Types of Hybrid Bio-Based Aerogel Materials

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Bio-based aerogels are derived from various renewable sources such as sugar cane, vegetable oils, proteins, starches, chitosan, alginate, pectin, lignin, cellulose, and proteins, which have been shown to be useful in the production of aerogels. These aerogels have special properties that make them well suited for packaging applications and in bioengineering. Studies in this field have led to advances that shed light on their diverse applications, improved properties, and innovative synthesis methods. Researchers have investigated alternative feedstocks for bio-based aerogels to broaden their sources and enhance sustainability. Studies have explored the use of waste materials, agricultural by-products, and unconventional sources to synthesize aerogels, aligning with the principles of a circular and green economy.

Keywords: bio-based aerogels ; hybrid packaging materials ; sustainability ; eco-friendly packaging

1. Introduction

Aerogels can be divided into two categories, namely organic and inorganic aerogels [1]. Each of these categories is divided into subcategories according to the type of materials and the structure of the gel (**Figure 1**) [1][2][3][4][5].

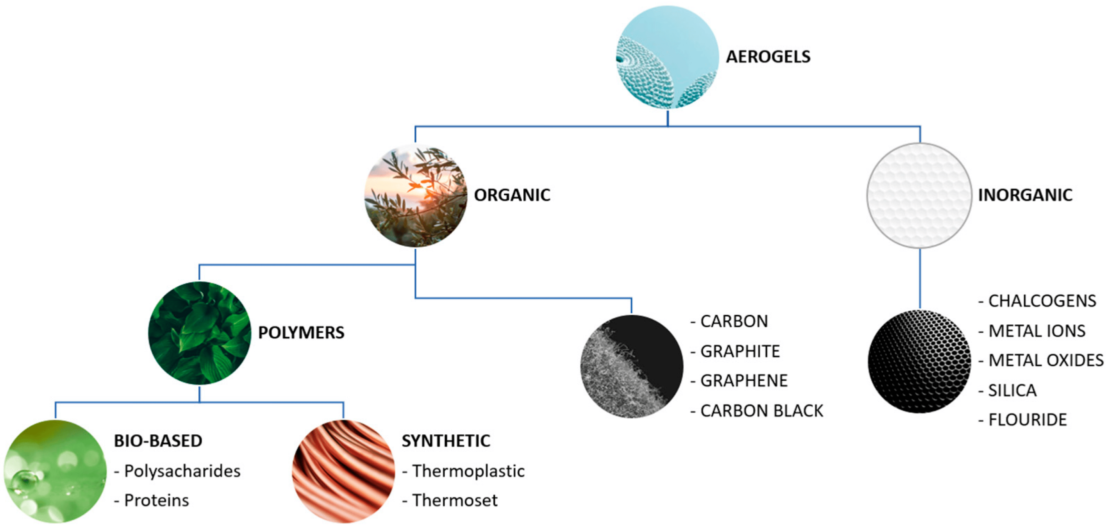

Figure 1. Classification of aerogels according to used raw materials [1][2][3][4][5].

Bio-based polymers are gaining ground in many areas, and the use of these compounds is a suitable alternative to reduce the environmental impact of certain packaging (e.g., food packaging) [2][3][4]. The attractiveness of these materials is usually related to the synthesis routes of biopolymer aerogels. Their potential to be customized through precise strategies gives them certain properties that suit their specific uses [5][6][7][8][9][10].

Bio-based aerogels have special properties that are well suited for packaging and also for biomedical purposes, such as applications in tissue engineering, regenerative medicine, and drug delivery [11][12][13][14][15]. As mentioned, such aerogels derived from renewable sources represent a promising class of materials with multiple applications.

This research analyses different types of the most commonly used bio-based aerogels (polysaccharide (cellulose, chitosan, alginate, starch)-, protein-, lignin- and pectin-based aerogels) and highlights their sources and selection criteria based on environmental friendliness and properties.

2. Polysaccharide-Based Aerogels

Polysaccharides, complex carbohydrates consisting of repeating sugar units, are at the forefront of interdisciplinary research due to their diverse and multi-faceted applications. As fundamental components of biological systems, polysaccharides play crucial roles in the cell structure, energy storage, and material processes and production. Polysaccharides are known for their ability to self-assemble into certain physical structures, which has already been explored by many researchers in the formation of aerogels, xerogels, and cryogels [16][17][18][19][20][21]. The group of potential polysaccharide aerogels includes cellulose, chitosan, alginate, pectin, and starch. Their properties such as porosity, low weight, and a large surface area improve their suitability for various applications, especially for drug delivery [22][23][24].

