The Journal of Green Energy and Environmental Engineering

Review Paper

Research Progress on the Preparation of Bio-Based Aerogels and their Application in Food

Bonitz Gessner[1,*], **Suman Ashish**[1], **Mohan Alsharaeh**[2,*]

[1] Center for Microtechnologies, Chemnitz University of Technology, Reichenhainer Str. 70, D-09107 Chemnitz, Germany
[2] Faculty of Civil Engineering and Architecture, Kaunas University of Technology, Kaunas LT-44249, Lithuania
*Corresponding author: MohanAlshish@zfm.tu-chemnitz.de

Abstract. Bio-based aerogel is a lightweight, porous and high specific surface area nanomaterial prepared from natural biomacromolecules, which has shown great potential for application in the food field in recent years.Bio-based aerogels exhibit excellent adsorption, sustained release, and biocompatibility. In this paper, the preparation methods of bio-based aerogels, including the types of raw materials, the mechanism of the sol-gel method and the drying process were systematically reviewed. The physical and functional properties of bio-based aerogels were discussed. The applications of bio-based aerogels in food preservation mats, food freshness indication labels, nutrient delivery carriers, and fat in artificial meat substitutes were summarized. In addition, the challenges of bio-based aerogels in terms of large-scale production, food safety and consumer acceptance were discussed, and the future development of bio-based aerogels in functional food and industrial production were prospected.

Keywords: *Bio-based aerogel; sol-gel method; water absorption and water stability; freshness pads; artificial meat fat substitutes*

Received on 02 March 2024, Accepted on 28 May 2024, Published on 15 July 2024

1 Introduction

Aerogels—ultra-light nano-porous solids—were first reported in the early 1930s when Kistler fabricated SiO_2 aerogel from a silica-gel precursor [1]. Usually built from inorganic networks—polyaniline, polyimide, polyurea, or silica—these solids offer huge surface areas, extreme porosity, minimal density, a high refractive index, and low values for both dielectric constant and thermal conductivity [2-5].Lately, as industries chase greener footprints, bio-sourced aerogels have rocketed to the top of the global R&D agenda.These plant-derived foams are born when the liquid in a wet gel is swapped out for a gas—typically CO_2—yielding an ultralight, pore-filled solid. A broad palette of biopolymers—think starch, cellulose, alginate, pectin, engineered cellulose derivatives, whey, or even egg-white proteins—can be coaxed into such airy networks.These polymers are plentiful, green, non-toxic and renewable, so labs routinely enlist them for food-grade aerogel projects.Using biopolymers as the base for bio-based aerogels can effectively overcome the brittleness of inorganic aerogels. Furthermore, modifying polymer molecules can regulate the properties of bio-based aerogels, thereby broadening their application scope[6].

In recent years, with advances in green manufacturing technology and the popularization of sustainable development concepts, research on the application of bio-based aerogels in the food field has gradually increased. This paper reviews the types of base materials and preparation methods of bio-based aerogels, and summarizes their applications in four aspects: food preservation pads, food freshness indication labels, nutrient delivery carriers, and fat substitutes in artificial meat. It also discusses the challenges faced and future development directions.

2 Substrates for Bio-based Aerogels

2.1 Polysaccharides

Polysaccharides are natural biomass materials, consisting of sugar chains formed by at least 10 monosaccharides linked by glycosidic bonds. These sugar-built foams are ultra-porous, feather-light, surface-rich and fully compostable—traits that make them highly attractive for food-tech uses. Thermogravimetric experiments have shown that polysaccharide aerogels have excellent high-temperature resistance and can be used for food insulation packaging. Furthermore, polysaccharide-based aerogels expose more functional groups on the aerogel surface, exhibiting excellent absorption and loading capacity for functional active compounds, and have the ability for targeted delivery, improving the bioavailability of loaded substances and protecting them from environmental influences[7]. In recent years, common polysaccharide types for polysaccharide-based aerogels include starch, pectin, cellulose, chitosan, and sodium alginate.

2.1.1 Starch

Starch, nature's most common sugar chain, is harvested from everyday crops—wheat, maize, rice, cassava, potato, soybean. When converted into an aerogel it becomes a 3-D lattice that weighs almost nothing (0.02-0.10 g cm^{-3}), hides ~90 % empty space, and exposes up to 197 m^2 of surface in every single gram.Compared to other bio-based aerogel preparation processes, starch-based aerogel preparation includes additional steps of starch gelatinization and retrogradation. Figure 1 shows the preparation steps of starch-based aerogel. Gelatinization temperature and retrogradation time are the core parameters in the starch aerogel preparation process[9]. Starch is heated in water to form a gelatinized solution, which, upon cooling, forms a hydrogel through molecular chain recombination[10].Next, water inside the hydrogel is swapped for a low-surface-tension fluid—ethanol is typical—to curb shrinkage, after which the sample is dried to lock in the starch scaffold.

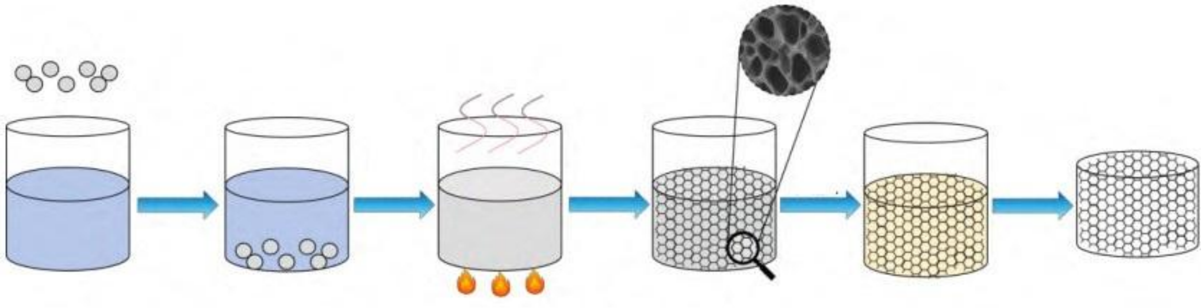


Figure 1 Starch-based aerogel preparation steps[11]

How the starch lattice looks and behaves hinges on the botanical origin of the starch, its amylose/amylopectin balance, and any extra ingredients tossed into the mix.Maize-starch foams show a smooth, open 3-D mesh, whereas pea-starch versions carry chunkier pore walls because their voids vary widely in size.A high amylose content usually enhances the mechanical properties of starch aerogel. Studies have shown that starch aerogel prepared from pea starch with 40% amylose content has the highest specific surface area; as the amylose content increases, the specific surface area of the starch aerogel increases and it exhibits anti-volume shrinkage properties[14]. The main drawback of starch aerogel is its poor mechanical properties, which can be improved by using physical or chemical crosslinking agents. Sodium citrate, as a chemical crosslinking agent, can increase the hardness of starch aerogel and reduce its adhesion[15]. Crosslinked starch aerogel has uniform pore distribution and a 15% increase in crystallinity[16]. Starch aerogel,relying on its biodegradability, tunable functionality, and wide applicability, shows great potential in fields such as food, medical care, and environmental protection.

2.1.2 Pectin

Pectin, a sugar chain cocktail embedded in plant cell walls, is non-toxic, body-friendly and compostable, so aerogels made from it are popular carriers for drugs and edible wraps.Pectin foams assemble into a 3-D lattice that is nearly weightless (0.04–0.15 g cm^{-3}), hides >90 % empty space and exposes a sprawling 270–600 m^2 of surface per gram.These pectin scaffolds are laced with nano- to micro-scale pores, a bimodal maze that blocks heat and meters out drugs with equal precision. Pectin aerogel has certain mechanical strength, with a compressive modulus between 4 MPa and 18 MPa, and can withstand large deformations within a certain range without damage[20]. However, the mechanical strength of pure pectin aerogel is low, which can be alleviated by compounding with other materials or adding metal oxide nanoparticles. Li Feifei's team boosted a pectin foam with TiO_2 nanoparticles, ramping its tensile strength 5.3-fold and its Young's modulus 4.2-fold. With a conductivity hovering around 0.015 W m^{-1} K^{-1}, the pectin lattice rivals conventional insulators.In moist air the foam drinks water, swells and eventually collapses, forfeiting its insulating power; water-repelling tweaks slow the damage, yet long-haul durability remains an open question.

