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A Brief Review on the Preparation and Application of Silica Aerogel

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Abstract

The unique features of silica aerogel, such as its high specific surface area, low density (95% air), hydrophobicity, low thermal conductivity, and optical transparency, have attracted considerable attention from the scientific and technical communities. Silica aerogels are produced utilizing "sol-gel" technology, a reliable method that includes precursor preparation, aging, and drying. Due to its remarkable overall properties, silica aerogel has several potential applications in advanced technology and various other fields, such as thermal insulation, sound absorption, adsorption, flame retardation, sensing, and catalysis. This review primarily focuses on the manufacture and utilization of silica aerogel. The initial focus was on analyzing the progression of preparation procedures, followed by an exploration and evaluation of the current prevalent ways of preparation. Subsequently, an analysis is conducted to explore the potential of silica aerogel in various application areas, taking into account its distinctive characteristics. Finally, a comprehensive analysis of the future development path of silica aerogel is provided, along with some suggestions for enhancing the manufacturing process.

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1. Introduction

Aerogel, known as the "wonder material of the 21st century," holds the distinction of being the least dense substance on Earth.[1] It has a low density ranging from 0.001 to 0.200 g cm^{-1} and a high specific surface area between 500 and 1000 m^2 g^{-1}. This is due to its very porous structure, which resembles a pearl necklace with interconnected particles. Additionally, it has an air volume ranging from 80 to 99.8%.[2-4] Aerogels possess the lowest density among solid materials and exhibit exceptional thermal insulation properties due to their unique structure.

Samuel Stephens Kistler invented silica aerogel during the 1930s. Among the several types of aerogels, the silica aerogel category is now the most utilized and researched.[5] Due to the smaller size of the mesopore compared to the average distance air molecules may travel freely, silica aerogel exhibits a very low thermal conductivity, which is decreased to half that of still air. The most prevalent commercial use of silica aerogel is in this application.[6] The market for silica aerogel superadiabatic materials is seeing rapid global growth. The market for these materials, which are extensively used in architectural and industrial insulation applications, is expected to have an annual value of $220 million.[7]

This paper specifically reviews the process of preparing and using silica aerogel. Initially, the investigation focused on the advancement of techniques for producing silica aerogel. The primary methods of preparation were examined and discussed. Subsequently, an analysis is conducted on the many attributes of silica aerogel to explore its potential applications. In conclusion, this paper provides an overview of the future potential and enhancement techniques for silica aerogel.

2. Preparation of silica aerogel

Since its early publications in the 1930s, silica aerogel has played a significant role in both academia and industry.[8] The

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preparation technique for silica aerogel has always been the focus of research. The initial constituents or nanoparticles undergo hydrolysis to form a network structure, which is then followed by polycondensation. Subsequently, the liquid that has been trapped in the pores of the system is released without posing any risk to the structure of the network.[9,10]

The production of silica aerogel involves three fundamental steps: (1) The gel is created using the sol-gel process, where nanoscale sol particles are formed in the precursor solution through hydrolysis and condensation catalyzed by a catalyst; (2) The gel is then aged in its original solution to prevent shrinkage during drying; (3) Finally, the gel is dried under specific conditions to maintain its structure.[9-16] Fig. 1 depicts a schematic representation of the three processes involved in this process: preparation, aging, and drying procedures.

2.1 Preparation of the precursor

The sol-gel preparation procedure entails dispersing colloidal particles to create a three-dimensional network that spreads across the solution volume.[17] In the sol-gel process, the precursor acts as the starting material and needs to be able to break down in the reaction media while simultaneously being reactive enough to contribute to the creation of a gel.[9] Possible solvents that can dissolve the precursors include salts, amines, acylates, oxides, complexes, hydroxides, and alkoxides.[9,13]

Kistler conducted a reaction between an aqueous solution of sodium silicate (water glass) and hydrochloric acid, thereby presenting the initial instance of silica aerogel formation.[8,18-21] The hydrogel derived from this precursor can be obtained through either simple neutralization or a two-stage process involving sol-gel transition followed by drying.

Nevertheless, the process of producing aerogel using the Kistler technique is characterized by its lengthy duration and demanding manual effort. Due to the time-consuming procedures of solvent exchange and washing, the entire process of synthesizing aerogel from sodium silicate requires over a week.[22] In the 1960s, Teichner *et al*.[18] improved the method of making aerogel by dissolving tetramethoxysilane (TMOS) in methanol, which reduced the time needed for aerogel synthesis to just 12 hours. Due to their versatility and ease of chemical reactivity, silane oxides are commonly employed as precursors in sol-gel chemistry.[6] However, the toxicity linked to TMOS presents a barrier to its use in industry.[1,23] Tamon *et al*.[24] synthesized silica aerogel by employing tetraethoxysilane (TEOS) and utilizing HCl and NH_3 as catalysts for the hydrolysis and condensation reactions. TEOS is a gentle and less damaging substance, which makes it a practical starting material for creating silica aerogels.

The hydrolytic reaction involves the substitution of the alkoxy group with the hydroxyl group. This leads to the formation of a silanol group, which then undergoes a condensation reaction to produce a siloxane link (Si-O-Si). During this process, alcohol or water is released as a byproduct. Polycondensation leads to the formation of open and annular oligomers by connecting silicon tetrahedral species, which then form networks of silica gel. The final gel structure retains intermediate components with S-OR (where R is typically methyl or ethyl) and Si-OH functionalities.[18]

Renjith *et al*.[25] used TEOS and methyltrimethoxysilane (MTMS) as precursors and employed a cost-effective, energy-saving, and scalable atmospheric drying process to successfully prepare silica aerogel materials. They obtained a flexible microporous three-dimensional polymer foam-silica aerogel composite material with excellent oil-absorbing performance by embedding the silica aerogel into the voids of the foam substrate. The flexible composite material

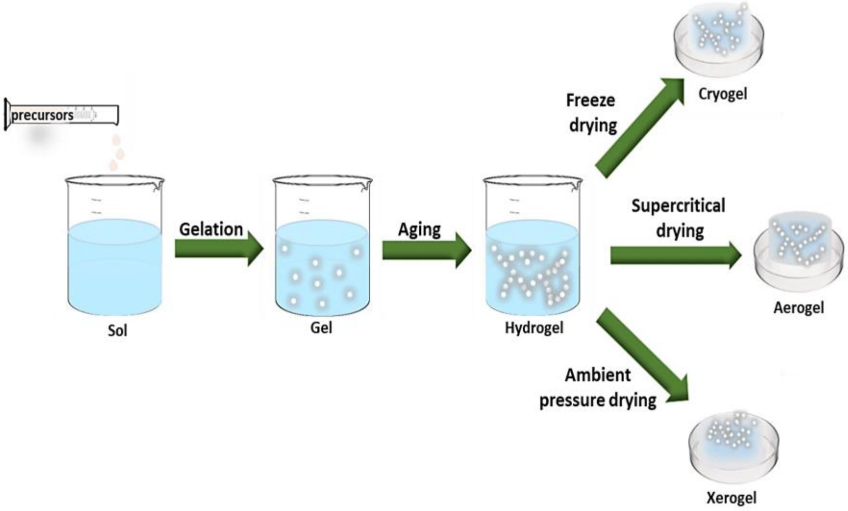

Fig. 1 The stages of gel formation. Reproduced with the permission from [9].

exhibited excellent structural stability. In the contact angle test, the foam-aerogel composite material showed excellent hydrophobic characteristics, proving its excellent hydrophobicity.

Despite the fact that sodium silicate is cheaper than alkoxysilane, researchers continue to examine the use of sodium silicate as a raw material for making silica aerogel due to its cost efficiency. Liu *et al*.[22] utilized sodium silicate as a source of silicon and employed a simplified solvent boiling process. They then carried out hydrophobic modification, solvent exchange, sodium ion purification, and drying consecutively in the same reactor under environmental pressure (Fig. 2a). This approach introduced a novel and efficient method for synthesizing superhydrophobic silica aerogel, while also conserving energy. This solution eliminates the need for sodium ion exchange pretreatment before to gelation, as well as the need for post-gelation washing to remove Na^+. Consequently, the overall duration of the synthesis process is significantly reduced, and the amount of solvent used is quite little, resulting in energy conservation and reduced waste emissions (Fig. 2b).

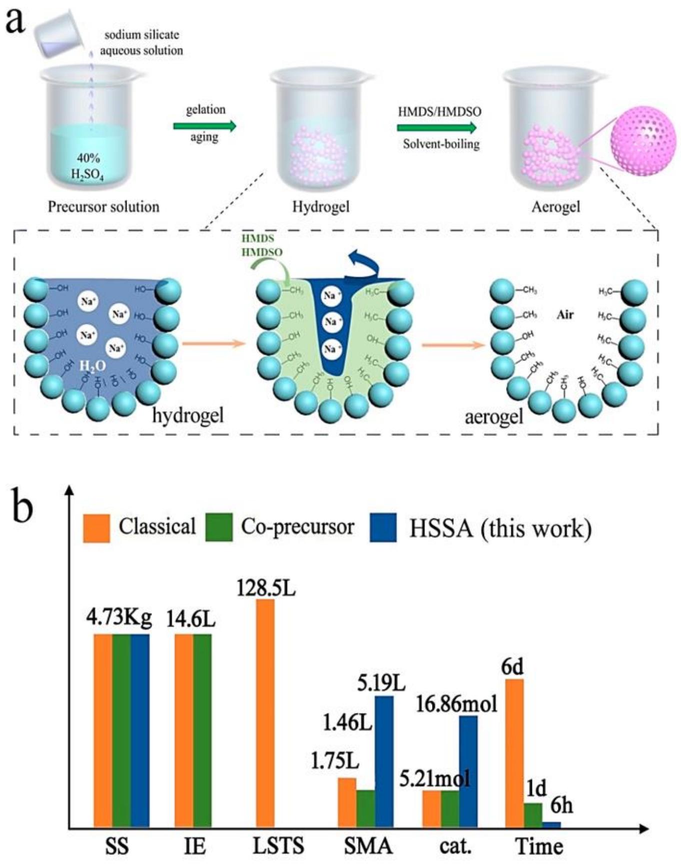

Fig. 2 (a) Schematic description of the HSSA strategy; (b) comparison of the reagent consumption between different approaches. Reproduced with the permission from [22], Copyright 2021 American Chemical Society.