In connection with the use of polysaccharides for the production of aerogels, many of the further described bio-based polysaccharide aerogels in the field of packaging have been investigated and researched for their properties such as biodegradability, biocompatibility, non-toxicity, bioactivity, and environmental friendliness [25][26][27][28][29][30].

2.1. Cellulose-Based Aerogels

Cellulose, a ubiquitous biopolymer found in plant cell walls, serves as an important starting material for bio-based aerogels. The synthesis of cellulose-based aerogels involves a careful process aimed at utilizing the unique properties of cellulose. The extraction of cellulose involves a variety of sources, including various plants and plant-derived materials such as rice straw, hemp, cotton, wood, potatoes, and bagasse [31][32][33][34]. The complex performance characteristics of cellulose, including degree of polymerization, size, crystallinity, and thermal stability, are closely related to the plant species and extraction processes, which include pretreatment, post-treatment, and comminution [34][35][36][37]. This relationship influences the structure and performance of cellulose aerogels. While cellulose can be synthesized from bacterial cultures (bacterial nanocellulose) such as *Acetobacter xylinum*, resulting in higher crystallinity (80%) and the absence of impurities such as lignin and hemicellulose, the in vitro synthesis of low molecular weight cellulose is possible through cellulase catalysis or ring-opening polymerization [31]. In addition, cellulose derivatives such as carboxymethyl cellulose, cellulose esters, and cellulose ethers are available via grafting, sulphonation, and TEMPO-mediated oxidation, utilizing the high chemical reactivity of the hydroxyl groups in each glucose unit of the cellulose chain [38][39]. There are many reviews that comprehensively address the structure, properties, and applications of cellulose and its derivatives [40][41][42][43][44]. The mechanical properties and moisture affinity of aerogel materials are significantly improved by the use of cellulose and its derivatives [44][45][46]. The advantages of using cellulose as an aerogel precursor are manifold: there is an infinite and renewable supply of cellulose raw material; the abundance of hydroxyl groups in the cellulose chain eliminates the need for crosslinking agents, thus simplifying the aerogel manufacturing process; and the chemical modification of cellulose facilitates the improvement of the mechanical strength and structural properties of cellulose aerogels. The categorization of cellulose aerogels based on raw materials leads to three different groups [47]: natural cellulose aerogels (nanocellulose aerogels, bacterial cellulose aerogels), regenerated cellulose aerogels, and cellulose-derived aerogels.

It is well known that cellulose-based aerogels have exceptional properties that make them well suited for sustainable packaging applications. With a surface area of 200 to 1000 m^2/g and a porosity of often more than 90%, these aerogels have an extensive network of interconnected cellulose fibrils [44][45][46][47][48]. This intricate structure contributes to their remarkable insulating properties and makes them extremely effective in thermoregulation. The mechanical strength of cellulose-based aerogels is remarkable, which is due to the robust network of cellulose fibers. This property is particularly advantageous in packaging applications where durability and resistance are of paramount importance. The light weight of these aerogels makes them even more attractive as it offers them a good balance between strength and lower material density. Hybrid PVA/cellulose/nanocellulose aerogels show promising properties for the controlled release of bioactive compounds in food systems, which could benefit bioactive packaging structures, as explored by de Oliviera [49]. Cellulose-based aerogels have attracted considerable attention due to their renewable and biocompatible properties. These aerogels can be produced from various sources such as fruit waste [31], cellulose nanocrystals (CNCs) [32], and NaOH/urea solution [33].

They have an ultra-low density, high porosity, and low thermal conductivity, which makes them suitable for heat-insulating applications [34][37]. Aerogels containing cellulose nanocrystals from rice and oat hulls have been proven to be water absorbers for food packaging and show promising industrial applications in various fields [29][30][50].

The hierarchical structure of cellulose-based aerogels enables the incorporation of nanoparticles, which increases their multifunctionality. There is a third generation of aerogels: nanocellulose-based aerogels, which are based on abundant and sustainable cellulose as a raw material [51][52][53][54][55]. These aerogels seamlessly combine the traditional aerogel properties such as high porosity and large specific surface area with the exceptional properties of cellulose. Currently, nanocellulose aerogels have proven to be a fascinating platform for various functional applications in different fields, including adsorption, separation, energy storage, thermal insulation, electromagnetic interference shielding, and biomedical applications [38][39][40][41][42][43].

