics of biomass-based aerogels. Most of the hydrophobic modification of traditional aerogels needs to be achieved *via* chemical modification.[71] The process is difficult, and the selectivity of carbon-based aerogels is poor, and the resulting nanoparticles may cause pollution again. All these indicate that biomass-based aerogels are a good choice for the adsorption of oily pollutants (Table 4).

Although biomass-based aerogels have good adsorption capacity, its large-scale application still faces some obstacles. For example, hydrophobic modification processes often require the use of toxic solvents such as hexadecyltrimethoxysilane or high-energy technologies such as chemical vapor deposition (CVD), which increases production costs. In fact, the current demand for the adsorption of oily pollutants places high demands on rapid productivity, and current freeze-drying or supercritical drying methods cannot be achieved without significant infrastructure investment. In order to give full play to the adsorption function of biomass-based aerogels, the future work should focus on solvent free modification and continuous production processes.

The hydrophobic modification of biomass-based aerogels provides a feasible way for the absorption of oily pollutants and also environmental remediation. Selective adsorption provides a new research idea for maximizing the adsorption function of biomass-based aerogels. By selectively cleaning up pollution, the ecological environment can be better improved, so as to achieve green and sustainable development.

4.2. Application of biomass-based aerogels in flame retardancy and thermal insulation

Aerogels have a nanopore structure, which can limit molecular motion and reduce heat conduction, thereby achieving thermal insulation. However, due to the particularity of its raw materials, biomass-based aerogels usually have flammable characteristics and are extremely flammable when heated. Therefore,

Table 3 Comparison of the adsorption properties of three aerogels

Material	Cellulose aerogel	Chitosan aerogel	Alginate aerogel
Main functional groups	–OH	$–NH_2$, –OH	–COOH
Charge type	Neutral	Cationic type	Anionic type
Typical adsorption mechanism	Hydrogen bonding, van der Waals forces	Chelation, electrostatic attraction	Ion exchange and coordination
Pollutant affinity	Polar organic compounds	Heavy metal and anionic pollutants	Heavy metals, cationic dyes

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Table 4 Comparison of traditional aerogels and biomass-based aerogels in the adsorption of oily substances

Material	Traditional aerogels (such as inorganic aerogels)	Biomass-based aerogels	Reference
Hydrophobicity	Chemical modification	Easily modified	71 and 72
Adsorption selectivity	Poor selectivity	Achieved by pore size design	60 and 73
Environmental friendliness	Non-degradable	Biodegradable	16 and 23
Pliability	High brittleness	Good flexibility	74

there are few pure biomass-based aerogels reported to achieve flame retardant and thermal insulation properties. The flame retardancy of cellulose aerogels is usually achieved by alleviating the thermal decomposition process and promoting carbon formation.[75,76] Therefore, for biomass-based aerogels, more research studies have combined biomass and graphene to achieve flame retardant and heat insulation functions. However, with the development of research in recent years, an increasing number of green and sustainable preparation methods have emerged to achieve the flame retardant and thermal insulation properties of biomass-based aerogels.[77]

4.2.1. Pure biomass-based aerogel. Pure cellulose aerogels prepared by Luo *et al.*[78] using waste cotton yarn as the raw material and depositing biomass tea polyphenols on its surface have achieved solid-phase flame retardancy. The limiting oxygen index (LOI) of this aerogel (BTCA) increases with the increase in deposition treatment time and the amount of summer and autumn tea. The LOI is up to 32.7%, and it can be extinguished by itself to achieve pure biomass flame retardancy of cellulose aerogels. This LOI exceeds most pure polymers (<25%) but remains below phosphorous-modified hybrids (LOI > 50%).

However, many studies have shown that biomass-based aerogels have shown great potential in thermal insulation and flame retardancy, and research in this area still has a long way to go.