2.2 Aging

Some alcohol groups that have not reacted remain in the silica ridges of the gel after the sol has reached the gel stage. In order to strengthen the silica network, it is necessary to manage the pH, concentration, and moisture content of the covering solution for a sufficient duration of time.[9,15,26,27] Condensation and hydrolysis may occur during this operation. Two mechanisms that can affect the properties and structure of the gel during aging are the chemical reaction of reprecipitation of dispersed silica on the particle surface, which forms a bond between the particles (polymer bridging or siloxane bonding), resulting in neck growth, and the precipitation and dissolution of small particles, which leads to the formation of wider particles.[9,26-28] The process of aging is governed by diffusion. Although the silica network is in a solid state, the convection or associative transport of the material stays consistent, regardless of the thickness of the gel, which does affect diffusion. Therefore, the production of aerogel is constrained by the increasing thickness of the gel during each processing stage, which limits the volume that can be generated.[9,26] Prior to the subsequent stage, which is the drying process, it is necessary to remove any remaining water in the pores that may have been left during the aging process. Ethanol-siloxane mixes are commonly used in aging methods. Following the aging process, the gel should be cleansed using ethanol and heptane to eliminate any residual moisture within the pores.

2.3 Drying

The drying stage is the final step in the sol-gel process. Extracting the solvent from the gel matrix without generating capillary forces or two-phase interfaces is a critical stage in the production of aerogels. This non-destructive liquid-phase removal process may be used to make a porous solid that has the same shape and volume as the original gel.[1] The drying process is a crucial phase in the production process of aerogels. It is closely linked to the composition of the gel, which determines the pore size and structural qualities of the finished aerogel.[9] Therefore, it is essential to choose the appropriate drying method. Presently, freeze drying, air drying, and supercritical drying are the most commonly employed drying methods.[1,27,29-32]

2.3.1 Supercritical Drying (SCD)

The initial production of aerogels occurred in the 1930s, which coincided with the advancement of the supercritical drying process.[9,31,33] Supercritical drying has become the most widely recognized drying technology for preparing low density aerogel. Supercritical drying often yields aerogel with favorable attributes such as strong structural integrity, high porosity, and a large specific surface area.[20,34] The process of gel drying is an essential step in supercritical drying as it suppresses the liquid-gas interface, hence decreasing capillary force and avoiding pore collapse.[1,27,31] However, there are two main disadvantages associated with supercritical drying: the high cost of the required equipment to work at high pressure and its intricate experimental conditions.[35-37]

During the supercritical drying process, closed containers are used to expose solvent-rich gels to gases such as carbon dioxide (CO_2) or methane. The goal is to increase the temperature and pressure of the reactor above the threshold at which the residual solvent in the gel pores reaches a critical level. When the parameters in the high-pressure vessel exceed the critical threshold, the liquid transitions into a supercritical fluid state, allowing every molecule to flow freely and removing surface tension.[9,27,28]

2.3.2 Ambient Pressure Drying (APD)

Air Pressure Drying (APD) is a dehydration technique that may be employed in industrial production environments. This approach guarantees that no new chemical bonds are formed during the drying process by deactivating the pore surface of the wet gel.[29] The environmental pressure drying method consists of two main steps. The initial stage involves silylation, a process that involves modifying each Si-OH group to produce hydrophobic aerogels by inhibiting the attachment of water molecules. This is achieved by replacing the current solvent with a solvent that does not contain water, and by using silanizing agents (such as chlorotrimethylsilane, hexamethyldisilazane, etc.) to ensure that the hydrogen atom (H) on the Si-OH group is replaced by an alkyl group (CH_3). The process of evaporative drying under environmental pressure consists of three sequential processes, with the second step being the focus. The initial drying phase occurs when the volume difference inside the gel, caused by the evaporation of liquid, reaches a state of balance after a time of heating. During the first descent phase, capillary forces result in the direct flow of the liquid from a section of the cavity to the outside. Finally, the second phase of the decreasing rate takes place, in which the liquid slowly spreads outwards from the dry gel.[26,38]

2.3.3 Freeze drying

Freeze drying, also known as lyophilization, is another option for drying aerogels. This method is environmentally friendly, simple, and economical, and can produce aerogels with low shrinkage and high porosity.[29,39] In this process, the liquid in the pores is frozen and sublimated under low pressure.[9,27,29] The freeze-drying cycle involves three steps: firstly, the temperature for sublimating the solvent in the pores is lowered below the triple point; in the second stage, the system is evacuated; the final step is controlled under isobaric conditions.[1]

3. Application of silica aerogel

Silica aerogel has the characteristics of high porosity, low density, low thermal conductivity, high light transmittance, super adsorption capacity, super high specific surface area and flame retardant.[13,14,38,40,41] These properties make silica aerogel widely used in various fields (Fig. 3).[42] With the rapid development of new compositions, process technologies, and enhancement strategies for structures and drying methods,

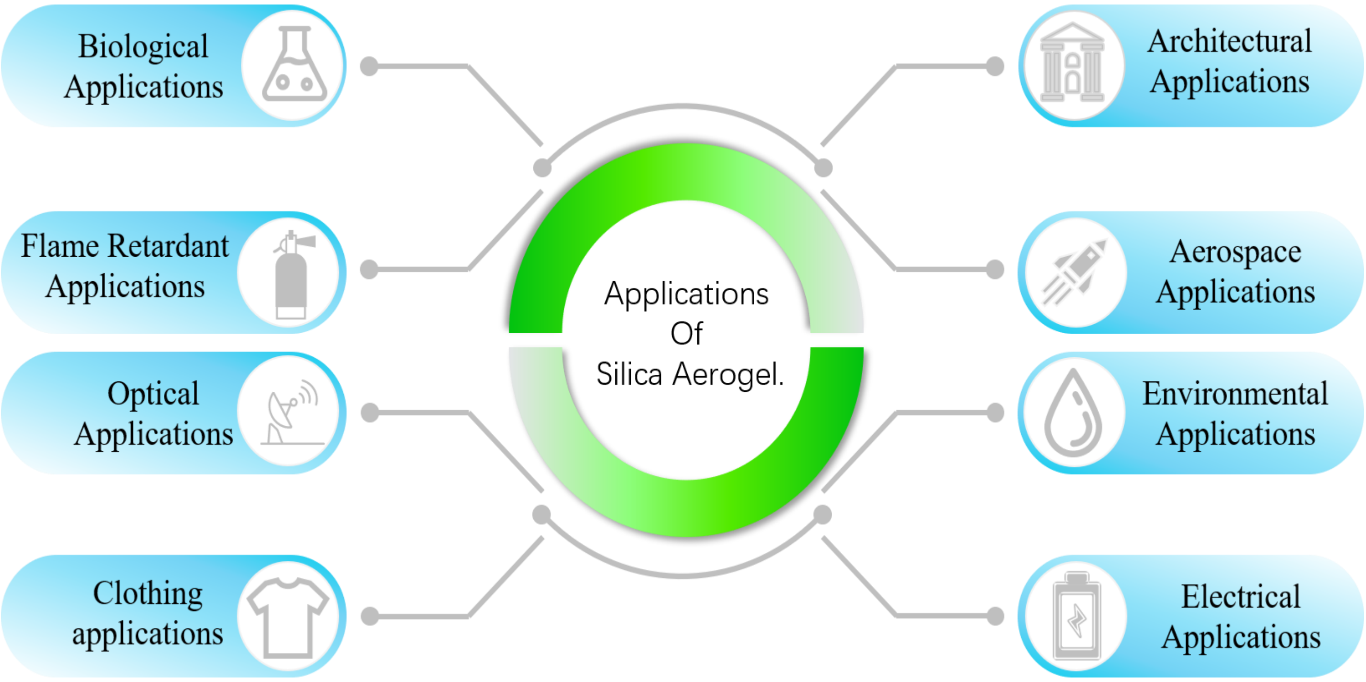

Fig. 3 Various applications of silica aerogel.

silica aerogels have emerged as a material class with great potential for advanced technological applications since the early 21st century.[9]

3.1 Architectural applications

Because of their superior physical characteristics, namely their transparent appearance and low heat conductivity, aerogels have a wide range of potential applications in the building industry.[43,44] It may be utilized, for instance, as a lightweight thermal insulation structure of super high-rise structures, as well as a solar collector cover plate, roof insulation material, energy-saving window glass, and thermal insulation layer of industrial and civil buildings.[9] Because of its special qualities, aerogel is used in lightweight, energy-efficient construction. Silica aerogel's effective thermal conductivity at room temperature is half that of air and other commercial thermal insulation materials (EPS foam, mineral wool).[40,45] When compared to conventional insulating materials, the yearly heat loss of residential buildings is anticipated to be greatly decreased with the application of silica aerogel.[27] One of the greatest insulators is silica aerogel, despite the fact that it is still very expensive when compared to more conventional materials.

Furthermore, silica aerogel has a strong sound-insulating effect due to its porous structure.[9,27] The amount of energy lost when sound waves are continually released from the gas phase to the solid phase, which lowers the amplitude and speed of the sound waves and causes them to slow and dissipate more quickly, is what determines how much sound attenuation occurs in silica aerogels.[6,46] Because of this, silica aerogel may be an effective sound-absorbing material. Because of this, silica aerogel is also often utilized in auditorium, music hall, and theater ceiling tiles.

By substituting methyl triethoxysilane for methyl trimethoxysilane, Li *et al*.[47] created a translucent, flexible, hydrophobic silica aerogel in an aqueous CTAB solution by using a cationic surfactant. This study offers a simple method for producing transparent, hydrophobic, light-weight, and flexible silica aerogels. These materials are used in window profiles and building drains because of their improved sound insulation, decreased thermal conductivity, and increased thermal stability (Fig. 4).

Saboktakin *et al*.[48] have fabricated a nanocomposite by reinforcing 1, 4-cis-polybutadiene/CMS with silica aerogel. The tensile characteristics and dynamic mechanical properties of 1, 4-cis-polybutadiene/CMS nanocomposites were significantly improved when a little amount of silicon was added. The tensile modulus and strength of mesoporous silica nanocomposites containing 1, 4-cis-polybutadiene were enhanced to a similar extent. The nanocomposite has demonstrated favorable thermal and mechanical characteristics and is harmonious with other silica aerogel-polymer systems that have been previously employed in building applications.