In addition, the cellulose concentration and the drying method can influence the micromorphology and crystalline structure of aerogels. The introduction of flame-retardant particles such as zinc borate improves the thermal stability and flame retardancy of cellulose aerogels [48][54][55]. These materials have the potential for various applications including oil spill treatment, energy storage, actuator development, and packaging [54][55]. The use and modification of cellulose-based aerogels offers a wide range of possibilities in the field of materials science and technology.

The environmental friendliness of cellulose-based aerogels is based on the renewable nature of the cellulose sources. The cellulose obtained from plant-based raw materials ensures the sustainable life cycle of the aerogels. In addition, the biodegradability of cellulose meets the environmental protection goals and addresses concerns associated with the disposal of packaging materials. The biodegradability of cellulose-based aerogels meets the increasing demand for environmentally friendly packaging solutions. With their complex synthesis process and outstanding properties, cellulose-based aerogels offer a glimpse into the future of sustainable packaging materials. The combination of environmental friendliness, insulating properties, and mechanical strength makes cellulose-based aerogels promising candidates for overcoming the environmental challenges associated with conventional packaging.

2.2. Chitosan-Based Aerogels

Chitosan-based aerogels are produced through a careful synthesis process that begins with the deacetylation of chitin from crustacean shells. This process converts chitin into chitosan, a biopolymer with a wide range of applications. The chitosan is then dissolved in a suitable solvent, often acetic acid, resulting in a viscous solution. Gelation is brought about using methods such as freeze drying or supercritical drying, which promotes the development of a three-dimensional porous structure characteristic of aerogels [55][56]. The resulting aerogels have a network of interconnected pores, which contributes to their light weight and porous nature [55][56][57][58].

Chitosan-based aerogels have a number of properties that make them highly suitable for sustainable packaging applications [59][60][61]. In particular, their inherent biocompatibility makes them safe for direct contact with food, which is a crucial aspect in the packaging of consumer goods. Aerogels also have exceptional antibacterial properties, a property that can extend the shelf life of packaged goods by inhibiting microbial growth. In addition, chitosan-based aerogels have a large surface area and porosity, which improves their heat-insulating properties. This combination of properties makes them versatile materials that are suitable for different packaging requirements.

The mechanical strength of chitosan-based aerogels is remarkable and provides a robust framework for potential packaging applications [62][63][64][65]. The interconnected network of chitosan molecules contributes to the structural integrity of the material and ensures a long shelf life under various packaging conditions. This tensile strength increases the versatility of chitosan-based aerogels as they can withstand the rigors of transportation and handling while maintaining the integrity of the packaged contents [57][66].

The environmentally friendly profile of chitosan-based aerogels is emphasized by the fact that they are derived from a by-product of the fishing industry. The use of crustacean shells, which would otherwise be considered waste, is in line with the principles of sustainability and resource efficiency. In addition, the biodegradability of chitosan ensures that these aerogels have a minimal impact on the environment at the end of their life cycle and are a more environmentally friendly alternative to conventional packaging materials. Chitosan-based aerogels exhibit remarkable compatibility with various materials, which facilitates their integration into hybrid composites. The ability to combine chitosan-based aerogels with other substances opens up opportunities to tailor the properties of the resulting hybrid materials to the specific requirements of sustainable packaging. This versatility in hybridization expands the range of potential applications for chitosan-based aerogels in the packaging industry. Their unique combination of biocompatibility, antibacterial properties, mechanical strength, and environmental friendliness make them versatile materials that can make an important contribution to promoting environmentally conscious packaging practices.

2.3. Alginate-Based Aerogels

The synthesis of alginate-based aerogels requires a careful process to utilize the unique properties of these marine-derived polysaccharides. Sodium alginate is extracted from marine algae, usually brown algae, via a series of alkaline treatments such as with Na_2CO_3 [67][68][69][70]. After extraction, the sodium alginate is mixed with a crosslinking agent, often calcium ions, to effect gelation [66][67][68]. The resulting gel is then subjected to supercritical drying, a critical step that transforms the gel into a porous aerogel structure while preserving its intricate network.