2.1.3 Cellulose

Cellulose, the planet's most plentiful biopolymer, is locked inside plant cell walls and can be freed by mechanical grinding, chemical pulping or enzymatic digestion.This renewable, compostable and eco-friendly chain can be puffed into aerogels that are >90 % empty space and weigh only 0.001–0.3 g cm^{-3}. Currently, lignocellulosic materials have been proven suitable for developing aerogels[24-26]. Cellulose materials can be extracted from by-products of agriculture and forestry, such as fruit shells, leaves, stems, and seeds. Cellulose aerogel possesses a sturdy porous architecture; however, prolonged immersion allows water molecules to penetrate and disrupt the fragile intermolecular interactions—especially hydrogen bonding—causing the aerogel to disintegrate and become suspended in the liquid. TTo block water uptake and keep the scaffold intact when wet, a thin polymer skin is routinely wrapped around the cellulose, turning its surface from water-loving to water-repelling.

2.1.4 Chitosan

Chitosan aerogel is a 3-D porous scaffold whose framework is built from chitosan—chitin that has been stripped of its acetyl groups.Chitosan aerogel combines the lightweight and high porosity (97%) of aerogels with the biodegradability and biocompatibility of chitosan[27]. Chitosan aerogel's backbone is studded with $-NH_2$ and $-OH$ handles that can stitch chains together either physically or via aldehyde chemistry, weaving a continuous nano-net. The resulting solid is feather-light (≤0.06 g cm^{-3}), leaves only ~3 % of its volume as matter, and hosts pores that span angstrom-scale micropores to micron-scale macropores.Pure chitosan aerogel has relatively poor mechanical properties; a common method is to introduce components such as sodium lignosulfonate, phytic acid, or silicon dioxide to optimize mechanical strength, adsorption performance, or environmental responsiveness. The study by ZHAO Jin et al. found that the compressive strength of pure chitosan aerogel was about 12.8 $kPa\cdot cm^3\cdot mg^{-1}$; after adding sodium lignosulfonate, it increased to 37.3 $kPa\cdot cm^3\cdot mg^{-1}$[29]. Research on composite chitosan aerogels and chitosan aerogels in the food field has gradually shifted from basic performance exploration to functionalization and industrialization.

2.1.5 Sodium Alginate

Sodium alginate is a linear chain of β-D-mannuronate and α-L-guluronate sugars stitched together end-to-end through 1,4-ether links.The backbone is crowded with $-OH$ and $-COO^-$ handles that love water, yet the whole chain is green—safe for cells, vanishes harmlessly, and leaves no trace. Freeze-dry it and you get an airy solid that is 95.6 % empty space, with cavities from nano-slits (≈13 nm) to micron chambers (≈2 µm) and an internal surface that reaches 80 m^2 per gram. The compressive strength of sodium alginate aerogel increases with the concentration of sodium alginate and the addition of reinforcing agents. The sodium alginate aerogel studied by CHENG Yi had a strength of 40 kPa, and the sodium alginate-methylene bisacrylamide aerogel had a strength of 80 kPa[33]. Freeze-dried alginate scaffolds block heat at just 0.029 W m^{-1} K^{-1}—outperforming common rubbers and plastics—and their fire resistance can be pushed even higher by embedding nano-clay platelets.

2.2 Proteins

Proteins are one of the ideal substrates for bio-based aerogels. Proteins have advantages such as degradability, biocompatibility, molecular designability, hydrophilicity, hydrophobicity, and gelation properties, making protein aerogels applicable in different fields[35]. Protein aerogels usually have porosity exceeding 90%, making them outstanding in adsorption, catalysis, and drug delivery[36]; Proteins have advantages[37]; Modified protein aerogels have increased mechanical strength and are suitable for food packaging and biomedical fields[38]. Natural protein aerogels are brittle, and some may collapse at high temperatures, requiring performancein structure modification (performance improvement through structural modification). Common structural modification techniques include two methods: first, enzymatic crosslinking technology. XIA Tianli et al. used transglutaminase to modify whey protein aerogel, increasing the compressive modulus to 14.5 MPa and making the pore size more uniform[39]. Second, the composite reinforcement material method, adding microcrystalline cellulose or carbon nanotubes to enhance mechanical strength and thermal stability[40].

2.3 Modified Fibers

Modified cellulose is processed to the micron or nanometer level by modifying natural cellulose through mechanical, chemical, or biological methods, with chemical modification being the most common, including esterification, etherification, sulfonation, graft copolymerization, etc[41]. Modified cellulose includes nanocellulose[42], carboxymethyl cellulose, etc. These modified celluloses have unique physical and chemical properties[43], such as solubility, thermal stability, biodegradability, and excellent mechanical properties[44].

2.3.1 Nanocellulose

Built on a nanocellulose frame, the aerogel weighs only 1 mg cm^{-3} and is 99.8 % empty space. Its enormous internal surface turns the entire scaffold into an active membrane, amplifying interfacial reactivity far beyond bulk cellulose.Nanocellulose aerogel also exhibits high strength, high toughness, and good compression recovery ability[46]. The nanocellulose aerogel prepared by WANG Xiaoyu et al. achieved a compressive strength of 0.913 MPa, far superior to traditional silica aerogel, combining flexibility and elasticity [47]. Due to its nanoscale size, nanocellulose has good biodegradability.

2.3.2 Carboxymethyl Cellulose

Carboxymethyl cellulose is a water-soluble derivative obtained after carboxymethyl modification, rich in carboxyl groups, possessing chemical modifiability and biocompatibility[48]. Carboxymethyl cellulose aerogel has the renewable and biodegradable characteristics of natural polysaccharides. Sol–gel chemistry followed by gentle drying weaves a nano-honeycomb that tips the scale at only 0.0196 g cm^{-3} yet leaves 98.7 % of its volume as air, delivering surprisingly high mechanical strength for so little solid.Touron's group found that locking silver nanowires inside a carboxymethyl-cellulose matrix stiffens the network by a factor of 71 compared with the nanowire aerogel alone.Carboxymethyl cellulose further acts as a flexible glue, markedly lifting the foam's resistance to compression. The compressive strength of the carboxymethyl cellulose/gelatin composite aerogel by GONG Ling et al. reached 3.03 MPa[50]. Carboxymethyl cellulose-based aerogels have better thermal stability and flame retardancy at high temperatures than traditional aerogels. For example, carboxymethyl cellulose/zinc-aluminum layered double hydroxide composite aerogel exhibits better thermal stability and flame retardancy[51].

3 Preparation of Bio-based Aerogels

The key points in preparing bio-based aerogels are two-fold: first, forming a three-dimensional network structure wet gel by regulating pH, temperature, or ion crosslinking (such as Ca^{2+} induced alginate gelation), a process called the sol-gel method. Second, drying the wet gel while preserving the gel's network structure. To make the wet gel, the biopolymer is first dissolved in water; once gelation starts, chemical reagents, physical triggers, or enzymes knit the chains into a continuous 3-D mesh.Drying simply evicts the pore liquid while leaving the solid skeleton intact, turning the delicate hydrogel into a stable, bio-sourced aerogel.