4.2.2. Functional modification of biomass-based aerogels. The common biomass-based aerogels are mostly flammable and difficult to use under high-temperature conditions. For this reason, many researchers have modified the aerogels to endow them with excellent properties such as high temperature resistance, strength and toughness.[73] There are three common flame-retardant modification methods: inorganic, organic and composite flame retardant.[67,79–81] Wang *et al.*[82] modified the whole biomass aerogel (P–HA–PA) with excellent thermal insulation and flame retardancy by using polylactic acid (PLA) as the matrix, and hydroxyapatite (HA) and phytic acid (PA) as flame retardants. Cao's team[18] used ammonium alginate (AL) and phytic acid (PA) as raw materials to prepare all-biomass-based polymer aerogels through physical crosslinking and directional freezing technology. There are many studies on the flame retardant and thermal insulation properties of biomass-based aerogels through functional modification. The modification methods are various, and the obtained aerogel materials also have many excellent properties,[83,84] which is very beneficial to broaden the application of biomass-based aerogels.

The aerogels of biomass sodium alginate and hydroxyapatite prepared by Luo *et al.*[85] were combined with graphene oxide, showing insulating properties at room temperature, while showing a conductive state at high temperatures, achieving a response within 1.5 seconds. Liu *et al.*[86] prepared a lightweight flame retardant aerogel combined with graphite and green hydroxymethyl cellulose. Through synergistic flame-retardant properties, this composite material enhances the flame retardancy of the material, exhibits excellent carbonization ability, and achieves an LOI of up to 53.5% (Fig. 11). At the same time, the low raw material cost of the biomass-based aerogel makes the material expected to achieve sustainable use, and its thermal insulation performance makes it show great potential in the application of healthy wearable devices. Wang *et al.*[87] proposed a biomass composite aerogel, which was prepared by a freeze-drying method using glucomannan, hydrophilic isocyanate, water-soluble flame retardant and water glass as raw materials and modified by a chemical crosslinking method. The total heat release rate of the composite aerogel material sample was reduced by 50.8%. Wang *et al.*[88] prepared cross-linked gelatin aerogels by a chemical cross-linking method, which have excellent flame retardant and thermal insulation

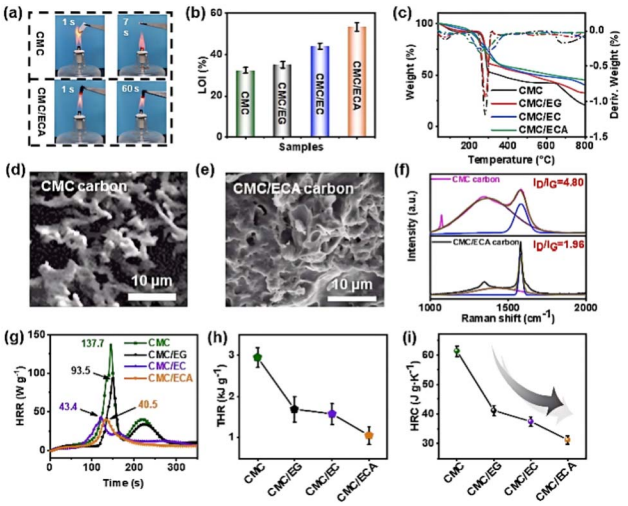

Fig. 11 Flame-retardant performance and combustion behavior of biomass aerogels. (a) Combustion test of CMC and CMC/ECA (under alcohol burner). (b) LOI values of CMC and CMC composite aerogels. (c) TG curves and DTG curves of composite aerogels in a nitrogen atmosphere. SEM images of carbon residue after combustion for CMC (d) and CMC/ECA (e). (f) Raman spectra of the aerogel after burning. HRR (g), THR (h), and HRC (i) of biomass aerogels.[86]

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properties, and achieved a conductivity of 32.8 mW (m K)$^{-1}$ and a limiting oxygen index of 29% at room temperature. The application of this aerogel under extreme conditions shows great potential.

In addition to the more conventional methods to achieve flame retardancy of biomass aerogels, in recent years, functional nanomaterials and other polymer materials have been compounded with bio-based materials, and extensive research has been conducted on the development of multi-field application-oriented functional composite aerogels by coating/impregnation, carbonization and other treatment methods. For example, metal–organic frameworks (MOFs) have transition metal centers for catalytic carbonization, which can flexibly combine organic ligands, effectively utilize biomass materials, and significantly improve the performance of their flame retardants.[89–92] Compared with MOF-integrated aerogels or organic–inorganic hybrid systems, biomass-based aerogels exhibit unique performance advantages. For example, MOF-based aerogels usually have a higher specific surface area (>2000 m^2 g^{-1}) and customizable porous structure, which are suitable for gas storage or catalytic reaction.[93] However, such systems often require complex synthesis processes and are costly. In contrast, although the performance of biomass-based aerogel is slightly inferior in extreme environments, it has outstanding advantages in sustainability and scale.