Tian *et al*.[49] developed a flexible and compressible integrated dual-network polyimide/silica (PSi) composite aerogel employing an in situ synthesis approach and an anisotropic polyimide nanofiber aerogel (PINA) as a template. The polycondensation process involves the formation of a hydrogen connection between polymethylsiloxane (PMSQ)

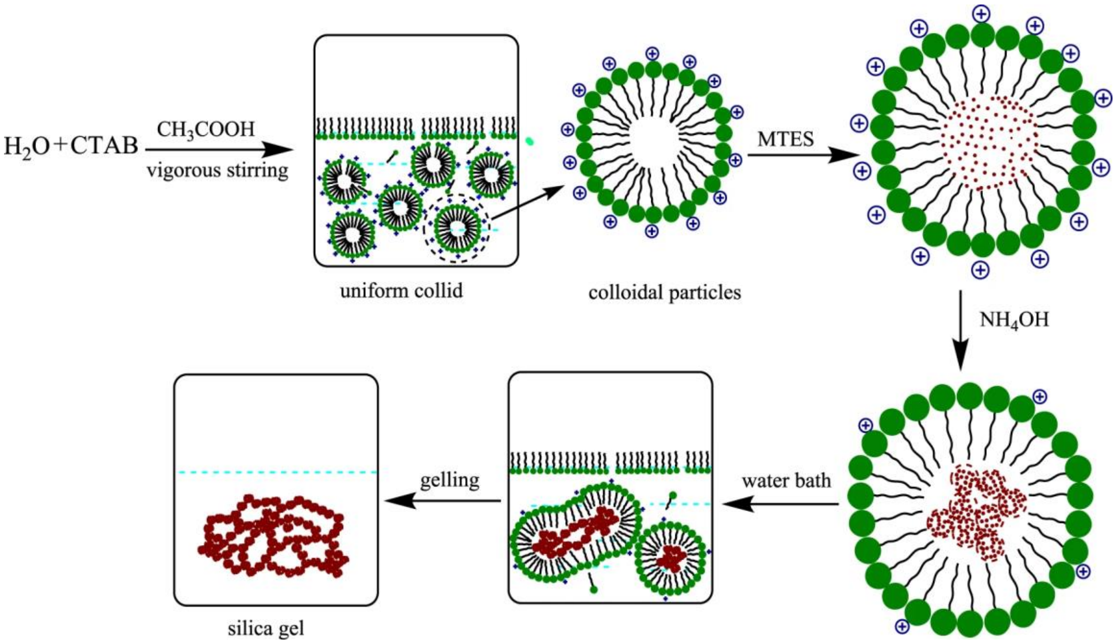

Fig. 4 The principle of preparation of MTES-based SiO_2 aerogel by CTAB. Reproduced with the permission from [47], Copyright 2019 Springer.

oligomers and PI chains. This interaction helps in evenly dispersing PMSQ colloid nanoparticles, resulting in the creation of a continuous double network of SiO_2 and PINA. The composite aerogel has excellent mechanical elasticity due to its anisotropic structure. It can endure 500 cycle fatigue tests and bear a radial compression strain of 50% without fracturing. Additionally, it demonstrates strong mechanical stability in the axial direction. Furthermore, PSi composite aerogels have a radially low thermal conductivity ranging from 20.3 to 27.5 mW m^{-1} K^{-1}, which is lower than that of the majority of organic aerogels (Fig. 5). The composite aerogel demonstrates exceptional flame-retardant capabilities due to the robust interfacial connection between the PINA matrix and the silica network. It can withstand ultra-high temperature flames without collapsing, even when organic components are consumed. The combination of these qualities makes composite aerogels highly valuable for use in building applications, particularly in challenging conditions where conventional polymer insulation materials are susceptible to fire hazards.

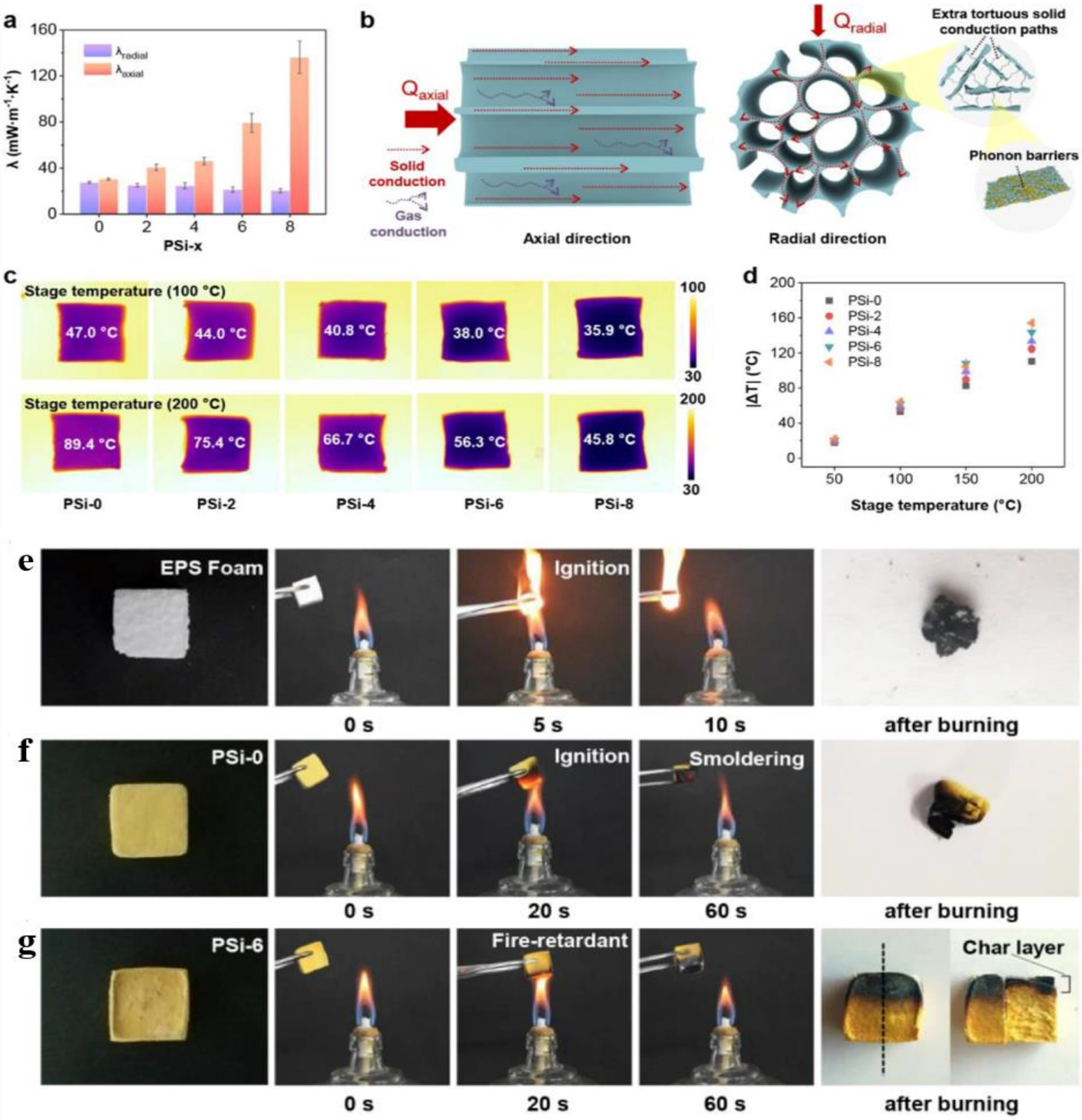

Fig. 5 (a) The thermal conductivities of the PSi aerogels in the axial and radial directions. (b) Schematic illustration indicating the mechanism to achieve excellent thermal insulation. (c) Thermographic images of the PSi aerogels on a hot stage with surface temperatures of 100 °C and 200 °C. (d) Temperature difference (ΔT) between the PSi aerogels surface and the hot stage with temperatures ranging from 50 to 200 °C. Photography of (e) EPS foam, (f) PSi-0 and (g) PSi-6 aerogels burning by an alcohol lamp at different times. Reproduced with the permission from [49], Copyright 2022 Elsevier Ltd.

3.2 Aerospace applications

The successful launch of Sputnik 1 by the Soviet Union in october 1957 marked the beginning of human space exploration. Since then, the space business has grown and expanded in a variety of ways, encompassing interplanetary travel and a number of Earth-orbiting missions. The study of aerospace materials dates back to the 1960s, and the constant quest to increase performance, decrease weight, and save costs is what propels material development.

Due to its low density and thermal conductivity values, silica aerogel is an attractive material necessary for thermal insulation in large aerospace applications[9,50,51] In addition, silica aerogel has excellent high and low temperature resistance, radiation resistance and excellent thermal insulation properties, which is suitable for thermal insulation of various space missions.[40,52] Silica aerogels are also used in the coating of space suits to provide thermal insulation.[50] Despite its low mechanical strength and restricted carrying capacity, silica gel aerogel has a specific use in some space missions. For instance, the aerogel structure may progressively slow down the motion of high-speed cosmic dust particles that are gathered from a comet's tail, trapping and conserving them well and giving samples for additional research[9,50,53] The requirement for non-destructive collection and preservation of such minute particles is perfectly met by the brittle character of aerogel.

To produce a PI-silica aerogel composite with little shrinkage, low density, low thermal conductivity, high hydrophobicity, and excellent fire resistance, Xi *et al.*[54] incorporated silica aerogel powder into a PI matrix. When subjected to 80% strain, the final sample does not break apart and has a notable ability to be compressed. In addition, it possesses excellent thermal stability, low thermal conductivity, and fire resistance (Fig. 6). The PI-silica aerogel composite aerogel has great potential as a material for the aerospace sector due to its exceptional overall properties.