3.1 Sol-Gel Method

At the heart of aerogel synthesis lies the sol-gel switch: a fluid colloid is coaxed into a continuous solid web.Step one of the sol-gel route is to pick a solvent—water, ethanol, or an ionic liquid—that both dissolves the precursor and nudges it toward gelling.The second step is sol formation, where intermolecular hydrogen bonds in the precursor solution are disrupted by physical or chemical methods to form a uniformly dispersed sol[53]. The third step is sol gelation, where the sol undergoes polycondensation and crosslinking reactions triggered by pH adjustment, temperature change, or catalyst addition, leading to gelation and the formation of a wet gel with a three-dimensional network structure. pH value, temperature, and reaction time affect the porosity and mechanical strength of the gel. The fourth step is aging, where the wet gel is left standing in solution for several hours to days, enhancing the network structure through Ostwald ripening and improving stability[54]. Step 5 swaps the pore water for a low-tension fluid like ethanol or acetone, cutting capillary pressure so the lattice survives the final drying step without caving in.The sol-gel method allows precise control over the pore size, porosity, and specific surface area of the aerogel. This method allows uniform mixing of the sol and can produce high-purity, nanoporous materials. Most reactions occur at room temperature or low temperature, resulting in low energy consumption. The only drawback of this method is the long cycle time, as sol formation, gelation, and aging can take several days. Thanks to its flexible chemistry and tunable architecture, sol-gel processing has become the go-to route for aerogels—an unrivaled tool when the scaffold must be built from biomass.

3.2 Drying Process

No step matters more than drying: how the liquid is removed decides whether the 3-D lattice stays intact, how strong it becomes, and what functions it can deliver.Picking the right drying strategy is therefore critical; freeze-drying and supercritical CO_2 extraction remain the two workhorse techniques.

3.2.1 Freeze-drying

Freeze-drying locks the pore liquid into ice crystals, then drops the pressure so the solid skips the liquid phase and exits as vapor, leaving the aerogel behind.Because ice sublimes without surface-tension drag, the scaffold stays intact—ideal for temperature-sensitive biopolymers.During the pre-freezing process, ice crystals form within the gel network structure. The continuously growing ice crystals can damage the gel channels, creating large voids inside the gel. Yet the same freeze front can set up steep thermal gradients that rip pore walls, denting the final architecture. To keep ice crystals dwarf-sized, labs dunk the wet gel straight into liquid nitrogen; the ultra-rapid chill makes nucleation outrun crystal growth, so only tiny ice seeds form inside the pores.

3.2.2 Supercritical CO_2 Drying

Supercritical CO_2 drying is currently the best method for preparing aerogels. It involves controlling pressure and temperature to bring CO_2 to its critical point, displacing the solvent in the gel until the fluid mixture in the pores is entirely in a supercritical state[57]. After restoring ambient pressure, a porous, disordered, low-density aerogel material with a nanoscale continuous network structure is obtained[58]. Although supercritical CO_2 drying can preserve the original gel structure, form smaller pores suitable for controlled release, and remove the solvent completely, the production cost is high, and more processing steps are required to ensure the stability of the wet gel and solvent replacement.

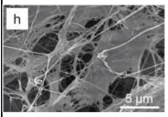
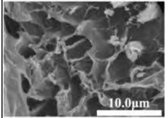
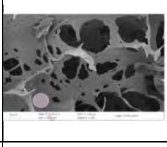
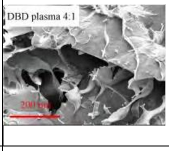
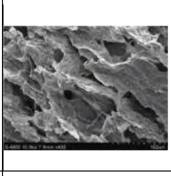
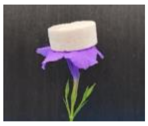
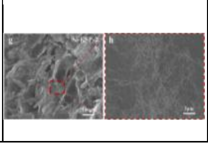
4 Physical Properties and Functional Characteristics of Bio-based Aerogels

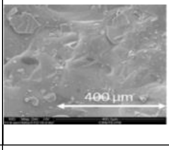
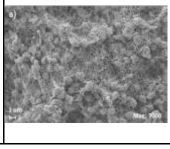
Bio-aerogels are judged first by their physical profile—shape, nanoscale texture, and load-bearing capacity—and second by how they handle water: uptake capacity and wet-state durability.Both the skeleton and the service life of a bio-aerogel are set by four knobs: which biopolymer is chosen and at what dose, how the chains are stitched together, how the liquid is removed, and every twist in the processing recipe.

4.1 Morphology and Microstructure

The properties of bio-based aerogels largely depend on their morphological and microstructural characteristics. These are crucial for optimizing performance, ensuring biocompatibility, improving mechanical properties, and fine-tuning composite delivery systems.

The morphological characteristics of bio-based aerogels include macroscopic morphology, surface morphology, and pore structure. At the macro level, it typically presents as a low-density, highly porous solid, manifesting in diverse geometries such as monoliths, thin films, fibrous mats, or particulate powders [59–61].Table 1 summarizes the morphological features and corresponding uses of various bio-sourced aerogels; both the external shape and the internal pore architecture dictate where these materials can be deployed.Monolithic shapes are preferred for heat-barrier layers and load-bearing scaffolds.Scanning electron microscopy shows the aerogel is laced with a continuous, three-dimensional lattice of micron- and nano-pores that interpenetrate throughout the matrix [62].Porosity is the hallmark of bio-sourced aerogels, defined by nano- to micro-scale dimensions, either narrow or broad size distributions, and geometries that range from perfectly spherical to highly irregular [63–64]. How pores are sized, shaped, and distributed governs both the uptake capacity and the heat-transfer resistance of plant-derived aerogels.Table 1 Morphology and application of different bio based aerogels

Substrate	Surface Morphology	Pore Structure	Preparation Method	Density	Application	Reference
Cellulose			Freeze-drying	0.031 g/cm³	New heat-resistant material replacing fossil-based polymer foams	[65]
Chitosan, Polyvinyl Alcohol			Freeze-drying	0.024 g/cm³	New acoustic material for thermal insulation/sound absorption	[66]
Gelatin, Gum Arabic			Freeze-drying	0.06 g/cm³	Real-time monitoring of shrimp freshness as intelligent packaging	[67]
Xanthan Gum, Egg White Powder			Freeze-drying	0.081± 0.006 g/cm³	New thermal insulation material for chicken packaging	[68]
Cellulose Nanofiber, Polyvinyl Alcohol			Freeze-drying	0.017 g/cm³	Food preservation mat for water/oil absorption and extending meat shelf life	[69]
Cellulose, Sodium Alginate			Freeze-drying	0.06603 g/cm³	New thermal insulation and flame-retardant material	[70]

Substrate	Surface Morphology	Pore Structure	Preparation Method	Density	Application	Reference
Sodium Alginate			Supercritical CO_2 Drying	0.043 g/cm^3	Controlled release of adsorbed β-carotene	[71]
β-Glucan			Supercritical CO_2 Drying	0.0348 g/cm^3	Loading and release of acetylsalicylic acid	[72]

4.2 Mechanical Properties

At the molecular scale, the cross-link topology governs the mechanical signature of biomass aerogels.These plant-derived aerogels withstand compressive loads in the 0.1–5 MPa window.Mechanical performance maps directly onto the aerogel lattice: coarser pores translate into lower load-bearing capacity. For example, when xanthan gum/agar aerogel has a porosity of 94%, its specific modulus can still reach 4.77 MPa[75]. In addition, the mechanical response is dictated by the inherent traits of the biomass feedstock. Studies have found that the compressive performance of pullulan aerogel improves with the increase of precursor material mass concentration[76]. Adding crosslinking agents to the biopolymer matrix can effectively improve the mechanical strength of the aerogel by regulating the crosslinking density and method. Common crosslinking agents include chemical crosslinkers, physical crosslinkers, enzymatic crosslinkers, natural crosslinkers, and composite crosslinkers. Through reasonable selection and optimization of crosslinking agents, the mechanical properties and functional characteristics of bio-based aerogels can be regulated to meet different application needs.