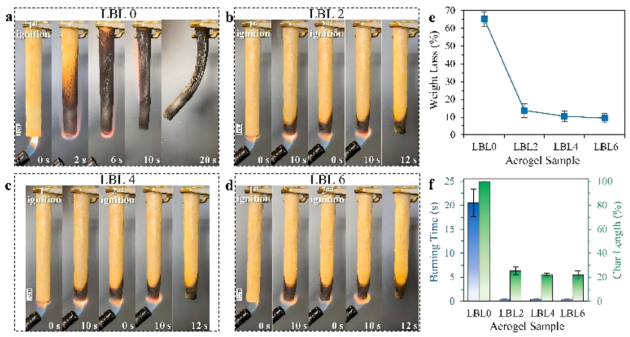

Fig. 12 Flame retardant properties of the aerogels. (a–d) Photographs of the flammability test results, which were performed by subjecting the aerogels to flames with two cycles each lasting for 10 s. The LBL-treated aerogels demonstrated excellent fire resistance with immediate self-extinguishing behaviour. (e) Weight loss during the test: LBL-treated aerogels retained most of their weight, while original aerogels experienced significant loss. (f) Burning time and char length of the aerogels during the flammability tests, indicating that 100% of the original aerogel burnt within 20 s, while the other aerogels did not show a continuous burn after removal of the fire source, and their char length was around only 22% of the original specimen length.[21]

It is worth mentioning that Varamesh *et al.*[21] deposited phytic acid and chitosan, two biomaterials with opposite charges, into the fully bio-based aerogel system and cross-linked them with citric acid. The LOI value of the aerogel obtained is as high as 63% (Fig. 12), which is the highest value of biomass-based aerogel at present. At the same time, the thermal conductivity of the aerogel developed is lower than 38.2 mW (m K)$^{-1}$, and it also has an excellent Young's modulus of up to 4.5 MPa, with very excellent performance.

From flammable biomass-based aerogels to composite aerogels[94,95] with thermal insulation effects, the performance improvement of biomass-based aerogels is mostly achieved by functional modification. Table 5 compares the relevant performance indicators of different materials, and it can be seen that the flame retardant characteristics of the functionally modified biomass-based aerogel are more prominent, and the mechanical properties of the modified aerogel are also improved. At the same time, due to the particularity of biomass materials, the sustainable development of materials has become possible, which is conducive to the realization of green low-energy development. However, it should also be noted that the commercialization of biomass-based aerogels is still limited. Compared with pure biomass-based aerogels, flame retardant additives (such as phytic acid and graphene oxide) increase the cost of materials.[96,97] Moreover, the processing time of functionalized aerogels is far longer than the production cycle of traditional thermal insulation materials. Therefore, how to transition from laboratory scale research to industrial application of biomass-based aerogels with flame retardant and thermal insulation properties is crucial.

This shows that functionalized modified aerogels will become a new development and research direction.

4.3. Application of biomass-based aerogels in the medical field

Biomass-based aerogels have excellent biocompatibility, and the biocompatibility of biomass-based aerogels stems from their surface functional groups simulating extracellular matrix (ECM). Hydroxyl and carboxyl groups promote cell adhesion and proliferation by interacting with cell membrane proteins, enhancing osteogenic differentiation. In addition, these

Table 5 Summary of relevant performance indicators of different materials

Material type	Representative materials	LOI (%)	Thermal conductivity (mW (m K)$^{-1}$)	Mechanical strength (MPa)	Reference
Pure biomass-based aerogel	Cellulose aerogel	23	15–40	0.5–6.2	28 and 98
Functionalized and modified biomass-based aerogels	LBL6	63	<38.2	4.5	21
	AL5PA1	57	34–38	25.1 ± 3.1	18
	Cu/ZIF-8@CS-MCS@BN aerogel	42.8	—	45.23	99
Inorganic aerogel	Cement aerogel	25	446.2	315.65	100
	TPP-SiO_2 aerogel	24.7	152	—	101
Mixed materials	ZIF/EP	22.4–32.1	—	—	102 and 103

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functional groups can form reversible bonds with drugs, thereby achieving a controlled release mechanism. This feature provides a possibility for medical applications. In order to better meet the needs of medical treatment, biomass-based aerogels usually need to be functionalized to achieve specific functions. Therefore, this article will mainly introduce the application of functionalized modified biomass-based aerogels in medical treatment.