Alginate-based aerogels have several properties that make them attractive for sustainable packaging [69][70][71][72][73]. The inherent biocompatibility of alginate enables safe contact with food, making these aerogels suitable for food packaging. Their high water absorbency is advantageous for scenarios where moisture resistance is critical for maintaining the quality of the packaged goods [70][71]. The porous structure of alginate-based aerogels contributes to their exceptional insulating properties, which effectively protect temperature-sensitive products during storage and transport. The environmentally friendly profile of alginate-based aerogels stems from the renewable nature of the algae that serve as the primary source of alginate [71][72][73][74]. Seaweed is abundant, grows quickly, and does not compete with food crops for arable land, which is in line with sustainable sourcing practices. In addition, the biodegradability of alginate ensures that these aerogels have a minimal impact on the environment and provide a responsible solution for the disposal of packaging materials at the end of their life cycle. They demonstrate versatility in packaging applications. Their compatibility with a wide range of substances, including liquids and solids, enables a variety of packaging solutions [74][75][76]. Whether as a coating material to extend the shelf life of fruit or as an insulating layer for temperature-sensitive pharmaceuticals, alginate-based aerogels demonstrate their adaptability and effectiveness for a variety of packaging requirements. The synthesis of hybrid materials via incorporating alginate-based aerogels into composite structures opens up new opportunities for innovation. By combining alginate with other materials such as cellulose or polymers, the properties of the resulting hybrid aerogels can be customized to meet specific requirements as researched by Zhang et al. [77].

Composite aerogels made from bamboo shoots, cellulose, and sodium alginate have been shown to have the potential for sustainable, biocompatible drug delivery, with potential applications in dietary supplements and cosmetics. Hugo et al. presented crosslinked aerogels made from cellulose nanofibers and alginate that enable the rapid, continuous, and large-scale production of porous, lightweight materials for energy storage, mechanical strain, and humidity sensors.

Such materials have the potential to be used not only for energy storage but also for other applications [78]. Most research has been conducted in the biomedical field, where alginate-based aerogels have been used for bone regeneration, wound healing, tissue engineering, etc. [79][80][81]. The synthesis and properties of alginate-based aerogels emphasize their potential as versatile and environmentally friendly materials for sustainable packaging.

2.4. Starch-Based Aerogels

Starch, one of the various natural polysaccharides, has gained increasing attention in research as a material for the production of aerogels, and promises diverse applications in various fields [82][83][84][85][86][87][88]. It is non-allergenic, non-toxic, and generally recognized as being safe, as well as being abundant and inexpensive. These properties make starch-based aerogels particularly attractive and well suited for nutritional and food applications [83][84][85]. Starch-based aerogels can be produced in a variety of shapes and dimensions, including monoliths, films, and microspheres ranging from nanoscale to micron sizes. Starch-based aerogels represent a remarkable class of bio-based materials that have significant potential for sustainable packaging applications. The synthesis of starch-based aerogels typically involves the extraction of starch from renewable sources such as corn, wheat, potato, or cassava [82][83][84]. The extracted starch is then mixed with a suitable solvent such as epichlorohydrin and glutaraldehyde. It reacts with the hydroxyl groups in the starch, causing crosslinking and forming a gel. Gelation is triggered by processes such as freeze drying or subcritical drying. This leads to the formation of a three-dimensional porous network, which is characteristic of aerogel structures. Starch-based aerogels have several key properties that make them attractive for sustainable packaging, such as biodegradability, versatility, and low cost, and they are a renewable resource [85][86][87][88].

These aerogels often exhibit high porosity and provide a large surface area that can be beneficial for various functions, including absorption and insulation. The crosslinked network of starch molecules in the aerogel structure contributes to its mechanical stability, making it suitable for applications where durability is important. The use of starch as a raw material for aerogels is in line with sustainability goals as starch sources are renewable and widely available. The biodegradability of starch-based aerogels further enhances their eco-friendly profile and minimizes their environmental impact throughout their life cycle. One potential application for starch-based aerogels is food packaging. By incorporating lignocellulosic nanofibrils, the water absorption of waxy maize-starch-based aerogels could be reduced from 15 g/g to 12 g/g, as shown by Ago et al. [89]. The mechanical properties of the resulting composite aerogel are comparable to those of polystyrene foam. This composite aerogel is therefore a promising environmentally friendly and sustainable alternative for packaging. Starch-based aerogels containing agar or microcrystalline cellulose also have the potential to be used for the controlled release of active ingredients, as an absorbent, and as a source of resistant starch [90]. On the other hand, aerogel based on konjac glucomannan/starch enriched with wheat straw has a high potential for thermal insulation due to its low thermal conductivity and good thermal stability [91]. In the context of sustainable packaging, where the focus is on reducing the environmental footprint, starch-based aerogels are a compelling solution.