4.3 Water Absorption and Water Stability

Uptake and wet-stability dictate service life; when soaked in DI water these networks swell to roughly twenty times their own mass [77].Upon first wetting, polar sites draw water in, triggering swelling; the advancing front then meets hydrophobic domains that resist further hydration.Balancing non-covalent and covalent contacts between water and hydrophobic segments stabilizes the skeleton and imparts recoverable elasticity. Maximum uptake is reached when the rates of water imbibition and retention converge to equilibrium. Beyond that threshold, continued swelling compromises the lattice integrity [78].The water stability of aerogels is related to crosslinking treatment. The soaking method is commonly used to study the water stability of bio-based aerogels. Crosslinked aerogels can maintain their original morphology in water for a long time without easily collapsing or decomposing. In contrast, uncrosslinked aerogels, after a period in water, due to excessive water absorption, have their three-dimensional network structure destroyed. Aerogels prepared by chemical crosslinking form a stable and durable network through covalent bonds, are not easily destroyed by water, and are suitable for long-term applications. Physical crosslinking (such as hydrogen bonding) has a lower degree of crosslinking, poorer stability, and is prone to failure in aqueous

4.4 Nutrient Delivery Carriers

With the growth in demand for healthy nutrition and the expansion of the functional food and nutritional supplement market, many functional ingredients (such as vitamins, minerals, probiotics, antioxidants) are prone to inactivation or degradation during processing, storage, and digestion, leading to reduced bioavailability. Bio-based aerogels, due to their unique properties, have become ideal nutrient delivery carriers. Bio-based aerogels load functional components through methods such as physical adsorption, chemical bonding, or embedding. Bio-based aerogels can themselves serve as a source of dietary fiber and also as delivery carriers for prebiotics or probiotics[110]. As nutrient delivery carriers, bio-based aerogels possess excellent delivery properties such as sustained-release performance, protective performance, and targeting performance. Clare et al. used corn starch aerogels to encapsulate Fe^{2+} and folic acid, improving their bioavailability. By rationally designing and optimizing the loading methods, delivery performance, and preparation process of bio-based aerogels, efficient loading, targeted delivery, and precise release of functional ingredients can be achieved, promoting their industrial application in the food and pharmaceutical fields.

4.5 Fat Substitutes in Artificial Meat

As global demand for meat climbs year-on-year, innovation in meat analogues has moved to the forefront of food-science priorities.Studies on artificial meat have largely concentrated on red-meat alternatives, leaving the replacement of animal fats comparatively under-investigated. Oleogels have been floated by several teams as lipid stand-ins, trimming saturated and trans fats to deliver healthier formulations.Aerogel-templated oleogels lock in large volumes of oil and keep it from bleeding out.A brief dip of the aerogel in oil is enough for surface tension and capillary suction to convert it into an oleogel.Capillary pull drags oil molecules into the aerogel’s pores, where surface forces trap them both within the network and on the outer particle skins.Experiments report that one gram of aerogel routinely soaks up more than two grams of oil.Plazzotta’s team, for instance, demonstrated this with an oleogel assembled from whey-protein aerogel clusters. the oil outweighed the aerogel itself by more than fivefold.After high-speed spinning, the gel stayed oil-tight and mimicked the pliable, spreadable texture of standard solid fats.Advances in technology and deeper research have enabled bio-based aerogels that replicate the mouthfeel of fat to be incorporated into reduced-fat dairy and meat items.

5 Starch-based Aerogels and their Application in Food Packaging

Packaging shields fresh or processed foods from oxidation, microbes, and bumps; cheap, high-barrier plastics still dominate the market. Yet these same plastics are petroleum-bound and refuse to break down, so every wrapper outlives the snack it protected.Films spun from proteins or polysaccharides rot away naturally, giving packagers a compost-ready alternative. Among them, starch is abundant in resources and has good biocompatibility. The high density of hydroxyl groups it contains can form intra- and intermolecular hydrogen bonds with other components in packaging materials, making it an ideal source for food packaging materials[4].

An aerogel is born when the liquid in a hydrogel is gently removed, leaving behind a feather-light, porous solid.Its huge internal surface, open pores, heat tolerance, and ability to hold water make the ultralight solid a promising wrapper candidate. Since starch is widely sourced, renewable, and abundant, using appropriate and cost-effective drying methods can produce low-cost, biodegradable aerogel packaging materials[5]. During the preparation of starch-based aerogels, various shapes and sizes can be produced according to the selected molds, and more complex structural designs can be achieved by combining processing technologies such as granulation and 3D inkjet printing, showing broad application potential in practical production and use[6] (Fig. 2a). Furthermore, compared to starch films prepared by the casting method, aerogels retain a unique internal porous network structure (Fig. 2b). This structure gives them low density and also provides good thermal insulation, which is particularly important for food packaging requiring temperature control[8]. Strong water absorption capacity also allows aerogels to absorb exuded liquids from food, providing a relatively dry environment conducive to preservation[9]. This article reviews the preparation methods of starch-based aerogels, analyzes the main factors influencing their preparation, discusses recent applications in food packaging, and finally points out development trends and challenges faced by starch-based aerogels in the food packaging field.

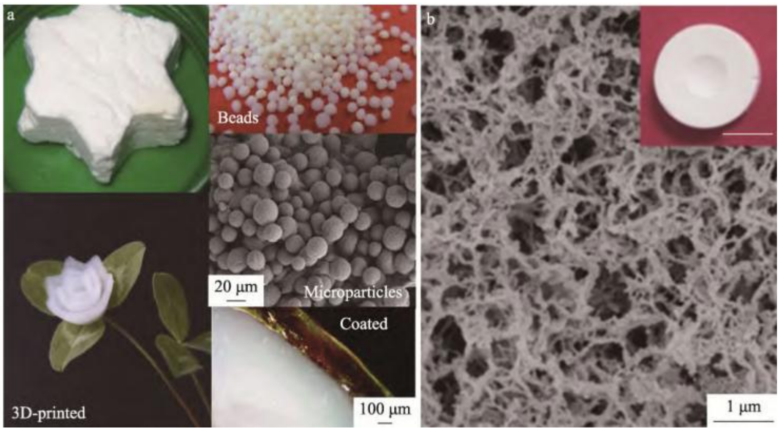


Figure 2 Starch-based aerogels of various sizes and shapes (a)[6] and microstructure of starch-based aerogels (b)[7]

Starch is a glucose-chain polysaccharide that comes in two architectural flavors: linear amylose and branched amylopectin. Amylose is a straight-chain polymer of D-glucose units joined end-to-end via α-(1→4) linkages.Amylopectin packs extra branches: a linear α-(1→4) backbone sprouting side-chains through α-(1→6) junctions.Inside each starch granule, amylose fills the disordered layers while amylopectin builds the neatly stacked crystalline sheets.

When starch granules are heated in water to a certain temperature, they swell, accompanied by the leaching of amylose, the disruption of the ordered crystalline structure, and the rupture and collapse of the starch granule structure; this process is called starch gelatinization[11]. Gelatinized starch undergoes structural reorganization upon cooling to a certain temperature, where starch molecules reorder and form a certain degree of crystallinity; this is the retrogradation phenomenon. During this period, starch molecular chains intertwine to form double-helix structures and subsequently form the spatial network structure characteristic of gels[12]. The type and content of starch, as well as the presence of small molecules and macromolecular polymers, can all influence the gelatinization and retrogradation of starch, thereby affecting the properties of the gel[13]. For salt solutions, some ions present in the solution carry positive or negative charges and may generate electrostatic interactions with the hydroxyl groups of starch[14]. This interaction can alter the binding state between starch molecules and water and hinder the formation of hydrogen bonds between starch molecular chains, thus affecting starch gelatinization and retrogradation[15]. Some low molecular weight polysaccharides like mono/disaccharides, due to their good hydrophilicity, compete with starch for water during gelatinization, reducing water availability[16-17]. Furthermore, high molecular weight polysaccharides usually delay the retrogradation process of starch. This is because they contain more hydrophilic groups and have larger molecular volumes, which can immobilize water molecules and increase the concentration of starch molecules in the continuous phase, thereby hindering the movement of starch molecules and reducing the possibility of recombination between amylose and amylopectin during retrogradation[18-19]. However, a well-controlled gelatinization and retrogradation process is key to preparing high-performance starch-based aerogels. Therefore, investigating the gel properties is crucial for the preparation of starch-based aerogels.