Rong *et al.*[104] proposed a silk fibroin (SF)–chitosan (CS) aerogel that can be used for bone regeneration, and this aerogel can achieve pore regulation to better mimic the extracellular matrix. Functional modification enhances the mechanical strength of the aerogel and the surface becomes rougher, which is more conducive to promoting osteogenic differentiation. Later, Long *et al.*[105] also proposed a three-dimensional hierarchical silk nanofiber aerogel with nanofiber texture. This kind of aerogel can imitate the fibrous structure of the extracellular matrix and make it perfectly match with bone tissue, so as to promote the adhesion, proliferation and differentiation of bone marrow mesenchymal stem cells and achieve the purpose of bone regeneration (Fig. 13). We found that biomass-based aerogels play a certain role in promoting bone regeneration, which provides hope for the treatment of patients with bone defects. At the same time, biomass-based aerogels have also played a role in monitoring the release of dopamine from living cells stimulated by high concentrations of K^+, adsorbing lead in the human body, and constructing medical sensors.

It is worth introducing that the above-mentioned supercritical drying method has the advantages of mild, no solvent residue and stable structure, which makes the aerogel realize the application in drug treatment and show a very broad application prospect in medicine. The article of García-González *et al.*[24] mainly introduced the use of supercritical CO_2 impregnation method to load drugs into aerogels (Fig. 14) to

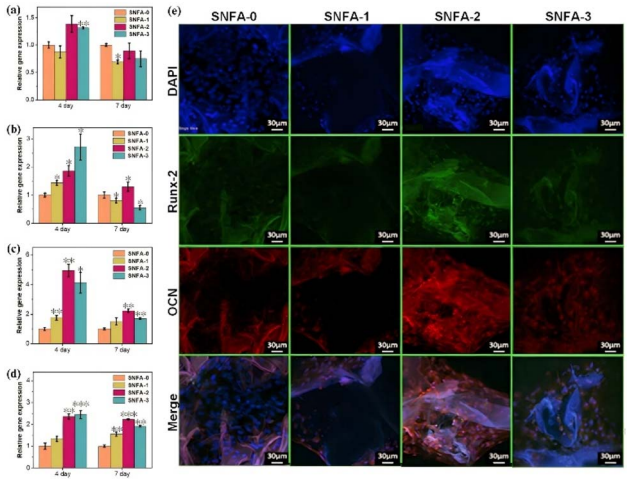

Fig. 13 (a–d) Relative gene expression of Col I, ALP, Runx2 and OCN associated with the osteogenic differentiation of rBMSCs seeded on the prepared scaffolds culture under osteogenic induction environment on day 4 and day 7, respectively. (e) Immunofluorescent staining pictures of Runx2 and OCN of rBMSCs seeded on the prepared scaffold culture under osteogenic induction environment on day 7.[105]

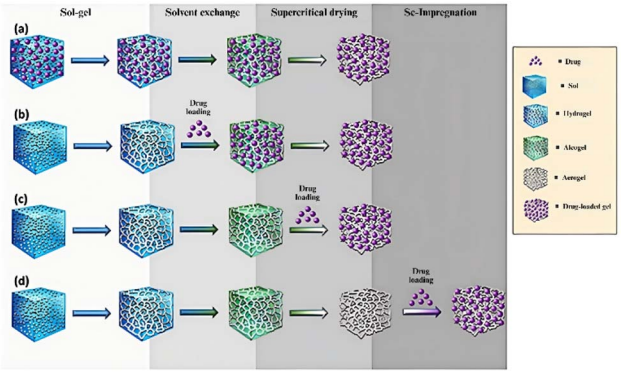

Fig. 14 Strategies to load drugs into aerogels: (a) drug added to the precursor solution; (b) drug added to the gel; (c) drug incorporated during the supercritical drying; and (d) formation of aerogel followed by drug loading.[24]