Cheng *et al.*[55] devised a straightforward and practical method for producing flexible and malleable aerogels that are capable of enduring extremely high temperatures and pressures. The technique employs commercially accessible silica aerogel particles (SAM), alumina ceramic fibers, and self-sacrificing hydroxypropyl methyl cellulose (HPMC) polymers as the primary ingredients. Silica-alumina hybrid ceramic aerogels (SACA) were created by the process of combining molding and environmental drying. Subsequently, the SACA underwent high-temperature treatment using the "Phoenix Nirvana" technique, resulting in the formation of the fire regeneration SACA (FR-SACA) with a bionic bird's nest structure (Fig. 7). The FR-SACA that was acquired possesses an extremely low density of 0.01 g/cm^3, a low thermal conductivity of 0.029 W/m·K, and exceptional mechanical characteristics. In addition, FR-SACA demonstrates the ability

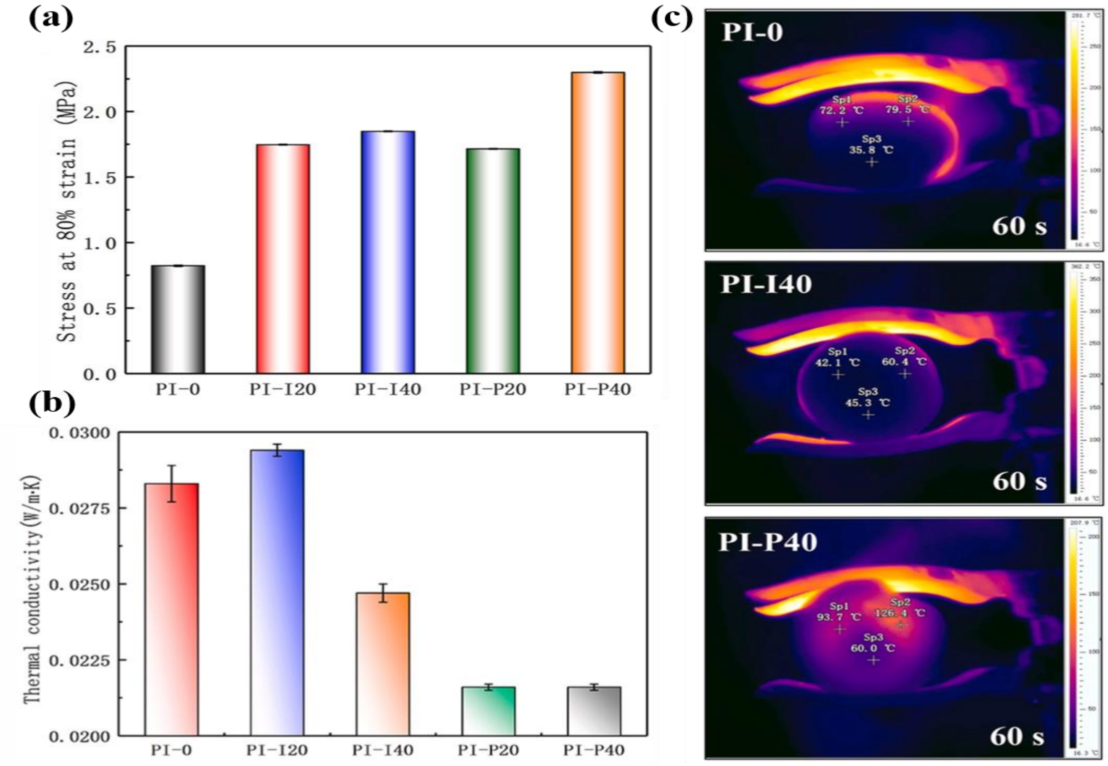

Fig. 6 (a)stress at 80% strain and (b)of the PI-silica aerogel composite aerogels,(c) Pseudo-color thermal images of PI-0, PI-I40 and PI-P40 after burning with butane blowtorch for 1 min. Reproduced with the permission from [54].

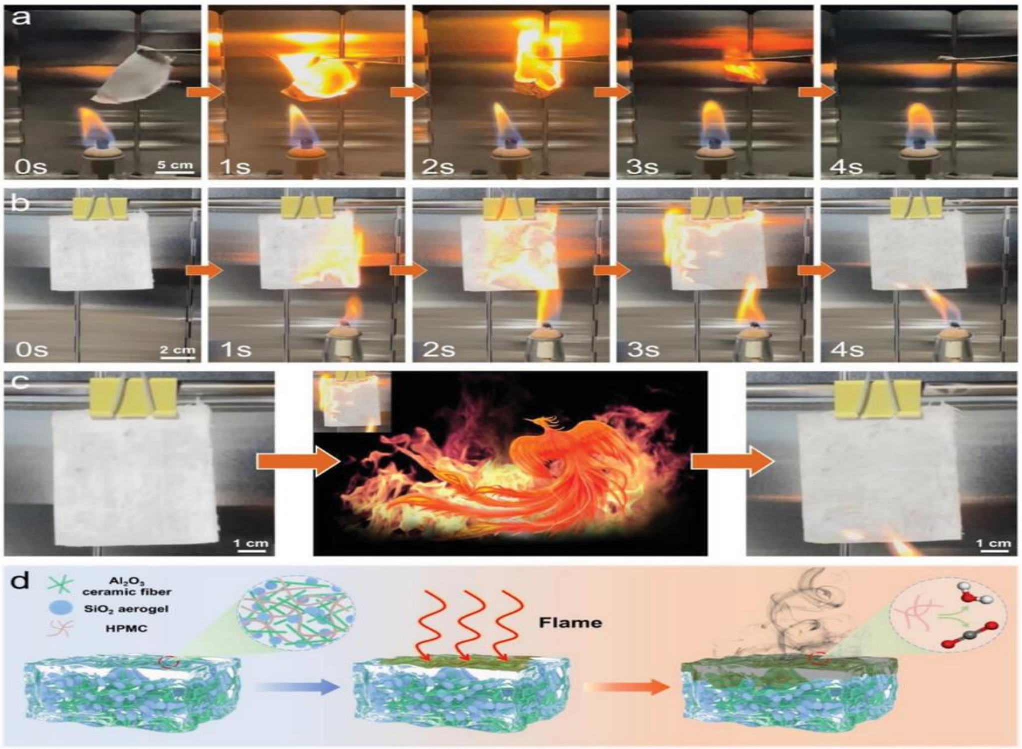

Fig. 7 (a) The combustion process of silica aerogel and HPMC composite film. (b) The combustion process of SACAs. (c) Illustration of the fire-reborn process of SACAs, the middle cartoon shows the Phoenix Nirvana. (d) Schematic diagram of the reaction during the combustion process of SACAs. Reproduced with permission from [55], Copyright 2023 Wiley-VCH GmbH.

to maintain its structural integrity when exposed to a butane flame at a temperature of 1300 °C, exhibiting a temperature reduction of over 80%. The exceptional characteristics of FR-SACA make it a great choice for providing thermal protection in very challenging conditions. This study addresses the constraints of conventional ceramic aerogels and introduces flexible deformable aerogels with improved thermal stability, offering a viable approach for efficient thermal regulation in harsh environments.

3.3 Clothing applications

Silica aerogel is increasingly being utilized in the domain of personal garments and footwear.[1,56-58] The preparation techniques of different aerogels have been extensively researched. The porous structure of silica aerogels provides excellent thermal insulation capabilities and low density, making it superior to many fiber materials.[59] As a result, silica aerogels have great potential for use in personal apparel.

Omranpour *et al*.[60] employed the gel spinning technique to transform the mTPU-SA slurry, which has a high viscosity, into aerogel fiber. This novel structure integrates the environmentally friendly, biocompatible, and biodegradable properties of the base material with the low density, high specific surface area, and high porosity of the aerogel material. These sophisticated fibers have many applications, such as in protective gear and stretchable clothes, particularly in challenging conditions.

Kim *et al*.[57] introduced an electrospinning technique to fabricate polymer nanofibers packed with silica aerogel by enhancing the conventional sol-gel chemical production of silica aerogel (Fig. 8). Aerogel nanofibers provide exceptional insulating characteristics, mostly attributed to their multi-scale porous structure, which encompasses both micropores and nanopores. This polymer nanofiber is anticipated to stimulate technical advancement in the realm of thermal insulation apparel applications.

Xue *et al*.[61] fabricated a dual-layered organic/inorganic aerogel fiber by employing polyamine (PAA) as a catalyst and organic phase, and TEOS as the precursor for SiO_2 and the inorganic phase. This was achieved by a process of co-gelation and freeze spinning. The combination of the SiO_2 network and PI matrix results in the PI/SiO_2 aerogels with exceptional thermal stability (>300 °C) and a low thermal conductivity in heated environments (75.6 mW m^{-1} K^{-1} at 350 °C). Furthermore, the PI/SiO_2 aerogel fabric has hydrophobic properties with a water contact angle (WCA) of 119.8°. It also possesses a low thermal conductivity of just 58.8 mW m^{-1} K^{-1} at 100% relative humidity at a temperature of 80 °C (Fig. 9). The PI/SiO_2 aerogel textile, being a novel form of thermal insulation textile, exhibits significant potential for application

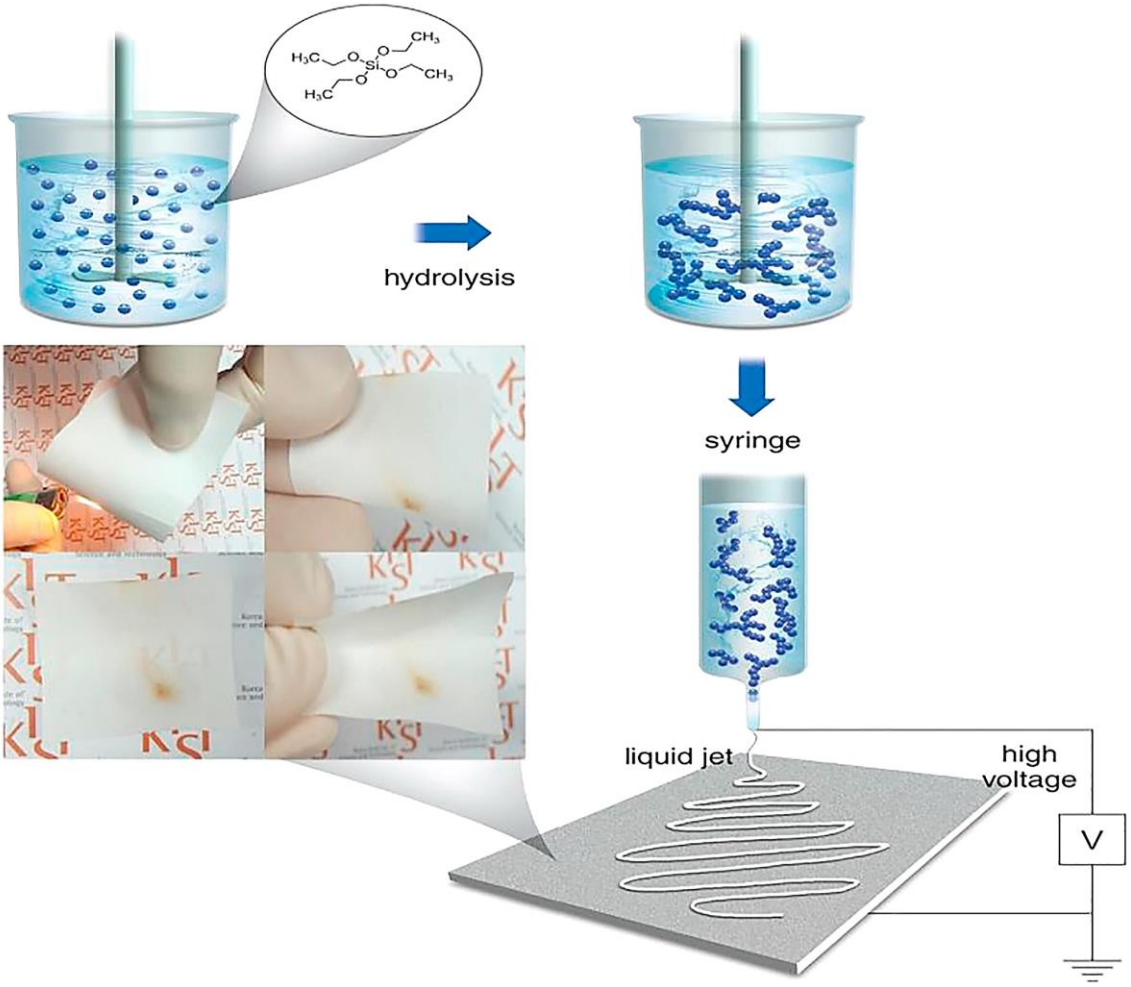

Fig. 8 Schematic for the proposed electrospinning of the silica aerogel-filled nanofibers. Reproduced with the permission from [57], Copyright 2018 Elsevier B.V.