The preparation of starch-based aerogels generally follows the traditional aerogel preparation method, namely the sol-gel process. This process includes key steps such as raw material dissolution, mixing or polymerization, gelation, and drying; except for drying, the other steps can be categorized as the preparation of starch-based hydrogels. The solvent casting method is commonly used to prepare blocky starch-based aerogels (Fig. 3a). Starch is gelatinized with water under heating conditions, then the sol is poured into a cylindrical mold and subjected to retrogradation at a certain temperature, finally obtaining the product after drying[20]. Emulsion gel methods can also be used to prepare starch-based aerogel microspheres[21] (Fig. 3b). Typically, a water-in-oil emulsion is prepared using a starch/water suspension containing surfactant mixed with an oil phase. Heating and stirring form starch-based hydrogel microspheres. The dried starch-based aerogel microspheres show good potential application in constructing oral drug delivery systems[22]. Additionally, starch-based aerogels can be prepared using foaming techniques such as baking, molding, and extrusion. These methods usually involve mixing starch, foaming agents, and other fillers in a mold, then placing them in a high-temperature and high-pressure environment. Under these conditions, the foaming agent in the mixture gradually forms bubbles, and water in the system begins to evaporate, ultimately forming a solid foam material with a porous structure. Aerogels prepared by this method also have potential as packaging materials[23]. Beyond tweaking the recipe, you can dial in starch level, pH, gel and dry temperatures, plus holding times, to fine-tune the aerogel’s architecture.The target is a starch aerogel that stays airy—packed with pores yet locked in a rigid 3-D lattice. Here we outline how to set a starch hydrogel and then dry it into an aerogel.

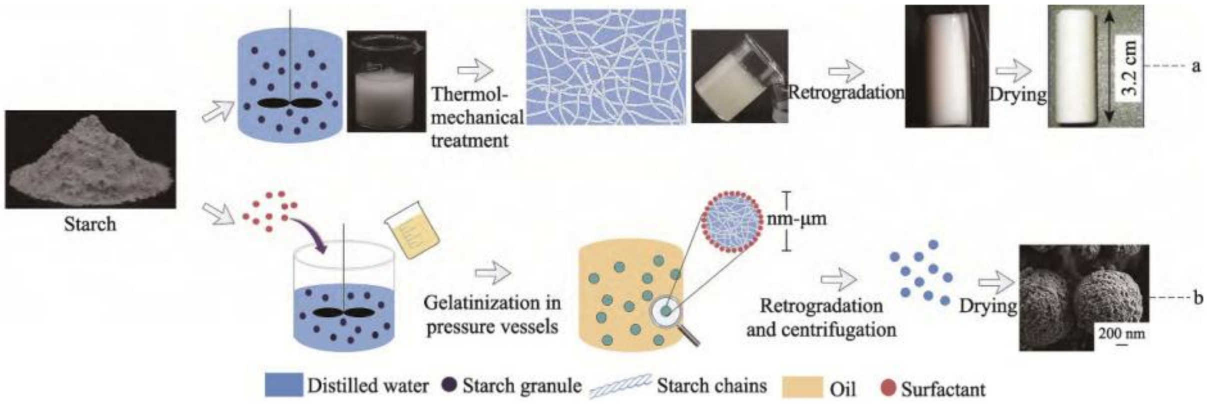


Figure 3 Preparation process of blocky starch-based aerogels (a) and microsphere starch-based aerogels (b)

Food packaging serves as a protective barrier for food, reducing mechanical damage, over-ripening softening, and microbial spoilage of fresh produce or packaged food caused by long-term storage or long-distance transportation. Lately, food-packaging scientists have zeroed in on ultralight scaffolds made from proteins or polysaccharides as green wrap-around options.Their high mechanical properties, thermal stability, and excellent water-holding capacity meet the necessary conditions for food packaging material production[74].

Starch-based aerogels possess high compressive modulus and mechanical strength, which can reduce deformation of foods like fruits, vegetables, and fresh meats caused by squeezing. Meanwhile, good barrier properties also reduce the contact between food and oxygen, moisture, and pathogens[75]. Furthermore, high water absorbency allows starch-based aerogels to be used as moisture absorbents, preventing water condensation, thereby reducing the water activity in packaged food and limiting microbial growth, achieving the purpose of extending shelf life[76]. Dhua et al.[77] used solvent exchange and supercritical drying to prepare starch-based aerogels for packaging fresh spinach leaves (Fig. 4). Research showed that starch-based aerogels could absorb condensed water produced by transpiration of fresh spinach leaves, reducing moisture accumulation inside the packaging and delaying microbial growth. Unpackaged spinach leaves spoiled after 2-3 days at room temperature, and after 6-7 days under refrigeration. Spinach leaves packaged with aerogel treatment had their shelf life extended to 6 days at room temperature and 10 days under frozen conditions, respectively. Fresh meat and fish products contain high moisture and are highly prone to spoilage. Starch-based aerogels can similarly act as moisture absorption pads to absorb exudates from such foods[78]. Coast et al.[9] used corn starch aerogel with the highest water absorption capacity to package fresh chicken breast. Results showed that the aerogel could absorb up to 39% of the exudate within a 7-day storage period.

Figure 4 Application of starch based aerogel as vegetable packaging[77]

The large specific surface area of starch-based aerogels is beneficial for adsorbing water, active compounds, and some polar molecules in solutions. Therefore, they can be loaded with antioxidant or antimicrobial active compounds to prepare active food packaging (Fig. 5[79-81]), thereby achieving the function of extending food shelf life, rather than just serving as an inert protective barrier[82-84]. Chen et al.[85] used dialdehyde starch and chitosan to prepare an antibacterial aerogel pad loaded with nano-copper ions for packaging fresh pork. Results showed that the aerogel pad absorbed a large amount of pork exudate, extending the shelf life under refrigeration to 14 days. Compared to unpackaged pork samples, those packaged with the aerogel pad retained their original red meat color, and the pork pH remained below 6.2 during the 14-day storage period, indicating freshness. Measurement showed that the migration of nano-copper ions into the fresh pork during storage was only 3.38 mg/kg, within the food safety range. Compared to synthetic antioxidants and antimicrobials, natural active compounds are green, non-toxic, and less likely to cause allergies, giving them broader prospects in active food packaging[86]. Franco et al.[87] loaded quercetin, which has antioxidant and antimicrobial properties, onto starch/calcium alginate aerogel and found that the release rate of quercetin from the aerogel was slower compared to pure quercetin. Zou et al.[40] prepared aerogels using three types of starch with different amylose/amylopectin ratios and measured their loading and release characteristics for theophylline. Research showed that waxy corn starch aerogel, due to its higher density, had a significantly higher theophylline loading efficiency (240%) compared to potato starch-based aerogel (182%) and pea starch-based aerogel (100%). Release kinetics experiments showed that all aerogel samples could release 60% of theophylline within 30-70 minutes, and almost completely release (98%) within 3-13 hours, with the specific release rate depending on the raw material and drying method of the starch-based aerogel. The above studies all indicate that starch-based aerogels have the function of controlling the release of active compounds, providing sustained antibacterial and antioxidant protection for food. Starch-based aerogels can also be used to package fat-rich foods. Compared to directly adding antioxidants to food, active food packaging with controlled release functionality is more effective in inhibiting lipid oxidative rancidity[88]. Mirmoeini et al. blended acetylated potato starch with cellulose and thyme oil to mold an antimicrobial foam wrapper for cheese.They first pinpointed the lowest thyme-oil vapor dose that halted E. coli O157:H7, then ran antibacterial checks on the foam. Results showed that aerogels containing essential oil at a concentration of 50 times MID reduced the psychrotrophic bacteria count in cheese by 3 logarithms, and the yeast/mold count by 1 logarithm. Furthermore, aerogels with essential oil concentrations of 50 times and 25 times MID reduced the initial bacteria in cheese to undetectable levels after 7 days and 14 days of storage, respectively.