achieve controllable drug release rate and controllable release pH. This method can realize the dispersion of drugs under mild conditions without destroying the activity of drugs, and can be used for oral drug delivery, transdermal drug delivery, pulmonary drug delivery and other aspects. Alavi *et al.*[42] also proposed that curcumin can be loaded into aerogels by an impregnation method in the process of supercritical CO_2 drying. The aerogels showed controllable release behavior in a simulated gastrointestinal environment. The article proposes that the aerogels prepared by a supercritical drying method have a nanoscale pore structure, which is beneficial to improve the loading and bioavailability of curcumin.

In the study introduced above, it was also found that the preparation of biomass-based aerogels by a supercritical drying method also has broad application prospects in drug transportation. This shows the great potential of biomass-based aerogels in the medical field. Table 6 summarizes the main differences in the application of three typical aerogels in the medical field.

4.4. Application of biomass-based aerogels in other aspects

In addition to the above-mentioned main applications of biomass-based aerogels, due to the sustainable characteristics of biomass-based aerogels, the research on biomass-based aerogels has become increasingly abundant in recent years, and the related application research has also involved more and more fields. For example, Cabrera-Villamizar *et al.*[40] proposed that cannabis cellulose-based aerogels can be used as sustainable and functional packaging materials. This aerogel has developed a new material using cannabis cellulose and bioactive extracts isolated from straw, which is conducive to reducing plastic pollution and is conducive to green development. Duan *et al.*[52] modified hydrophobic nano-SiO_2 by covering hydrophobic nano-SiO_2 with methyltrimethoxy and cetyltrimethoxysilane. At the same time, due to its non-toxic raw materials, it shows great application prospects in the field of food insulation materials. In a word, the non-toxic and mild characteristics of biomass will make it play a huge potential in many fields and

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Table 6 Comparison of the application of three aerogels in the medical field

Material	Main application scenarios	Reason	Reference
Cellulose aerogel	Composite with other materials to create bone tissue engineering scaffolds	Cellulose has good stiffness and can provide mechanical support	106 and 107
Chitosan aerogel	Wound dressing	Aminoprotonation ($-NH_3^+$) destroys bacterial cell membranes	108 and 109
Alginate aerogel	Drug controlled release system	Carboxyl groups ionize and expand in the intestine (pH 7.4), releasing drugs	110 and 111

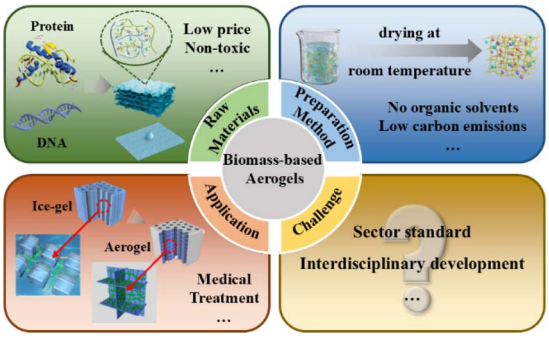

Fig. 15 Challenges and opportunities of biomass-based aerogels.

also provide a feasible way for green development and related research.

In the process of material design, although it is hoped that the performance of aerogel is good in all aspects, there is a performance trade-off between different properties, which should be focused on in practical applications. The introduction of flame retardants (such as phosphates and halogen compounds) will destroy the continuity of biomass molecular chains. At the same time, high flame retardancy usually requires the formation of a dense carbon layer to reduce the porosity. For example, a cellulose-based aerogel prepared by Zhou and others has an LOI of 46%, but its compressive modulus is only 630 kPa.[112] Therefore, attention should be paid to the contradiction between flame retardancy and mechanical strength, which can be optimized by constructing chemical or physical cross-linking networks.[21,113,114]

At the same time, there are contradictions between high porosity and mechanical strength, biodegradability of biomass-based aerogels and long-term use demand. For example, hydrophobic modification can extend the service life (such as wax coating improving water resistance), but it can inhibit degradation. In the future, controllable degradation materials can be designed through dynamic covalent bonds (such as imine bonds) to balance environmental friendliness and stability. These contradictions are all worth paying attention to, so it is necessary to balance the relationship between various properties and maximize the role of materials.