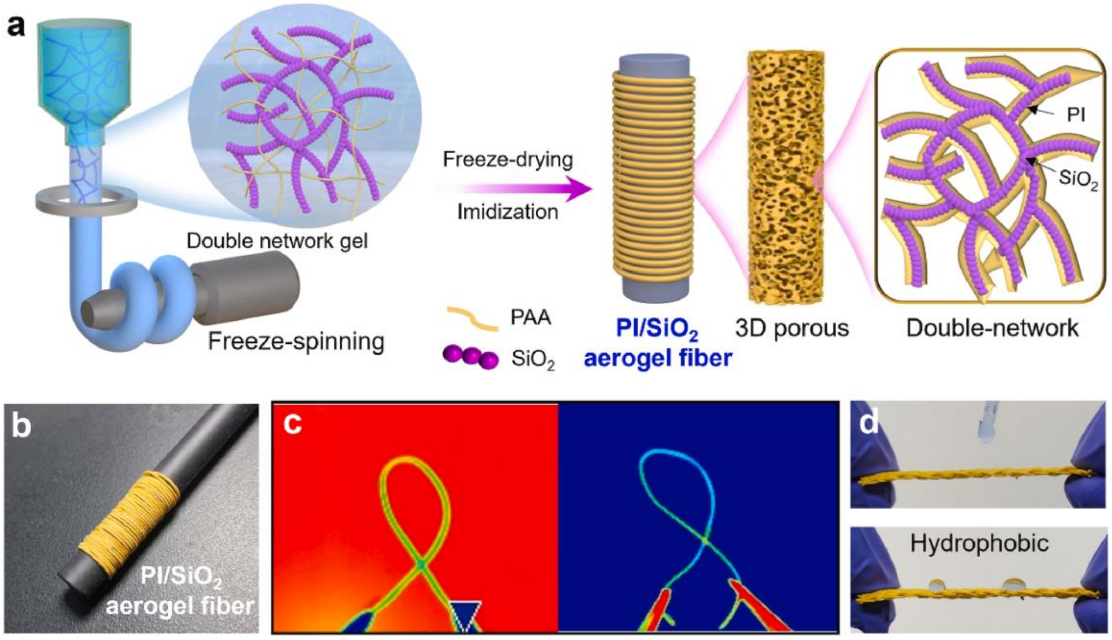

Fig. 9 Preparation of double-network PI/SiO_2 aerogel fibers. (a) Schematic diagram of fabrication of double-network PI/SiO_2 aerogel fibers. (b) A roll of PI/SiO_2 composite aerogel fibers. (c) The PI/SiO_2 aerogel fiber could be easily bent in hot (300 °C) and cold (-196 °C) environment. (d) Water drops onto the hydrophobic PI/SiO_2 aerogel fabric without spread and permeation. Reproduced with the permission from [61], Copyright 2023 Elsevier Ltd.

in hot and humid environments.

3.4 Environmental applications

Silica has hydrothermal stability and high thermal properties, and is a strong and stable adsorption material.[62-64] It's an inexpensive, high-performing, non-toxic component. Superhydrophobic silica aerogel has proven to be a highly effective absorbent for a variety of organic liquids, including grease. Because of their unique absorption ability, aerogels may be employed again as absorbents.[28,65,66] Additionally, by taking part in the capture, recovery, and conversion of atmospheric CO_2 into more valuable goods, they may be employed as a creative means of reducing greenhouse gas emissions.[67-69] The elimination of volatile organic pollutants, oil-water separation, dye adsorption, gas phase purification, and other significant environmental uses of silica aerogels.[70,71] Saharan *et al*.[72] provide a sol-gel technique for producing chitosan-silica aerogel, which offers superior control over the reaction compared to hydrothermal or chemical bath deposition methods. The aerogel that is produced shows improved oil entrapment and has a structure that consists of micro and nano-sized pores. The aerogel underwent hydrophobization treatment using hexamethyldisilazane (HMDS), which enhanced its capacity for oil adsorption. A novel and straightforward method for tackling and improving significant pollution of soil, water, and oil involves the use of mixed aerogel for oil extraction (Fig. 10). In the future, it is probable that commercial applications may utilize mixed and organic aerogels to increase the ability to absorb oil.

Jia *et al*.[73] employed supercritical carbon dioxide (Sc-CO_2) as a foaming agent, isocyanate (MDI) as a chain extender, and silica aerogel with very low thermal conductivity as a filler to fabricate a foam board with an extremely low thermal conductivity. To address the limited foaming capacity of PLA, the melt strength of PLA was enhanced, and the bubble structure of PLA foaming material was modified using silica

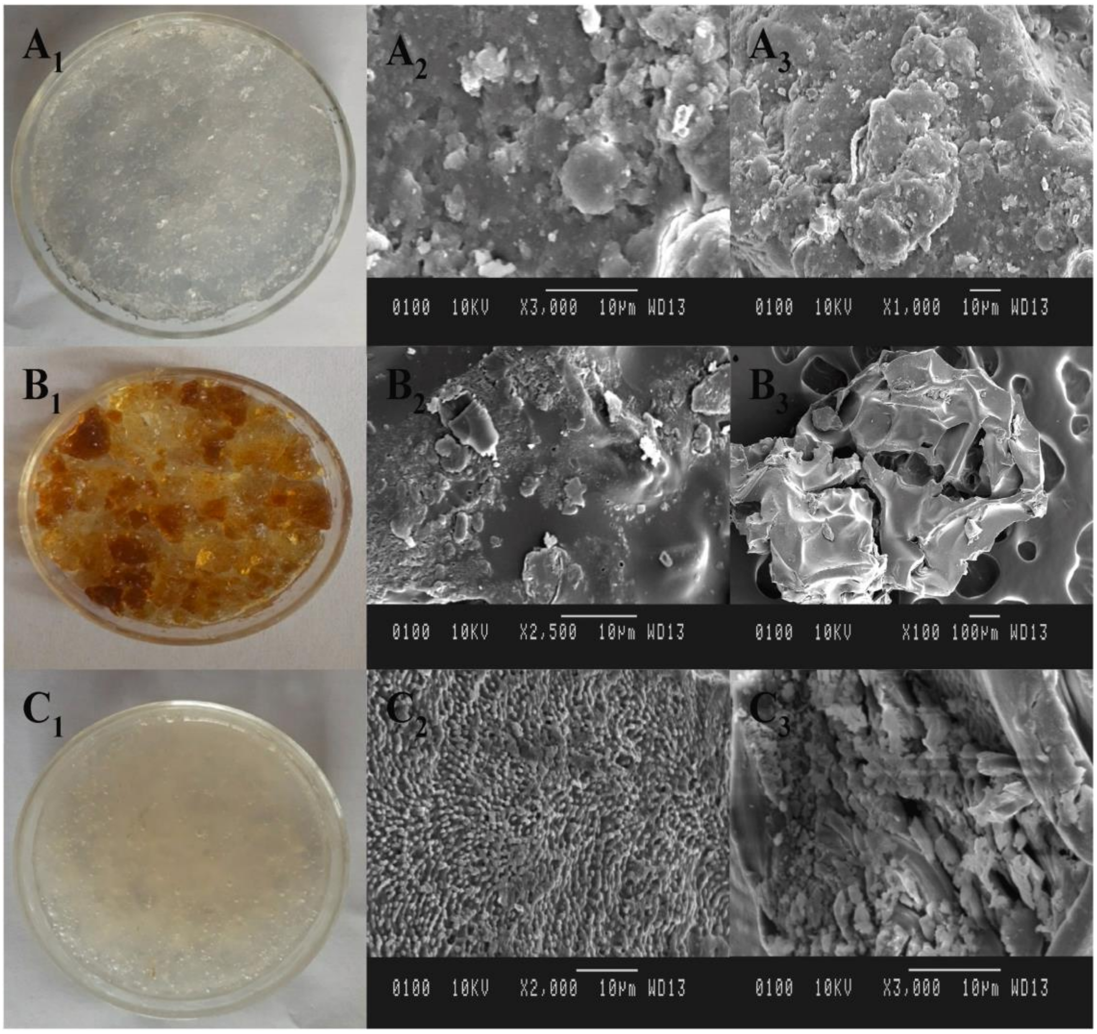

Fig. 10 Photographs of the aerogels: (A1) silica aerogel (0-CS), (B1) chitosan aerogel (100-CS), and (C1) chitosan–silica blend aerogel (25-CS) and SEM micrographs of these aerogels: (A2) unmodified silica aerogel, (A3) HMDS-modified silica aerogel, (B2, B3) chitosan aerogel with glutaraldehyde as the cross-linker, (C2) unmodified blend aerogel, and (C3) HMDS-modified blend aerogel. Reproduced with the permission from [72], Copyright Elsevier Ltd.

gel aerogel. An ultra-low density biodegradable insulating foam that may be utilized in many insulation applications.

Liu *et al*.[74] employed Methyltriethoxysilane (MTES) as the source of silica and devised two uncomplicated and efficient techniques to control the pore size of silica aerogels, eliminating the need for a template agent (Fig. 11). One method is to vary the water content in the reaction system, resulting in variable amounts of hydroxyl groups. These hydroxyl groups then induce the primary particles to combine and form bigger secondary particles. Another approach is to incorporate a crosslinking agent to modify the silicon network structure to varying extents. The performance of aerogel in practical applications is determined by its pore size and pore structure. As the aerogel's pore size expands, its ability to adsorb volatile organic chemicals (VOCs) including dichloromethane, dimethylformamide, and hexane rises. This makes it very promising for many applications in environmental purification.

3.5 Electrical applications

It is crucial to isolate all electrical components, such as capacitors and resistors, in electronic equipment. Failure to do so might result in severe short circuits if power is distributed uniformly. Due to its extremely low density, silica aerogel, the lightest known solid, may be effectively utilized in various electrical components after appropriate modifications to meet specific needs. Several researchers are now examining the application of aerogel in the field of electricity.