2.5. Pectin-Based Aerogels

Pectin, which consists of α-(1–4)-linked D-galacturonic acid residues and is composed of homogalacturonan and rhamnogalacturonan, has at least 17 different monosaccharides in its structure [92]. The behavior of pectin in solutions is determined by the ratio of methylated or amidated groups to non-modified galacturonic acid, which in turn influences the properties of the resulting pectin-based materials [92][93][94][95]. The model explains the mechanism of the crosslinking reaction with divalent metal ions, whereby the crosslinks are formed by divalent ions occupying electronegative cavities in the bifurcated band structure of the carboxyl groups [94]. Pectin-based aerogels derived from pectin, a complex polysaccharide found in plant cell walls, represent a unique class of bio-based aerogels. The synthesis process usually starts with the extraction of pectin from citrus fruits, apples, or other plant sources [92][93]. The extracted pectin is then dissolved in water. The water-soluble components of plant cell walls, including pectin, can be released and extracted using a water-based extraction process. Gelation is initiated through methods such as freeze drying or supercritical drying. This process leads to the formation of a three-dimensional network, resulting in the porous and light structural characteristics of aerogels. Amidated pectins, which are characterized by a low methyl ester content, can form gels over a wide pH range in the presence of divalent cations. In addition, the introduction of alcohols, such as ethanol or tert-butanol, enhances the hydrophobic interactions between the pectin chains, resulting in higher mechanical strength for the hydrogels [95][96]. In contrast, the presence of amide groups, as observed in low-methylated, non-amidated pectins, leads to the formation of gels with better mechanical properties [95][97]. As researched by Tkalec et al., the ethanol-induced gelation of pectin, alginate, xanthan gum, and guar gum accelerates the production of aerogels that have a large surface area and are suitable for life-science applications [98]. These aerogels have special properties that make them interesting for various applications, including sustainable packaging. With their inherent biocompatibility and biodegradability, these aerogels are in line with environmentally conscious principles. The porous structure contributes to their low weight and therefore offers advantages in packaging, where weight reduction is important. In addition, pectin-based aerogels can have unique mechanical properties that are influenced by the specific pectin sources, allowing for versatility to meet different packaging requirements. The molecular arrangement within the aerogel matrix contributes to variations in mechanical strength, flexibility, and porosity, making pectin-based aerogels adaptable to specific packaging requirements.

The ability of pectin to absorb water makes these aerogels suitable for packaging applications where moisture control is critical. Hong-Bing et al. found that aerogels made from pectin and clay derived from renewable sources showed accelerated biodegradation compared to wheat starch. The addition of clay and polyvalent catalysts further increased the biodegradation rates [99]. The biodegradability of pectin is in line with the growing demand for environmentally friendly packaging materials and helps reduce the environmental impact.

3. Protein-Based Aerogels

Proteins exhibit a high degree of complexity and have a sophisticated supramolecular chemistry that offers fascinating possibilities for material production. The current research takes specific properties, including the self-assembly of proteins into fibrils and the propensity of proteins or protein-derived materials to form gels, as notable examples of their valuable properties [100][101][102][103]. Protein-based aerogels derived from natural proteins such as soya, whey, or silk represent a compelling category in the field of bio-based aerogels. The synthesis process involves the extraction of proteins from sustainable sources, followed by dissolution in a suitable solvent. Gelation is usually induced by methods such as freeze drying or supercritical drying, which enables the formation of a three-dimensional aerogel structure [100][101][102][103]. The resulting protein-based aerogels exhibit a porous and crosslinked network that reflects their aerogel nature. The inherent biocompatibility of proteins makes these aerogels safe for contact with food and makes them viable candidates for food packaging. Depending on the protein source, these aerogels can have different mechanical properties, ranging from flexibility to robustness, offering great versatility for packaging solutions. Researchers have used protein nanofibrils that were effectively combined with gelatin to create aerogels with enhanced mechanical properties [101][103].