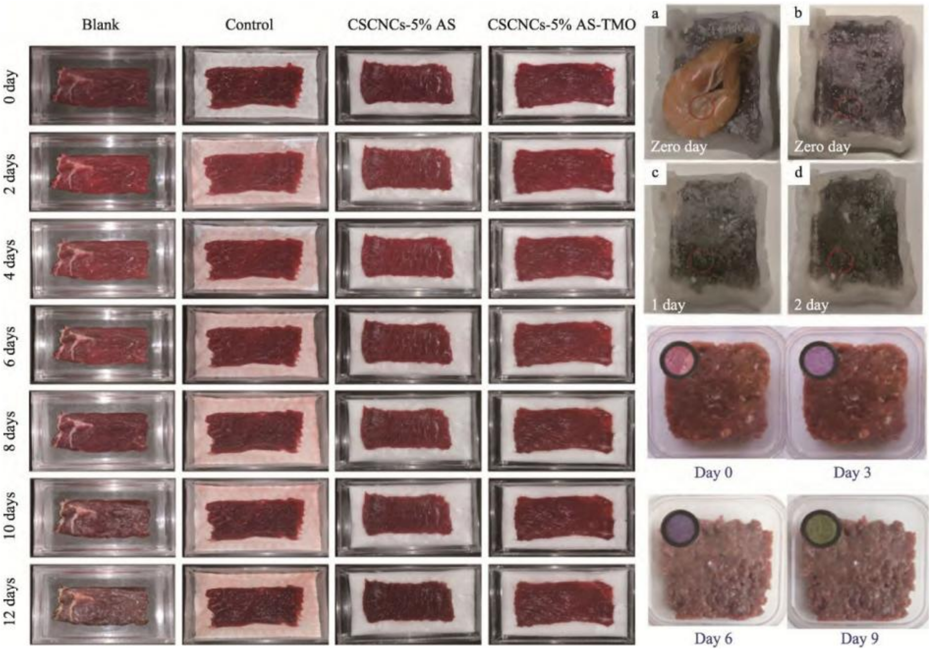


Figure 5 Application of starch based aerogel as vegetable packaging[79-81]

As shoppers wake up to sustainability, biodegradable wraps have vaulted from niche curiosity to headline research territory. Shifting farm and factory feedstocks to starch-based recipes squeezes more value out of crops, throttles reliance on finite petro-resources, and fuels greener growth. Starch aerogels outperform their mineral cousins by marrying biodegradability with surprising bounce, giving the bio-sector a lightweight yet sturdy scaffold.Scaling up starch aerogels could pit packaging demand against dinner plates, siphoning arable land and crops away from the food chain.Therefore, the selection of raw materials should primarily focus on waste from agricultural processing or food production to enable sustainable large-scale production of low-cost starch-based packaging materials. Current research on starch-based aerogels mainly focuses on their preparation and the improvement of functional properties, including the influence of raw material type, gelation and drying processes, and the loading of other substances on the final properties of starch-based aerogels. To boost performance without blowing the budget, tune the starch source, dose, gel set-up, and drying protocol in one coordinated sweep. Next-gen starch foams must survive splashes and heat spikes—only then can they guard juices, sauces, or quickly spoiled foods without falling apart.At the same time, attention should be paid to retaining the excellent biodegradability of starch-based aerogels, avoiding over-modification leading to non-recyclability and resource waste. For starch-based aerogels loaded with active compounds, their release and absorption effects in vivo and in vitro should be considered, and the safety risks after ingestion of food packaged with such aerogels should be a key focus.

5 Conclusions and Prospects

Bio-aerogels are feather-light sponges cooked from nature’s own polymers—think polysaccharides, proteins or tweaked cellulose—then dried to leave a skeletal void.Their vast internal acreage, tailor-made pores and body-friendly chemistry have lately nudged these green foams onto food-tech center stage.In the food arena these plant-grown lattices shine as wrap-around shields, tiny nutrient ferries, and selective sponges for unwanted molecules. In practical applications, the performance of bio-based aerogels is optimized through material compounding, structural design, and surface modification. Although the development trend of bio-based aerogels is booming, there are also bottlenecks and challenges. For example, difficulties in large-scale production: the supercritical CO_2 drying equipment used in the preparation of bio-based aerogels is expensive, and freeze-drying consumes high energy; there is a need to continue developing low-cost, energy-saving, and continuous production processes to scale up production. Food safety needs to be examined: the functional components (such as nano-silver) and chemical crosslinking agents (such as glutaraldehyde) added to bio-based aerogels pose certain risks in food applications; the migration risk of metal nanoparticles needs to comply with FDA/EFSA standards; residues of chemical crosslinking agents may limit food applications, necessitating the development of natural crosslinking systems. Many bio-aerogels wilt in damp air, turning from crisp foams to soggy lumps; a splash-proof coat—think silane armor—is still a work in progress.To move bio-aerogels from bench to belt, tighten the CO_2 loop to trim drying hours and recycle both feedstocks and solvents—every reclaimed gram shaves the price tag.

Bio-based aerogels face both opportunities and challenges in the food industry. To overcome these challenges in the future and continue in-depth development in the food field, research can continue in directions such as developing temperature-sensitive, photosensitive, or gas-sensitive intelligent responsive aerogels, edible bio-based aerogels, and circular economy models. Through green manufacturing technology, precise functional design, and multidisciplinary collaborative innovation, the large-scale application of bio-based aerogels in the food field can be promoted, assisting the development of a sustainable food industry.

Plant-sugar foams are quietly becoming wrapstars: we walk through how starch pedigree, solids load, gel recipe, linker dose and drying style tune the final mesh, then scan fresh trials where these airy shields guard edibles instead of plastics. Starch foams do more than cushion veggies, cuts or curds: their sponge-like pores load up on guardians—antioxidants, antimicrobials—then meter them out slowly, giving produce a safer ride from farm gate to dinner plate.For packaging different types of food, the conditions and parameters of the preparation process should be reasonably adjusted to meet different functional needs. Developing low-cost starch-based aerogels that combine excellent mechanical strength, water retention, and bioactivity is the main research direction for their use as food packaging.

References

[1] KISTLER S S. Coherent expanded aerogels and jellies[J]. Nature, 1931, 127(3211):741.

[2] DHAVAL E P R, PARALE G V, CHOI H, et al. Sol-gel synthesized homogeneous nanofibers to multidimensional in-situ and ex-situ silica nanofiber aerogels in thermal management applications[J]. Chemical Engineering Journal, 2025, 503: 158485.

[3] PIERRE A C, PAJONK G M. Chemistry of aerogels and their applications[J]. Chemical Reviews, 2002, 102(11):4243-4266.

[4] HARYEONG C, TAEHEE K, TAEHO K, et al. Ultralow dielectric cross-linked silica aerogel nanocomposite films for interconnect technology[J]. Applied Materials Today,2022,28:101536.

[5] PARALE G V, KIM T, CHOI H, et al. Mechanically strengthened aerogels through multiscale, multicompositional, and multidimensional approaches: a review(Adv. Mater. 18/2024)[J]. Advanced Materials, 2024, 36(18): 2470138.

[6] WANG S, WANG F, MA S, et al. Research progress on polysaccharide-based aerogel food packaging[J]. Food Science, 2023, 44(19):340-349.

[7] SUBHAMOY D, KUMAR A G, POONAM M. Aerogel: functional emerging material for potential application in food: a review[J]. Food and Bioprocess Technology,2022,15(11):2396-2421.

[8] ZHAO D, ZHANG X, ZHANG Y, et al. Recent advances in the fabrication, characterization and application of starch-based materials for active food packaging: hydrogels and aerogels[J]. Sustainable Food Technology, 2024, 2(3): 615-634.

[9] LUCILE D, RICHARD B, WALTRAUD V, et al. Starch aerogels: a member of the family of thermal superinsulating materials[J]. Biomacromolecules,2017,18(12):4232-4239.

[10] BAUDRON V, TABOADA M, GURIKOV P, et al. Production of starch aerogel in form of monoliths and microparticles[J].Colloid and Polymer Science, 2020, 298(4): 1-18.