Feng *et al*.[75] developed a novel composite diaphragm by integrating hydrophobic silica aerogel with a polypropylene (PP) diaphragm. The composite diaphragm, consisting of hydrophobic silica aerogel with numerous holes, has excellent insulating properties and a strong affinity for electrolytes, such as ethylene carbonate (EC)/dimethyl carbonate (DMC), DMC/1,3-dioxolane (DOL), and Diglyme. This diaphragm effectively compensates for the inherent flaws of PP diaphragms and enhances their overall performance. The material possesses a three-dimensional porous network structure, which effectively hinders heat transmission, enhances the surface area and surface energy of the diaphragm, and promotes the mobility of the electrolyte. Furthermore, the hydrophobic groups and the three-dimensional porous structure of the silica aerogel layer synergistically enhance the affinity and electrolyte retention capacity. It offers a novel approach to enhance power battery safety and minimize battery polarization.

Ma *et al*.[76] developed a hybrid film, denoted as A-SiO_2/Phorbol 12-myristate 13-acetate (PMA), by incorporating an amorphous silica aerogel into a polymethacrylate (polytrifluoroethyl methacrylate)/polyhydroxyethyl methacrylate matrix. This film was meant to serve as an artificial solid electrolyte interface layer for the modification of lithium metal anodes. The amorphous silica aerogel can undergo a chemical reaction with Li to produce Li-Si alloy, resulting in a rise in the Young's modulus of the solid Electrolyte Interphase (SEI) layer. Porous amorphous silica aerogels possess a large specific surface area and offer many pathways for ion movement, hence facilitating

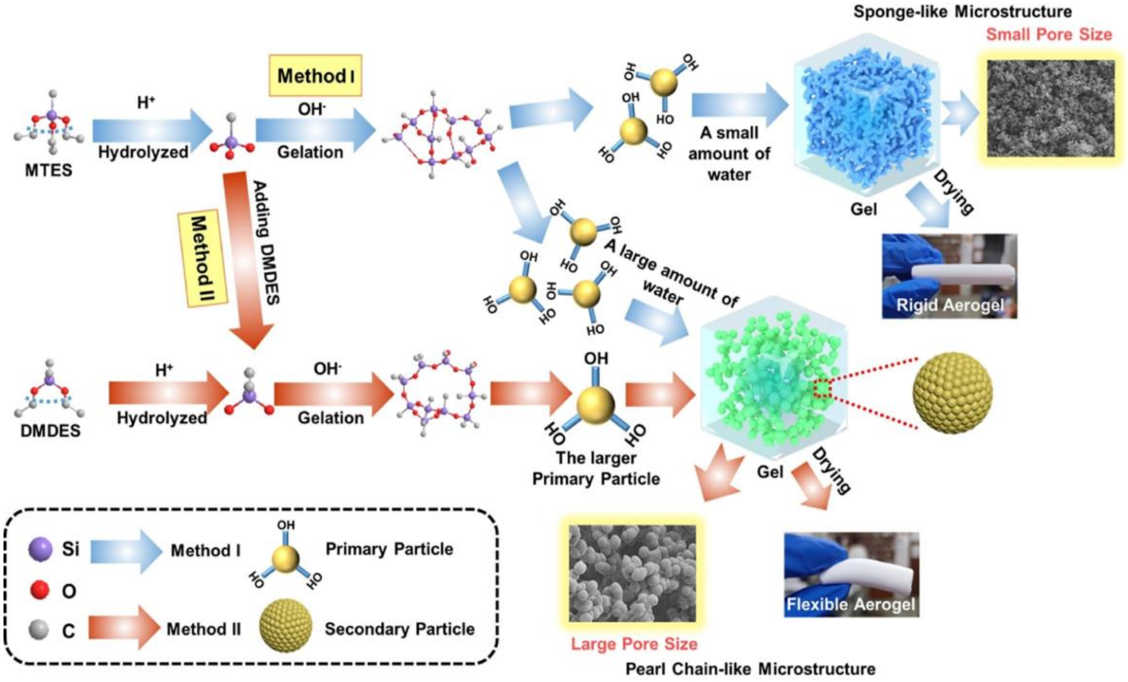

Fig. 11 Schematic diagram of the formation mechanism of silica aerogel with different pore size diameters using MTES as the silica source. Reproduced with the permission from [74], Copyright 2022 Elsevier B.V.

high ion conductivity. The a-SiO_2/PMA thin films, in contrast to the conventional electrolyte-derived SEI with a loose and brittle structure, have the ability to suppress the formation of Li dendrites and control the even deposition of Li. This characteristic makes them very valuable for practical applications in high-energy LMBs.

Kim *et al*.[77] synthesized a nanocomposite polymer electrolyte with single-ion conductivity using a functionalized SA molecule that is chemically attached to a weakly bound anionic monomer (Fig. 12). This monomer is then transformed into a lithium single-ion conductive ionomer on the surface of the SA molecule, resulting in the formation of a framework. The SANPE framework utilizes interconnected silica nanoparticle-based SA networks to enhance the overall strength of the nanocomposite polymer electrolyte. The nanoscale network structure of the SA also serves as a conduit for rapid ion migration and facilitates high lithium-ion mobility due to its continuous and extensive specific surface area. The integration of SA and weakly bound anions in this innovative technique presents a very promising approach to enhance ion conductivity, lithium transfer number, mechanical strength, and energy storage capacity all at once.

3.6 Biological applications

Silica aerogels possess high porosity, excellent stability, a porous structure, easy surface functionalization, adsorption properties, and a large specific surface area.[78] These characteristics provide unique properties and excellent accessibility of the inner surface through open pore networks, making them suitable for use as carrier materials in medical applications.[9,79] The hydrophobic/hydrophilic properties of the aerogels can be adjusted as needed to control the release rate of the drugs carried within. Hydrophobic aerogels can slow down the drug release, while hydrophilic aerogels can speed up the release process. This property makes aerogels an ideal high-efficiency drug carrier material due to their biocompatibility and biodegradability with no toxic side effects on humans; they are completely safe and reliable for human use. By optimizing the properties of aerogels, precise control over drug release behavior can be achieved to attain optimal therapeutic effects.[80,81]

Due to their specific physical properties such as general biocompatibility, high and customizable porosity, and mechanical strength, aerogels are suitable materials for tissue engineering.[81-83] Depending on synthesis conditions, silica-based aerogel surfaces contain numerous silanol functional groups that enhance bioactivity by promoting cell adhesion, proliferation, and differentiation while exhibiting controlled biodegradation or absorption rates during new tissue formation.[81,84] Therefore, silica-aerogel-based composite materials are often used as bone scaffold materials in bone tissue engineering.[85]

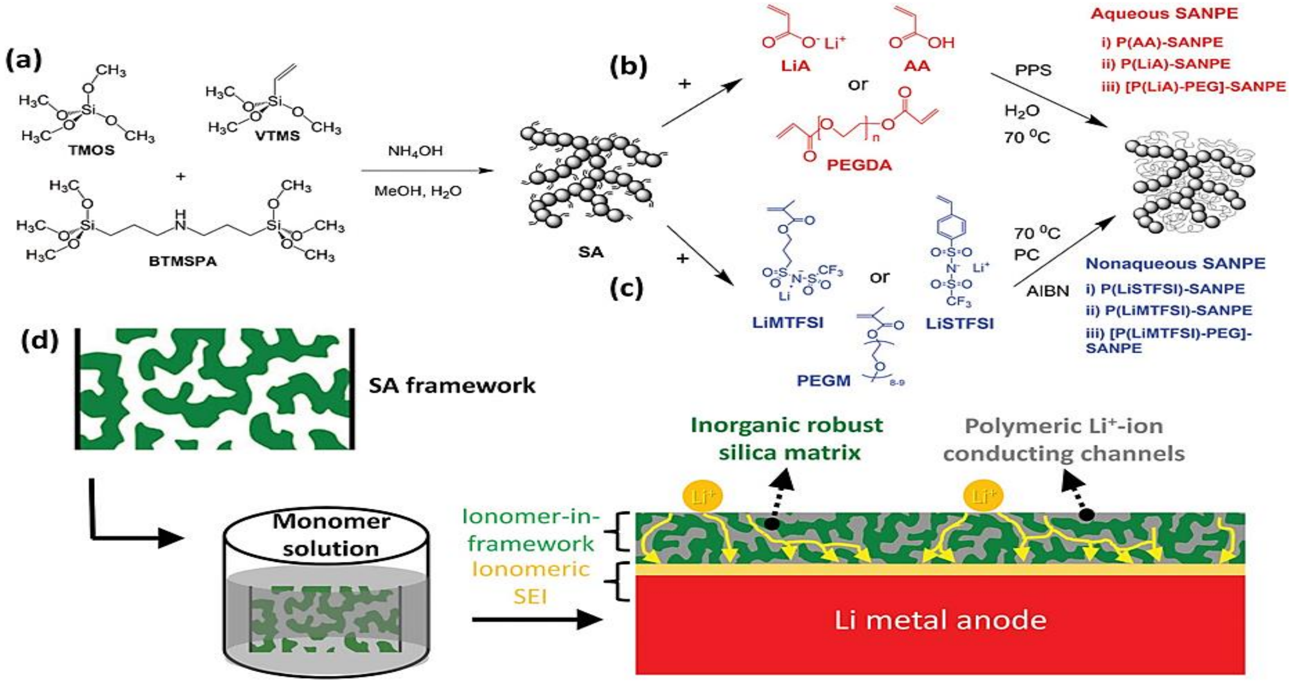

Fig. 12 Schematic description of a) silica aerogel (SA) and b) aqueous and c) non-aqueous SANPEs, where SAs were grafted with ionic monomers (LiA, AA, LiMTFSI, or LiSTFSI) or polar groups (PEGDA or PEGM) via free radical polymerization. d) Schematic images of SA-integrated single-Li^+ conducting nanocomposite polymer electrolytes, composed of inorganic robust silica matrix and polymeric Li^+ conducting channels (ionomer-in-framework). Reproduced with the permission from [77], Copyright 2023 Wiley-VCH GmbH.

A biocompatible scaffold with appropriate mechanical qualities was created by Pontinha *et al*.[86]; phosphates or other inorganic chemicals were not required. Polycaprolactone (PCL) composites and silica-aerogel can be employed in tissue engineering, particularly as materials for bone grafts. TEOS, which is hydrophilic, and MTMS, which is hydrophobic, were hybridized with PCL for this reason. The aerogel that was created using the sol-gel process was added to PCL to create these porous hybrid scaffolds. Compared to TEOS-aerogel composites, MTMS aerogel composites are more hydrophobic, have a larger surface area, and are denser. Within seven days of the in vitro trials, the scaffold demonstrated good cellular compatibility.