The application of mechanochemical processing has allowed the manipulation of gelling behavior and provided an environmentally friendly and scalable method to tune the properties and functionality of protein-based aerogels. This is a simple way to produce non-toxic and biodegradable aerogel materials with favorable mechanical strength [101]. The use of proteins as a raw material for aerogels is in line with sustainability goals due to their renewable nature. Proteins of plant or animal origin offer a biodegradable alternative to conventional packaging materials, addressing concerns about environmental impact and waste. The environmentally friendly profile of protein-based aerogels also extends to their potential for the circular economy, emphasizing the importance of responsible material use and disposal.

4. Lignin-Based Aerogels

Lignin, a complex and heterogeneous biopolymer derived from plant cell walls, has attracted attention as a sustainable starting material for aerogels. The synthesis of lignin-based aerogels involves the extraction of lignin from lignocellulosic biomass such as wood or agricultural residues [104][105][106]. Various methods, including dissolution in ionic liquids or other suitable solvents, are used to produce a homogeneous lignin solution, which is the prerequisite for subsequent gelation. The gelling process is often facilitated through freeze drying or supercritical drying. The structural properties of lignin-based aerogels are influenced by the lignin source. Different plant species and processing methods result in lignin with different molecular weights, compositions, and functionalities. This diversity gives these aerogels a range of mechanical properties and allows them to be customized for specific applications. The lignin-rich composition contributes to the unique structural subtleties observed in these aerogels. Such aerogels have special properties that make them promising materials for various applications including sustainable packaging. These aerogels often have a porous structure with a large surface area, which contributes to their low weight. The interconnected lignin networks within the aerogel skeleton provide mechanical stability, making them suitable for applications where both strength and flexibility are important. As Cantu et al. presented in their research, lignin-based aerogels can be produced from wheat straw via crosslinking with oligo (alkylene glycol) diglycidyl ethers and offer the potential for greater value-added utilization in chemical synthesis [104].

Due to their versatile properties, lignin-based aerogels have been produced from bacterial cellulose/lignin-based carbon aerogels in a catalyst-free, low-cost process, and these are suitable for flexible solid-state energy storage and other applications [105]. In addition, organosolv lignans from various lignocellulosic biomasses (aspen, pine, and barley straw) could be used to produce highly porous lignin-5-methylresorcinol-formaldehyde aerogels with a large surface area and high pore volume [106]. The inherent UV-blocking properties of lignin make these aerogels potential candidates for the protection of packaged goods against light-induced deterioration [106].

The use of lignin as a raw material for aerogels is in line with sustainability goals, as it is abundant in nature and is a by-product of various industries. The biodegradability of lignin-based aerogels ensures a minimized environmental footprint throughout their life cycle. In addition, the reuse of lignin from industrial processes such as pulp and paper production contributes to the circular economy by transforming a waste product into a valuable and sustainable material.

As described in the subchapters, various organic, bio-based aerogels, including cellulose, chitosan, starch, lignin, protein, and pectin, have different structural characteristics (**Table 1**). Overall, cellulose-based aerogels often have a fibrous network, while chitosan-based aerogels have an amorphous structure with inherent antibacterial properties. Such aerogels are known for their thermal insulation, while starch-based aerogels have structural variations influenced by the arrangement of the starch molecules and offer versatile functionality due to their porosity. Lignin-based aerogels, which are derived from plant cell walls, have a unique composition. Protein-based aerogels vary in structure depending on the protein source, and pectin-based aerogels show structural variations depending on the pectin source and extraction method. This diversity enables customization to specific packaging requirements, with the mechanical properties of the bio-based aerogels varying. Cellulose-based aerogels exhibit excellent mechanical strength due to their fibrous nature, while chitosan-based aerogels offer flexibility and robustness, making them particularly suitable for specific packaging requirements, and they also have antibacterial properties. Starch-based aerogels, which are influenced by the arrangement of the starch molecules, have mechanical properties due to their porosity. Lignin-based aerogels have unique mechanical properties due to their lignin content. Protein-based aerogels have versatile mechanical properties depending on the protein source, and pectin-based aerogels offer flexibility depending on the pectin source and extraction method. Understanding these mechanical variations is critical for selecting aerogels tailored to specific packaging applications.

Table 1. Advantages and disadvantages of different raw materials for bio-based aerogel packaging materials [1][2][3][4][5][6] [illegible] [96][97][98][99][100][107].