5. Conclusions

In summary, this review focuses on the classification, preparation methods and main application fields of pure biomass-based aerogels and their functional modified materials, and compares them with traditional aerogels,[93] which have significant differences and complementarities in many aspects. At the same time, the current development direction of biomass-based aerogel research is sorted out (Fig. 15). However, at present, the application of biomass-based aerogels is still mostly limited to the laboratory stage, and hence, its industrialization still has some limitations. To realize the potential of biomass-based aerogels, it is necessary to break through the standardized procedures of raw material processing, low energy consumption drying technology and other aspects to realize the industrialization of the aerogel.

5.1. Challenges in raw material selection

In terms of raw material selection, traditional aerogels have stable performance and are suitable for extreme environments, but the raw materials are non-renewable and will produce pollution during preparation. By combining biomass with other materials, materials with better performance can be obtained to adapt to more application scenarios. For example, the DNA-gelatin layered aerogel proposed by Wang *et al.*'s team[115] is formed by DNA aggregation, which achieved a light reflectivity of more than 100% in visible light and provided a tool for sustainable cooling materials. At the same time, the material

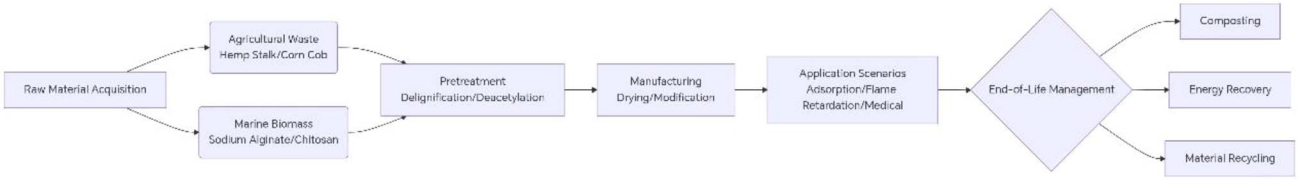

Fig. 16 Schematic of the entire life cycle of biomass-based aerogels.

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has high repairability, recyclability and biodegradability. This provides a new and researchable idea for the selection of raw materials for biomass-based aerogels. It can boldly combine low-cost and non-toxic raw materials with other materials and improve the biomass-based aerogels with insufficient thermal stability and poor rigidity to obtain some biomass-based aerogels with customized functions.

In particular, combining waste biomass (*e.g.*, corn cob, hemp) with functional nanomaterials (*e.g.*, MOFs, graphene) enables high-performance applications while reducing the environmental impact, that is, killing two birds with one stone. For example, cellulose nanotube@carboxymethyl cellulose (CNNT@CMC) composites extracted from corn cobs have a capacitance retention rate of 90% after 10 000 cycles,[116] which is comparable to synthetic materials. Future research can also quantify the impact of the life cycle to validate sustainability claims. However, it should also be noted that the performance of biomass raw materials will be affected by the environment, and the pretreatment process should be optimized to improve consistency.

However, at the same time, in the pretreatment process, the difference in biomass components such as the cellulose content in plant waste and the purity of crustacean chitin will lead to inconsistencies in aerogel properties, and a unified standard can be formulated for biomass purification to ensure batch-to-batch consistency. In terms of raw material costs, through cooperation with other industries, relatively low-cost raw materials such as bagasse marrow and shrimp shell waste[117,118] can be obtained to reduce the production costs. From the above-mentioned aspects, it lays the foundation for the industrialization of biomass-based aerogels.

5.2. Challenges in preparation technology

At present, the main problem encountered in the industrialization of biomass-based aerogels is that energy-intensive drying methods dominate in production and the preparation process can be further optimized, such as how to apply atmospheric pressure drying to large-scale production. At present, relevant research in the laboratory is gradually developing toward room-temperature and organic solvent-free conditions, and we should think about how to achieve a good transition from laboratory scale to industrial mass production, which is expected to reduce the cost and increase the efficiency of the preparation process while ensuring performance and conform to the trend of low-carbon emissions and green development. At the same time, it is conducive to solving the problems of complex process and high energy consumption in the traditional aerogel preparation process.