Qin *et al*.[87] integrated RES into silica aerogel and successfully generated these nanoparticles by using the aerogel's pore structure. As a consequence, there was an augmentation in the slow and gradual release of the substance, a decrease in its harmful effects on living cells, and an improvement in its effectiveness in treating medical conditions. The in vitro experiments show that RSA has positive biocompatibility and low cytotoxicity. In addition, it efficiently reduces the progression of inflammation by regulating the synthesis of TNF-α, type II collagen, and agglomerin in chondrocytes. The results suggest that silica aerogel may be used as a novel method for delivering medication orally, and RSA has potential for non-invasive treatment of exercise-induced osteoarthritis.

Yang *et al*.[88] employed tetraethoxysilane (TEOS) to chemically bond pea protein isolate (PPI) and form a composite gel, with the objective of improving the bioavailability of silicon-based aerogel. The PPI-Si aerogel displayed a dense mesoporous structure, leading to an oil retention capacity of 89.67% for PPI (10%)-Si aerogel, hence generating a very stable oil gel. The chemical oil gel effectively extended the duration of curcumin release in the stomach during in vitro digestion, hence enhancing the absorption of nutrients in the intestine. The results suggest that plant protein can improve the properties of silica aerogel, providing useful information for the application of silica aerogel in many industries, including food and non-food sectors.

Xu *et al*.[89] introduced a novel approach to create strong and long-lasting superamphiphobic silica aerogel surfaces (SSAS) for the purpose of multicellular spherical cultivation. SSAS were synthesized using chemical vapor deposition (CVD) utilizing Poly(3,4-ethylenedioxythiophene) (PEDOT) and soot particles as templates (Fig. 13). The excellent antifouling capabilities of this highly amphiphobic surface

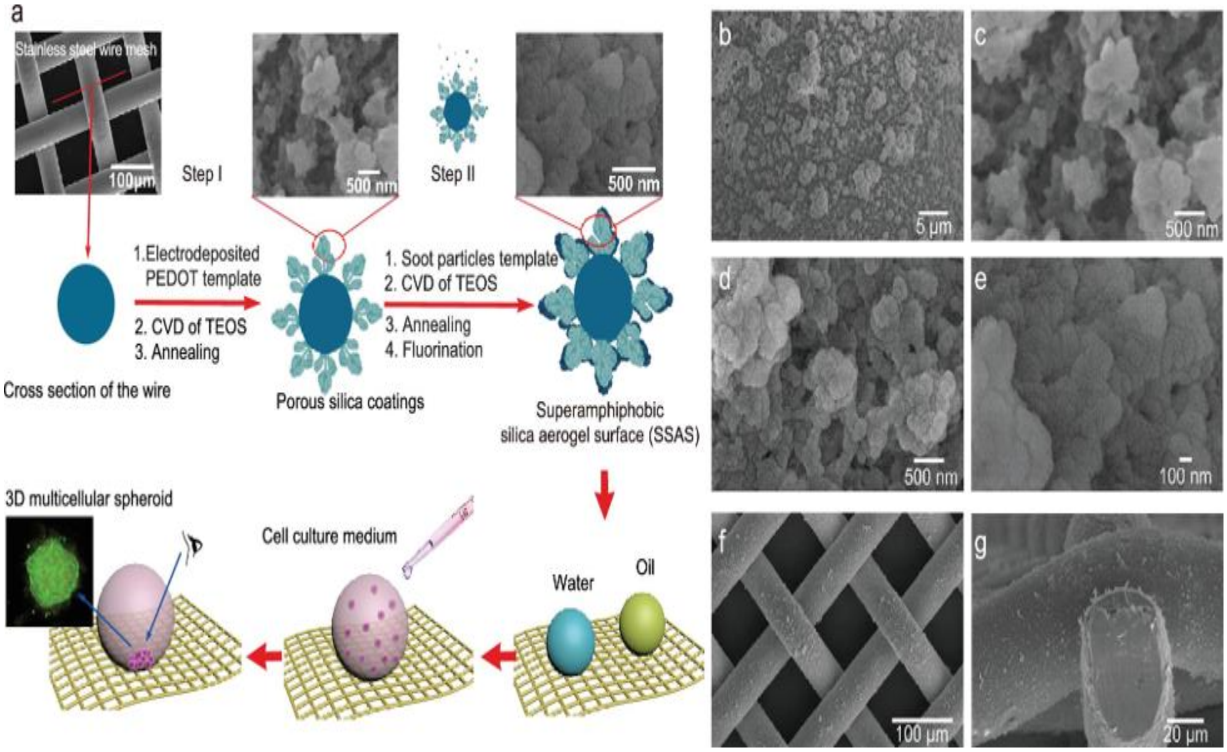

Fig. 13 (a) Fabrication of a superamphiphobic silica aerogel surface (SSAS) by a dual-template strategy and procedure for culturing 3D cell spheroids. (b) SEM image of a porous silica coating obtained on electrodeposited PEDOT by CVD of TEOS. (c) Magnified image of the porous silica coating. (d) SEM image of the SSAS. (e) Magnified image of the SSAS. (f) SEM image of an SSAS on a stainless-steel wire mesh. (g) Lateral SEM image showing that the SSAS uniformly covered the cylindrical wires of the mesh. Reproduced with the permission from [89].

have been proven by successful cultivation of cell spheres, indicating its effectiveness in preventing the adhesion of biological macromolecules and cells.

3.7 Flame retardant applications

In many cases, insulation must be flame retardant to minimize the risk of combustion, especially in building enclosures and electric vehicle battery packs. Aerogel made from inorganic silica is non-flammable and heat resistant up to 1200 °C.[9,27] Therefore, it can be used as a flame-retardant material inside buildings. Another possible application of silica aerogel is fire extinguishers. A recent study showed that hydrophobic nano silica encapsulated silica gel (HSESG) not only has efficient fire suppression performance, but also has excellent environmental friendliness and non-toxicity.[90]

Yu *et al*.[91] developed a distinctive composite aerogel consisting of a three-dimensional binary network structure composed of SiO_2 and phenolic resin (PFR). This structure is achieved by the utilization of TEOS as an inorganic precursor for the nanoscale separation of phases and the direct combination of formaldehyde and phenol as monomers. The PFR and SiO_2 components in the resulting PFR/SiO_2 aerogels permeate each other to form a binary network with domain sizes less than 20 nm. The PFR/SiO_2 aerogel possesses exceptional flame-retardant properties due to its interpenetrating binary network. This allows it to withstand high temperature flames without undergoing degradation. Additionally, it prevents excessive temperature increase on the non-exposed side, which could potentially pose a threat to reinforced concrete structures (Fig. 14).

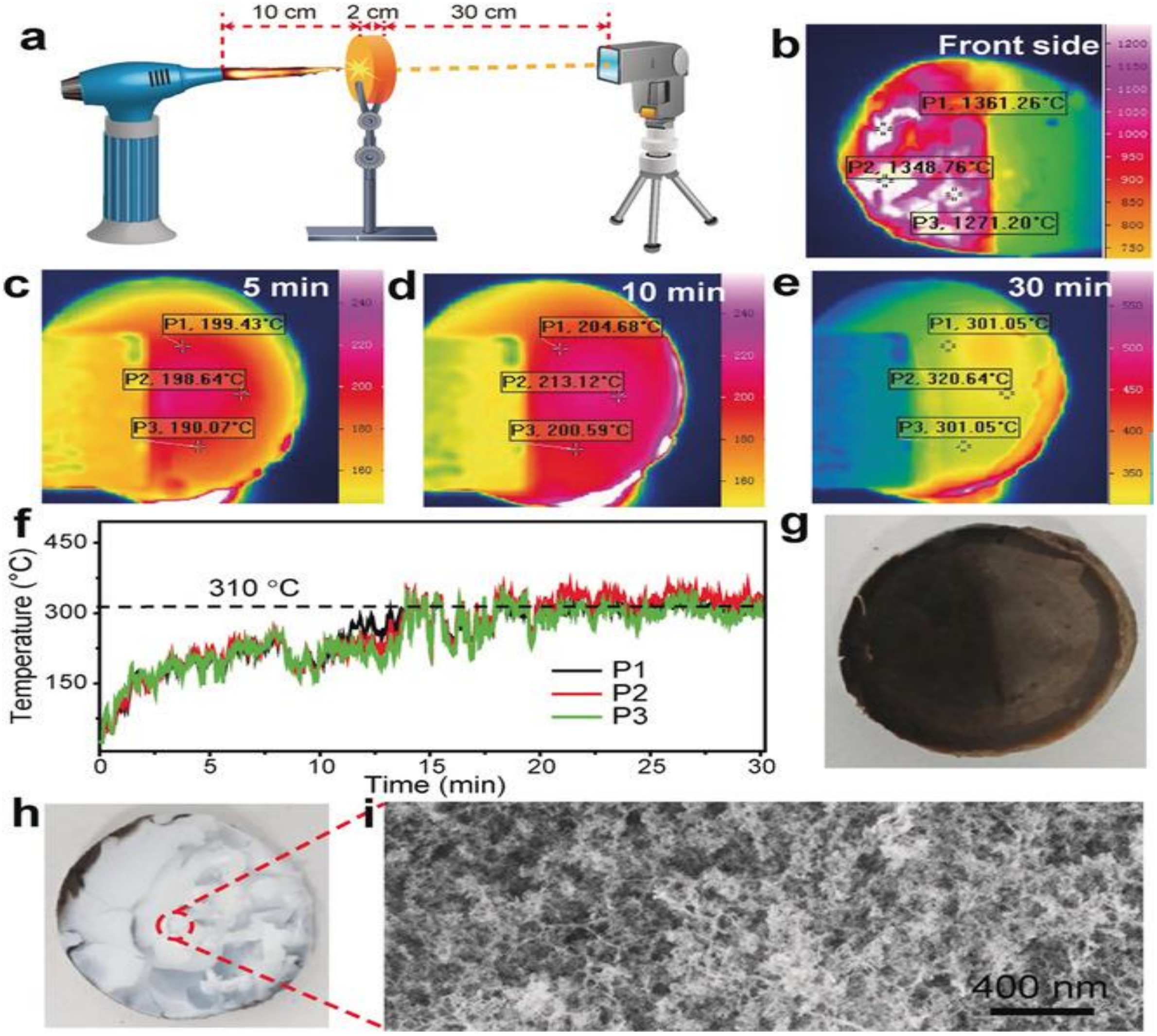

Fig. 14 Fire resistance of PSi-70 aerogel when heated at 1300℃ for a long time. a) Description of measuring devices using propane/butane spray guns. b) Front false color thermal image under the action of propane/butane burner flame. c) -e) false-color thermal images of the back of 2 cm thick PSi-70 aerogel at different times of 0 ~ 30min. Set P1, P2, and P3 as reference points to indicate temperature changes. f) Temperature distribution of the three reference points on the back over time. Photos of back (g) and front (h) after fire resistance test. i) SEM image of the remaining SiO_2 network on the front of PSi-70 aerogel after measurement. Reproduced with the permission from [91], Copyright 2018 Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim.