[11] SHEN J M. Study on the construction and toughening mechanisms of starch-based double network hydrogel[D]. Jinan: Qilu University of Technology,2025.

[12] LU H X, ZHONG C P, LUO S J, et al. Starch aerogel: production, modification and application[J]. Journal of Chinese Institute of Food Science and Technology, 2024, 24(1): 455-465.

[13] WU Z N, KONG Y, ZHANG Y X, et al. Preparation and structural characterization of different starch-based aerogels[J]. Food Science,2023,44(12):60-66.

[14] WANG Y, SU Y, WANG W, et al. The advances of polysaccharide-based aerogels: Preparation and potential application[J].Carbohydrate Polymers,2019,226:115242.

[15] ALI U, SANDRAYEE B, JERROLD D R, et al. In vitro digestibility of nanoporous wheat starch aerogels[J]. Journal of Agricultural and Food Chemistry, 2018, 66(36): 9490-9497.

[16] ABHARI N, MADADLOU A, DINI A. Structure of starch aerogel as affected by crosslinking and feasibility assessment of the aerogel for an anti-fungal volatile release[J]. Food Chemistry,2017,221:147-152.

[17] MOTTOLA S, VISCUSI G, OLIVA G, et al. Pectin/alginate aerogel containing ZnO produced from beetroot extract mediated green synthesis for potential applications in food packaging[J]. Journal of CO2 Utilization, 2025, 91: 103003.

[18] GROULT S, BUDTOVA T. Tuning structure and properties of pectin aerogels[J].European Polymer Journal, 2018, 108:250-261.

[19] RUDAZ C. Cellulose and pectin aerogels: towards their nano-structuration[D]. Latin quarter: Ecole Nationale Supérieure des Mines de Paris,2013.

[20] CYRIELLE R, RMI C, LAURENT B, et al. Aeropectin: fully biomass-based mechanically strong and thermal superinsulating aerogel[J]. Biomacromolecules, 2014, 15(6): 2188-2195.

[21] LI F F. Preparation and Application of TiO2-Pectin Composite Aerogel[J]. Digital Printing,2020,(4):75-80.

[22] GROULT S, BUDTOVA T. Thermal conductivity/structure correlations in thermal super-insulating pectin aerogels[J].Carbohydrate Polymers, 2018, 196: 73-81.

[23] TAO D D, BAI H Y, LIU S L, et al. Research progress of cellulose aerogel materials[J]. Journal of Cellulose Science and Technology,2011,19(2):64-75.

[24] ISAAC B, AMPARO L, PAULA G, et al. Multifunctional cellulosic aerogels from Posidonia oceanica waste biomass with antioxidant properties for meat preservation[J]. International Journal of Biological Macromolecules, 2021, 185: 654-663.

[25] ISAAC B, AMPARO L, LAURA G G, et al. PLA coating improves the performance of renewable adsorbent pads based on cellulosic aerogels from aquatic waste biomass[J]. Chemical Engineering Journal, 2020, 390(prepublish): 124607.

[26] ZAMAN A, HUANG F, JIANG M, et al. Preparation, properties, and applications of natural cellulosic aerogels: a review[J].Energy and Built Environment, 2020, 1(1):60-76.

[27] MA Q. Preparation, modification and properties of chitosan-silica composite aerogels[D]. Tianjin: Tianjin University,2014.

[28] SATORU T, SHANYU Z, WIM J M, et al. Chemistry of chitosan aerogels: three-dimensional pore control for tailored applications[J]. Angewandte Chemie(International ed. in English), 2020, 60(18): 9828-9851.

[29] ZHAO J. Structure design and performance regulation of chitosan aerogels[D]. Chendu: Sichuan Normal University,2021.

[30] LIU W, HENNING M, MAGALI C. Application of alginate hydrogels for next-generation articular cartilage regeneration[J].International Journal of Molecular Sciences, 2022, 23(3): 1147.

[31] TANG M W. Preparation and performance study of functional sodium alginate-based aerogels[D]. Qingdao: Qingdao University, 2019, 000516.

[32] MENG C, ZHANG H, ZHANG S, et al. The preparation of hydrophobic alginate-based fibrous aerogel and its oil absorption property[J]. Journal of Sol-Gel Science and Technology,2018,87:704-712.

[33] CHENG Y. Alginate-based aerogels: preparation, reinforcement and hydrophobic modification[D]. Haikou: Hainan University,2012.

[34] BANG T X, DA Z J, YI Y, et al. Nanoclay-reinforced alginate aerogels: preparation and properties[J]. RSC Advances,2024,14(2): 954-962.

[35] LORENZO B D, STELLA P, MICHELE M, et al. Hydrophilic or hydrophobic coating of whey protein aerogels obtained by supercritical-CO2-drying: Effect on physical properties, moisture adsorption and interaction with water and oil in food systems[J]. Innovative Food Science and Emerging Technologies, 2024, 91: 103530.

[36] STEFANNA M P, RODICA A V, BERNADETTE E T, et al. Polysaccharide-based edible gels as functional ingredients: characterization, applicability, and human health benefits[J].Gels,2022,8(8):524.

[37] OLGENBLUM I G, HUTCHESON O B, PIELAK J G, et al. Protecting proteins from desiccation stress using molecular glasses and gels[J]. Chemical Reviews,2024,124(9),5668-5694.

[38] BRODNJAK V U. Hybrid materials of bio-based aerogels for sustainable packaging solutions[J]. Gels, 2023, 10(1):27.

[39] XIA T L. Study on the preparation, modification and application of whey protein aerogel[D]. Wuxi: Jiangnan University,2018.

[40] JING J W. Study on preparation and application of anisotropic polyimide aerogel and its phase change material composites[D]. Beijing: Beijing University of Chemical Technology,2024,001781.

[41] JIANG S, SUN Z Q, XING Q, et al. Cellulose modification and application research progress[J]. Journal of Textile Science and Engineering,2024,41(1):75-85.

[42] CORDAZZO M D, LIRA U Z, NEMER C C M, et al. Influence of hemicellulose content and cellulose crystal change on cellulose nanofibers properties[J]. International Journal of Biological Macromolecules, 2022, 213: 780-790.

[43] LI Q, WANG A J, LONG K Y, et al. Modified fenton oxidation of cellulose fibers for cellulose nanofibrils preparation[J].ACS Sustainable Chemistry& Engineering, 2019, 7(1): 1129-1136.

[44] MARTYNA R, JOANNA M, MARCIN K, et al. Mechanical properties of bio-composites based on epoxy resin and nanocellulose fibres[J]. Materials(Basel, Switzerland),2021,14(13):3576.

[45] NATHALIE L, LENNART B. Nanocellulose-based foams and aerogels: processing, properties, and applications[J]. Journal of Materials Chemistry A,2017,5(31):16105-16117.

[46] BI S S, DONG X Y, SHU X J, et al. Research progress of nanocellulose aerogel and its thermal insulation applications[J]. Henan Chemical industry,2025,42(4):1-7.

[47] WANG X Y, YAN X Y, WU Z, et al. Enhanced mechanical stability and hydrophobicity of cellulose aerogels via quantitative doping of nano-lignin[J]. Polymers,2023,15(5):1316.

[48] LIN R J. Preparation, Modification and application assessment of (carboxymethyl)cellulose aerogels[D]. Hainan: Hainan University,2016.

[49] TOURON M, CELLE C, ORGAS L, et al. Hybrid silver nanowire-CMC aerogels: From 1D nanomaterials to 3D electrically conductive and mechanically resistant lightweight architectures[J].ACS Nano,2022,16(9):14188-14197.