5.3. Challenges faced by applications

From the perspective of application, the stable chemical properties of traditional aerogels make them still play an irreplaceable role in aerospace, electronic devices and other applications. The surface functional groups of biomass-based aerogels such as –OH, –COOH, and $-NH_2$ make them very important in adsorption and medical applications. Future research should focus on optimizing the density and distribution of these functional groups to enhance specific functionalities. At the same time, how to balance the cost and performance as well as the contradiction between each performance is an important step to realize the industrialization of biomass-based aerogels.

5.4. Other challenges

5.4.1. Synergy between biomass-based aerogels and other materials. The synergistic application of biomass-based aerogels and metal–organic frameworks (MOFs) has greatly improved the performance of the material,[119–121] but it is worth noting that the addition of MOFs will increase the production cost, and how to combine the two materials to give full play to their respective usefulness in the process of material preparation is also a challenge for the future development of biomass-based aerogels. Cao *et al.*[122] proposed that Zr^{4+} on MOF and –COOH on CMC are coordinated to form aerogels on CMC, and heavy metal ions are removed *via* electrostatic attraction and chelation between Pb(II) and –COOH, which not only solves the problem of difficult recovery of MOFs, but also improves the adsorption capacity of PB(II). Li *et al.*[123] used the physical interaction between cellulose aerogels and MOFs to anchor metal–organic frameworks (MOFs) on the surface of cellulose nanofibers (CNFs) aerogels (MOF-CNFs), enhancing their adsorption capacity for CO_2. At the same time, there are methods such as anchoring amino functionalized ZIF-8 to cellulose aerogel[124] by an *in situ* growth method, and the specific functions of materials obtained by different preparation methods are also different, so the study of the combination of two different materials also provides a feasible idea for the design of new materials.

5.4.2 Life cycle assessment (LCA) and biodegradability. Biomass-based aerogels have broad development prospects, and can be improved and optimized from many aspects to maximize the function of the material, and the material will also be expanded to more application scenarios in the future. Biomass-based aerogels can be verified through a full life cycle assessment (LCA), covering stages such as raw material acquisition, preparation, use, and disposal (Fig. 16). In the carbon emissions at the raw material stage, when agricultural wastes such as hemp stalks[40] and corn cobs[116] are used as raw materials, the carbon emissions are reduced by more than 50% compared with traditional silicon-derived aerogel. In the pretreatment process, the energy consumption for lignin removal accounts for 30% of the total. It is necessary to develop low-temperature biological enzyme methods (such as laccase) to replace alkaline treatment.[113]

In the function-degradability trade-off during the usage stage, for instance, the cetyltrimethoxysilane (HDTMS) coating extends the degradation cycle from 3 months to more than 2 years.[68] The phosphorus content in the soil increased by 0.8 mg kg^{-1} after degradation by a phytic acid (PA)-modified aerogel.[82] In scrapping management, the aerogel adsorbed by oil stains can be converted into energy *via* anaerobic digestion. In addition, the metal was recovered by acid treatment with MOF

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composite aerogels (such as Zr^{4+}-CMC[122]), with a Zr recovery rate of over 92%. Chitosan aerogel with chitinase-responsive chains added has a controllable degradation rate within 30 to 120 days.[105] The weight loss rate of starch/cellulose-based aerogel was over 80% after 21 days under industrial composting conditions (58 °C).[118] Life cycle assessment reveals that the physicochemical process of raw material waste and atmospheric pressure drying can reduce carbon emissions by 40%, but the inhibition of degradability by surface modification needs to be balanced. In the future, an LCA database will be established and enzyme-triggered controllable degradation technology will be developed to achieve a sustainable 'cradle-to-cradle' closed loop.

Author contributions

X. Y.: conceptualization, data curation, investigation, writing – original draft. W. M.: investigation, data curation, writing – original draft. X. S.: investigation. Y. P.: project administration, funding acquisition. All the authors discussed the results and reviewed the manuscript.

Conflicts of interest

There are no conflicts to declare.

Data availability

No primary research results, software or code have been included, and no new data were generated or analysed as part of this review.

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