Type of Raw Materials for Aerogel Production	Advantages	Disadvantages
Alginate-based aerogels	- biocompatible, suitable for different packaging applications; - mostly derived from brown algae, sustainable and renewable source for aerogel production; - are biodegradable, offering environmentally friendly disposal options at the end of their life cycle; - their production can be cost-effective due to the abundance of brown algae, potentially providing a more economical alternative to traditional aerogel materials.	- lower mechanical strength compared to synthetic counterparts, impacting their applicability in certain high-stress environments; - sensitive to moisture, affecting their stability and performance in humid conditions; - lower thermal stability compared to synthetic aerogels, restricting their use in applications requiring high-temperature resistance; - gelation and drying processes may require optimization for consistent and desirable properties and have limited resistance to certain chemicals.
Cellulose-based aerogels	- lightweight and high strength-to-weight ratio; - excellent thermal insulating properties; can be processed using eco-friendly methods; - biodegradable, renewable, and abundant resource, which reduces their carbon footprint; - cost-effective compared to some alternatives.	- limited mechanical strength compared to some alternatives; - need for additional treatments for optimal performance; - complex processing may pose challenges; - dependence on specific feedstock sources and energy-intensive processing methods.
Chitosan-based aerogels	- excellent adsorption capabilities, making them effective for removing pollutants, heavy metals, and other contaminants from liquids and gases; - biocompatible, sustainable, and renewable resource.	- lower mechanical strength compared to synthetic counterparts, affecting their structural integrity; - sensitive to high humidity, leading to potential degradation and reduced performance in humid conditions; - limited temperature resistance, and processing involves complex procedures; therefore, achieving uniform structures can be challenging, impacting scalability.
Lignin-based aerogels	- good thermal insulation properties; - sustainable and readily available raw material; - often a by-product of the paper and biofuel industries, reducing production costs for aerogels; - can be disposed of without harm to ecosystems.	- lignin sources can vary widely, leading to challenges in achieving consistent aerogel properties; - complex molecular structures, necessitating sophisticated processing methods; - may absorb moisture, impacting their long-term stability and performance; - may also exhibit brittleness, limiting their use in certain applications requiring flexibility.

Type of Raw Materials for Aerogel Production	Advantages	Disadvantages
Pectin-based aerogels	- easily modified to achieve a range of properties, enhancing their adaptability for various applications; - biocompatible, is a by-product of the fruit processing industry, making it cost-effective.	- varying properties depending on the source and extraction methods, leading to inconsistent performance; - sensitive to humidity and temperature, affecting their stability and performance in certain environments; - lower thermal and mechanical strength compared to synthetic aerogels; restricted use in high-temperature environments.
Protein-based aerogels	- excellent mechanical properties, lightweight, and with high porosity; - effective thermal insulation, suitable for diverse applications; - straightforward processing compared to some synthetic materials; - non-toxic and biocompatible, posing minimal health risks.	- varied performance depending on the protein source, requiring optimization; - limited availability of suitable protein sources for certain uses; - allergenic reactions possible depending on the protein source; - limited scalability and potential competition for food resources.
Starch-based aerogels	- non-toxic and pose fewer health risks during manufacturing and handling; - cost-effective, making them an economical choice for large-scale aerogel production; - biodegradable, contributing to environmental sustainability and reducing end-of-life concerns.	- lower mechanical strength; - sensitivity to moisture, potentially compromising the stability and performance of aerogels in humid conditions; - lower thermal stability, restricting their use in high-temperature applications; - the properties of starch-based aerogels can vary depending on the source and processing methods.

Biodegradability is a common feature of bio-based aerogels that come from renewable sources, such as the mentioned bio-based aerogels that meet sustainability goals. Their inherent biodegradability ensures responsible disposal at the end of their life, contributing to the circular economy. This eco-friendly profile makes them attractive alternatives to traditional packaging materials from non-renewable sources. Understanding these functional properties enables the strategic selection of aerogels for specific sustainable packaging applications. The versatility of bio-based aerogels opens up possibilities for various sustainable packaging applications. Cellulose-based aerogels offer robustness and thermal insulation. Chitosan-based aerogels with antibacterial properties are suitable for packaging perishable goods. Starch-based aerogels offer flexibility for different packaging requirements. Lignin-based aerogels meet specific packaging requirements due to their unique composition, and pectin-based aerogels are suitable for moisture-sensitive products. This versatility allows these materials to be strategically integrated into a range of sustainable packaging solutions.

The comparative analysis emphasizes the diversity of structural, mechanical, biological, functional, and application-related aspects of bio-based aerogels. Understanding these differences is crucial for informed decision making in the selection and design of sustainable packaging materials tailored to specific industry needs and environmental concerns.

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