[50] GONG L, AN X Y, KONG M M, et al. Study on the preparation and thermal insulation properties of cellulose composite aerogel[J]. Journal of Functional, 2024, 55(1): 1092-1097.
[51] LU Y C, YANG W. Preparation and characteristics of carboxymethyl cellulose/ZnAl-layered double hydroxide composite aerogels[J]. Anhui Chemical Industry,2017,43(6):72-74+77.
[52] WANG J, LI C, XV B. Basic principle, advance and current application situation of sol-gel method[J]. Chemical Industry and Engineering,2009,26(3):273-277.
[53] SACHIN C K, RADHAKRISHNA, SHREENAG U M. Synthesis of silicon di oxide nano-particles by sol-gel method for applications in geopolymer composites[J]. Electrochemical Society Transactions,2022,107(1):5533.
[54] SOLMAZ K, PINAR E Y, REIHANEH H, et al. Aerogel-based biomaterials for biomedical applications: From fabrication methods to disease-targeting applications[J]. Advanced Science(Weinheim, Baden-Wurttemberg, Germany), 2023, 10(23):2204681.
[55] GARC A-GONZALEZ C A, ALNAIEF M, SMIRNOVA I. Polysaccharide-based aerogels-promising biodegradable carriers for drug delivery systems[J]. Carbohydrate Polymers,2011,86(4):1425-1438.
[56] ULKER Z, ERKEY C. An emerging platform for drug delivery: aerogel based systems[J]. Journal of Controlled Release,2014,177:51-63.
[57] ALEJANDRA R, LUIS J V, ROSAS S A, et al. Biopolymeric fibrous aerogels: The sustainable alternative for water remediation[J]. Polymers,2023,15(2):262.
[58] QV K. Preparation and characterization of organic-inorganie hvbrid silica aerogel[D]. Hangzhou: Zhejiang University,2014.
[59] BUDTOVA T, AGUILERA D A, BELUNS S, et al. Biorefinery approach for aerogels[J]. Polymers,2020,12(12): 2779.
[60] FENG J Z, SU B L, XIA H S, et al. Printed aerogels: Chemistry, processing, and applications[J].Chemical Society Reviews,2021,50(6):3842-3888.
[61] THAPLIYAL P C, KIRTI S. Aerogels as promising thermal insulating materials: An overview[J]. Journal of Materials, 2014, 1:127049.
[62] THIERRY W, JUAN P, ADIL A, et al. Fractal structure in silica and composites aerogels[J].Gels(Basel, Switzerland),2020,7(1):1.
[63] SUCHOROWIEC K, PAPROTA N, PIELICHOWSKA K. Aerogels for phase-change materials in functional and multifunctional composites: A review[J]. Materials, 2024, 17(17): 4405.
[64] NITA E L, GHILAN A, RUSU G A, et al. New trends in bio-based aerogels[J]. Pharmaceutics,2020,12(5):449.
[65]] TANG J, WANG L Y, MU Y F, et al. Bamboo aerogel derived from waste bamboo flour for thermal insulation[J]. Materials& Design, 2025, 258: 114588.
[66] PENG J, XIAO Q Y, XUE J Y, et al. Chitosan/polyvinyl alcohol aerogels with improved structure for thermal insulation and noise reduction[J]. International Journal of Biological Macromolecules, 2025,323: 147175.
[67] WU Y, WANG Y M, CHEN Z X, et al. A colorimetric-stable multifunctional aerogel based on covalent organic framework-loaded blueberry anthocyanin: New prospects for active intelligent food packaging[J]. Chemical Engineering Journal,2025,521:166986.
[68] VAFANIA B, MILAD F, ALIREZA A. High performance thermal insulation aerogels of modified egg white powder and xanthan gum: Production, characterization, and application for food packaging[J]. Food Hydrocolloids,2025,172:111872.
[69] ZHAO X M, REN X Y, LI H M, et al. Novel cellulose-PVA bioactive aerogels with portulaca oleracea extracts for chilled meat preservation: Antimicrobial efficacy and microbial community modulation[J]. Food Research International, 2025, 219:117008.
[70] LIU W, XU J, SUN Q Q, et al. Mechanically robust, flame-retardant, and waterproof kapok fiber/sodium alginate composite aerogel for building thermal insulation[J]. International Journal of Biological Macromolecules, 2025, 318(2): 144842.
[71] BARMASE C, BASAK S, SINGHAL R S. Fabrication ofβ-carotene loaded alginate oleogels by the aerogel template method: Impact of pressure and temperature of supercritical carbon dioxide drying[J]. Food Structure, 2025,45: 100452.
[72] SALGADO M, SANTOS F, RODR GUEZ-ROJO S, et al. Development of barley and yeastβ-glucan aerogels for drug delivery by supercritical fluids[J].Journal of CO2 Utilization, 2017, 22: 262-269.
[73] DUMOULIN M, HAYASHI R. High pressure, a unique tool for food texturization[J]. Food Science and Technology International,Tokyo,1998,4(2):99-113.
[74] ARBANAH M, DABIN L, YONGHUN S, et al. Recent progress in polysaccharide aerogels: their synthesis, application, and future outlook[J]. Polymers,2021,13(8):1347.

[75] SINGH V, TIWARI A, TRIPATHI D N, et al. Microwave assisted synthesis of guar-g-polyacrylamide[J] Carbohydrate Polymers.2004;58(1):1-6.
[76] WANG Y, AI Y Y, XIAO H Y, et al. Preparation of copper-based chitosan aerogel and its adsorption properties for uranium[J]. Journal of Mianyang Teachers' College,2024,43(11):37-46.
[77] WANG S Y, WANG F J, LU C H, et al. Citral-loaded nanocellulose/sodium alginate aerogel packaging liner for fresh pork preservation[J]. Food Control, 2024, 155: 110031.
[78] CYNTHIA F C, EVRIM E, ANTONIO M A, et al. Superabsorbent food packaging bioactive cellulose-based aerogels from Arundo donatx waste biomass[J]. Food Hydrocolloids, 2019, 96, 151-160.
[79] MIAO C Z, HUANG W J, LI K N. Preparation of hydrogels and their application in the field of wastewater treatment[J]. Material Sciences,2024,14:761.
[80] TIAN R M, LUO X Y, XV G J, et al. Study on the biodegradability of konjac glucomannan/curdlan composite aerogel[J].Science and Technology of Food Industry,2023,44(7):143-151.
[81] ESCUDERO R R, ROBITZER M, RENZO D F, et al. Alginate aerogels as adsorbents of polar molecules from liquid hydrocarbons: Hexanol as probe molecule[J].Carbohydrate Polymers, 2008, 75(1): 52-57.
[82] IVANOVIC J, MILOVANOVIC S, ZIZOVIC I. Utilization of supercritical CO2 as a processing aid in setting functionality of starch-based materials[J]. Starch-Starke,2016,68(9-10):821-833.
[83] AMENAH B A, GENADA S, ZEYNEP U. Biodegradable polysaccharide aerogels based on tragacanth and alginate as novel drug delivery systems[J].Journal of Sol-Gel Science and Technology,2024, 109(3):748-756.
[84] RADWAN P J, PIQ TKOWSKI M. P, JANUS T, et al. Biodegradable, pH-responsive chitosan aerogels for biomedical applications[J]. RSC Advances, 2017, 7(52): 32960-32965.
[85] TONG, Y X, GAO H N, CHEN L P, et al. Research progress in modification and functionalization of bio-based aerogels[J]. Chinese Plastics,2024,38(2):87-94.
[86] LI S M, SAMUEL H, NATALIA S. Biopolymer-based hydrogels for harvesting water from humid air: A review[J].Sustainability,2023,15(1):848.
[87] TARIQ Z, IQBAL D N, RIZWAN M, et al. Significance of biopolymer-based hydrogels and their applications in agriculture: a review in perspective of synthesis and their degree of swelling for water holding[J]. RSC Advances, 2023, 13(35):24731-24754.
[88] SHAO L. Study on temperature/pH dual responsive alginate aerogel and its application in drug delivery[D]. Hainan: Hainan University,2018.
[89] WANG H J, SONG X J, MENG L W, et al. Preparation and sorption kinetics of CO2 absorption pad for food packaging[J]. Packaging and Food Machinery, 2018, 36(01): 1-4.