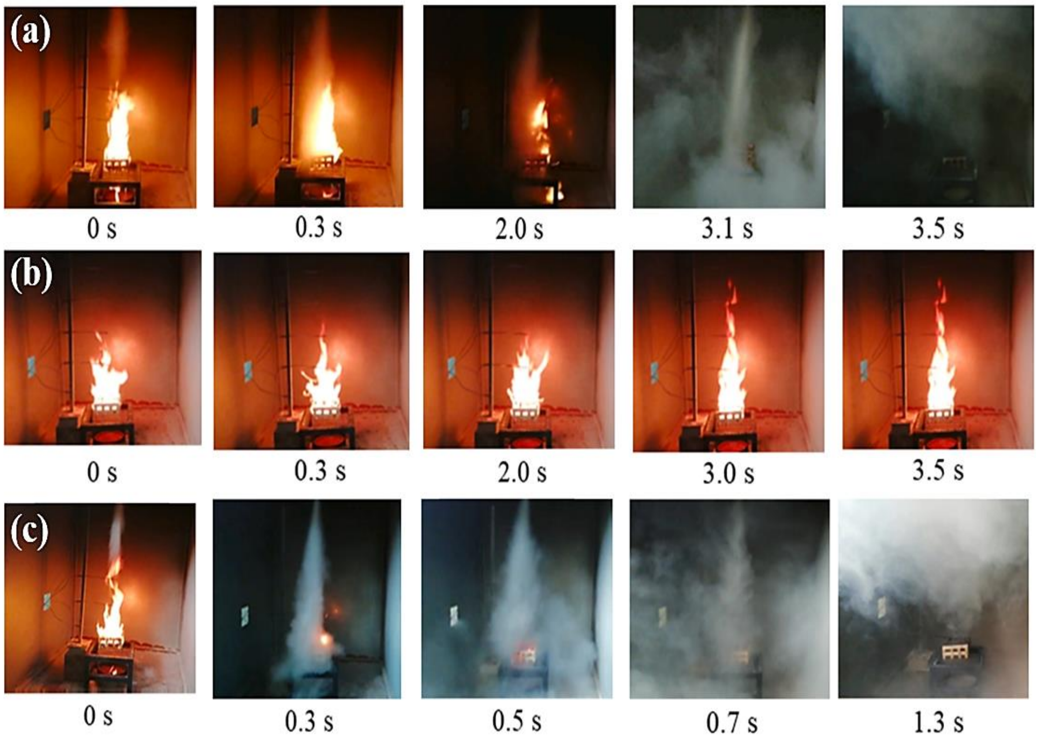

Fig. 15 Images of different extinguishing agents suppressing Type A fires: (a) ABC dry powder, (b) dry water, (c) HSESG. Reproduced with the permission from [90], Copyright 2020 Elsevier B.V.

He[90] and his colleagues replaced the process of hydration with the use of SiO_2 gel in a novel way to create hydrophobic SiO_2 enclosed SiO_2 gel (HSESG). It has been effectively utilized in a sequence of fire suppression trials (Fig. 15). The finding also highlights the material's lack of emission of poisonous and dangerous gasses during fire suppression, demonstrating its environmentally friendly nature.

3.8 Optical application

Due to its aerogel structure, silica aerogels have a low refractive index and low light absorption, making them highly beneficial for optical applications.[92] The optical characteristics of silica aerogels, such as light transmittance and refractive index, can be modified using synthetic factors like sol-gel and the drying process. As a result of Rayleigh scattering, the transparency of silica aerogels can vary between transparent and translucent.[93,94] Due to its unique optical properties, it may be employed as an efficient porous receiver in solar thermal energy systems. Due to its low effective wavelength (λ_{eff}) and high solar transparency, it has the potential to reduce heat loss and enhance light absorption, resulting in a significant improvement in the thermal efficiency of solar collectors.[95] Furthermore, silica aerogel possesses distinctive applicability in Cherenkov detectors,[95] glass Windows[14,96] and other applications.

Lee *et al*.[97] found that SiO_2 aerogel particles embedded in an organosilicon elastomer, such as PDMS, may be penetrated by an optical modulator, namely n-cetane, resulting in the creation of radiation-cooled metamaterials that exhibit transparency and flexibility. These transparent metamaterials have exceptional cooling properties, making them highly advantageous for use in windows and solar cells (Fig. 16). Due to its exceptional performance and ability to be mass-produced, this technology may be utilized for more efficient energy saving and the generation of renewable energy.

Ji *et al*.[98] employed trifunctional methyl trimethoxysilane (MTMS), difunctional dimethyl dimethoxysilane (DMDMS), and dimethyl sulfoxide (DMSO) as starting materials. These were subjected to hydrolysis and condensation reactions catalyzed by hydrochloric acid and ammonia. As a result, silicogel with varying block sizes was synthesized. By adjusting the MTMS to DMDMS precursor ratio to the best value, the resulting silica aerogel shows a wide range of high reflectance (99.7% in the visible wavelength range) that is not affected by the angle of observation. This makes it the most ideal ultra-white aerogel known so far, especially during solvent exchange and environmental drying. The ultra-white silica aerogel that is produced is utilized as a new benchmark whiteboard for enhanced spectrum calibration. It is also employed as a flexible projector curtain for optical displays

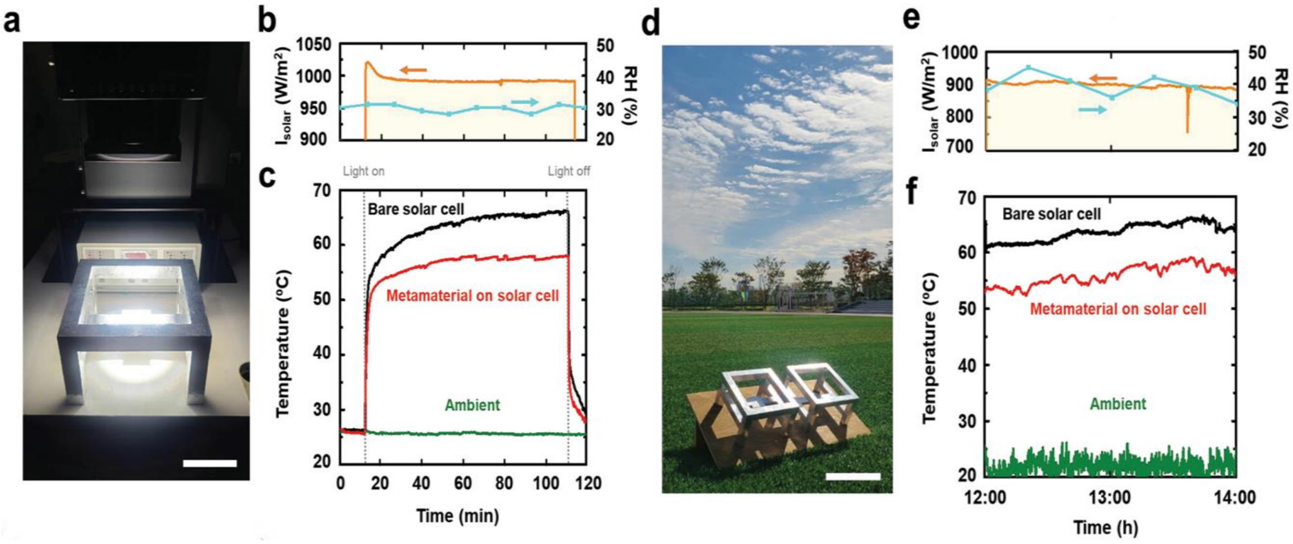

Fig. 16 Temperature monitoring of visibly clear radiative cooling metamaterials placed on top of commercial Si solar cells in a–c) indoor and d–f) outdoor conditions. Indoor and outdoor daytime radiative cooling performance of the metamaterial. (a,d) Photograph, (b,e) solar intensity (Isolar), relative humidity (RH), and (c,f) variations in ambient temperature (green curve), metamaterial on a solar cell (red curve), and a control bare solar cell (black curve) in indoor conditions under illumination by an AM 1.5G solar simulator and in outdoor conditions under solar irradiation in Seoul, South Korea. Scale bars: (a) 10 cm; (d) 25 cm. Reproduced with the permission from [97].

and as a transmitted light reflector in solar cells, resulting in a 5.6% increase in relative power conversion efficiency.

4. Conclusion

Silica aerogels, characterized by their very low thermal conductivity and open porous structure, find extensive use in several domains including thermal insulation, catalysis, physics, environmental remediation, optics, and high-speed particle capture. Aerogels have seen significant diversification in terms of their varieties, application domains, and preparation processes during a span of about 80 years. This study provides a thorough examination of the preparation methods and potential applications of silica aerogels. Extensive literature data demonstrates that silica aerogel materials have gained significant popularity in recent decades and are widely recognized as very promising novel materials. Currently, thermal insulation is the primary market for silica aerogels, particularly in circumstances where there is limited space. It is unquestionably the optimal choice in such scenarios. Aerogels possess a distinctive microstructure that gives them exceptional thermal insulation capabilities.

Nevertheless, silica aerogels presently have two additional formidable challenges. One limitation of silica aerogels is their intrinsic brittleness, which restricts their applicability due to the nanostructured extremely porous nature of these materials. The second limitation is the poor processability of silica aerogels, which hinders the exact casting of small objects and restricts the potential for downsizing.

As study progresses, these issues are increasingly being resolved. An optimal approach to improve the architecture of silica aerogels involves producing composite materials that have embedded fibers, hence significantly broadening its potential applications. Zhao *et al*. introduced a novel technique of direct inkjet printing, which effectively generated high-quality silica aerogel products.

To summarize, silica aerogels have a substantial impact on contemporary architecture, sophisticated aerospace applications, environmental remedies, and agricultural practices, while also presenting novel opportunities for technological advancements. Increased attention from researchers towards the preparation, design, and industrial uses of silica aerogels and their composites is desired in order to ensure a promising future for this material.

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Conflict of Interest

There is no conflict of interest.

Supporting Information

Not applicable.

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