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Review Article

The Role and Applications of Aerogels in Textiles

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Textiles have been used for clothing purposes since ancient times. However, due to their functional properties, their importance—as well as their use in various fields such as filtration, protective clothing, and medical applications—increased over time. Properties of the textile fabrics depend mostly on the fiber type, fabrication technique, and structure. Moreover, fabric porosity is one of the properties that provide comfort, increased thermal insulation, and filtration capability to the end products. The porous structure of woven, knitted, and nonwoven fabrics has been used for many years to get the desired porosity. Usually, macroporous structures are achieved using these types of textiles. Electrospinning is used to produce nanoporous textile fibrous web, but its poor mechanical properties and low production rate limit its use. Aerogels are solid materials with ultrahigh porosity at the nanoscale with low density and good thermal insulation properties, due to which they are considered potential insulation materials today. On the other hand, pure aerogels are sometimes brittle and have poor mechanical properties. Thus, they cannot be directly used in various applications. Consequently, textile reinforced aerogel composites have been developed, which could provide flexibility and strength to aerogels and impart nanoporous structure to textiles. This review summarizes conventional techniques to produce the porous structure in textiles followed by the modern techniques to develop a nanoporous structure. Further, different mechanisms to synthesize textile reinforced aerogel composites are discussed to get a nanoporous structure for filtration and thermal insulation applications. The porosity, mechanical properties, and thermal insulation of textile reinforced aerogel composites are also highlighted. In the end, we give a conclusion that not only summarizes the literature, but also includes recommendations for the researchers.

1. Introduction

Textiles are considered the most demanding materials in the world because they are needed in various applications. They are crucial for community, well-being, and societal health. People come across many textiles like those in apparel, interior textiles (wall coverings, bed linens, carpets, curtains, etc.), and industrial and technical textiles (bandages, filters, seat belts, etc.) every day and thus are dependent on textiles from cradle to grave. Furthermore, different textiles are not often viewed like supporting (interlining, interfacing) and insulating materials. Textiles such as protective helmets, kneepads, and shoulders can provide protection for sports; fibers can be used as reinforcement in tennis rackets and golf sticks. Moreover, as crops are protected by farmers using textile fabrics or people are protected from the sun and rain using tents, it can also be concluded that textiles also provide safety and comfort for humans and animals [1]. On the other hand, life is preserved by sewing the tissues and organs using different sutures and textile structures [2]. Textiles are used in homes and buildings to provide protection via the insulation of fiberglass and polyethylene as moisture and

wind barriers [3]. Absorbent and soft garments are used for easy care of newborn infants. There is a wide range of raw materials, structures, properties, and production methods used in these textiles. It might not be possible to develop these amazing textiles without the fibers [4–6].

Among various types of textiles, there is a sharp rise in the demand for technical textiles having special functionalities (such as fire resistance, thermal resistance, and antibacterial properties). These properties can be inherited or imparted via different physical or chemical modifications. As the necessity for textiles with diverse properties is increasing day by day, extensive research has been conducted globally on fabrics that protect outdoor and indoor environmental conditions [7]. Among the properties which are commonly investigated, thermal insulation and filtration are strongly related to the porosity [8, 9] and internal structure of the fabrics [10].

Fibers and fabrics have been used to achieve textiles with porous structures for years; however, their porosity can be attained only up to a limited extent. The regular fibers have pore sizes ranging from 35 μm to 66 μm, while the pore size of micro-denier fiber ranges from 12 to 25 μm [11]. The pore size of the woven fabric structure depends upon the interlacements, yarn count, and thread spacing. The pore size is not confined to the knitted structure because it undergoes expansion to take up the pressure fluctuations [12]. Among different fabric structures, the pore size of the nonwoven fabrics generally varies from 1 μm to 500 μm [13]. Thus, by using the conventional fabrics, with only micro size, porosity can be achieved.

Various techniques have been developed to attain the nanoporous structures. Among those, electrospinning is a versatile technique to obtain a nanoporous structure. It is the process used to develop porous nanofibers with diameters of 10 nm to a few micrometers [14]. On the other hand, this technique has a serious disadvantage. The resulting structures have weak mechanical properties limiting their use in various applications. Thus, a new composite, textile reinforced aerogel, has been developed to achieve both a nanoporous structure and good mechanical properties as compared to nanofibers.

Most of the work published on the application of aerogels in textiles is related to an increase in thermal insulation of textiles, and many reviews related to this topic have already been published. However, no one provided a detailed discussion about the porosity of textiles and the role of aerogels in controlling the porosity of the textiles. This review will introduce the reader to different materials, strategies, and commercial applications of aerogels in textiles.

In this review, three different strategies have been discussed (conventional to advance) to control the porosity of the fabrics.

(i) The first strategy is to use conventional techniques to develop a textile with a porous structure. The structure-property relationship of conventional textiles and pore size of fibers and different fabric assemblies has been discussed in detail.

(ii) The second strategy is the nanofibers that are produced using the electrospinning technique. The web prepared from nanofibers has a pore size in the nanometer range.

(iii) The third strategy is the introduction of aerogels onto the textile to enhance the characteristics of the textiles and to achieve the nanoporous structure. Textile reinforced aerogel composite provides the strength and flexibility to aerogels, and in return aerogels enhance the porosity of textiles for industrial applications. The production methods, properties, and applications of textile reinforced aerogel composites that could overcome the drawbacks present in the previous manufacturing technologies are discussed in this review.

2. Textile Assemblies

The basic unit of the fabric is a fiber which directly impacts the comfort, aesthetics, durability, environmental impact, appearance retention, care, cost, and sustainability. The basic properties of a good fiber are its length, strength, pliability, and cohesiveness. Different textile fibers are being used these days to make different fabrics. The first manufactured fiber was produced commercially in 1885. Before these days, the fibers which are most commonly known as cotton, silk, flax, and wool were produced from plants and animals. Natural fibers are in fiber form and can be got from animal, plant, or mineral sources. On the other hand, manufactured fibers can be produced from protein, cellulose, mineral sources, or synthetic polymers. Various fibers have been developed recently from plant materials such as soy silk, bamboo, banana fibers, and polylactide fiber. Moreover, azlon fiber is developed from the material which is the by-product of tofu production [15].

To end up with a textile product, fibers are primarily spun together to form a yarn. A yarn is a continuous strand of textile fibers, filaments, or materials, which is suitable for knitting, weaving, or otherwise intertwining to form a textile fabric. Most interior fabrics and apparel are produced from yarns. There are generally two types of yarns, filament yarn and spun yarn. Filament yarn can be produced easily as compared to spun yarn, which undergoes different operations to be made from the staple fibers. The quality and type of yarn has an impact on product quality, performance, and cost [16–18].

The second step is to obtain a fabric that is a plane-like structure produced from the yarns or fibers directly. Fabrics are used in interiors, apparel, and technical products. The method of fabrication of fabrics contributes to the texture, performance, appearance, and cost of the product. The name of the fabric can be determined from its manufacturing process like lace, felt, double knit, double cloth, and tricot. Fabrics can be produced from various materials like solutions (foams and films), fibers (nonwovens, felt, and fiber webs), yarns (woven, laces, knits, and braids) [19, 20].

Finishing is a process performed on the fibers, yarn, or fabric at any stage of its production, whether before or after

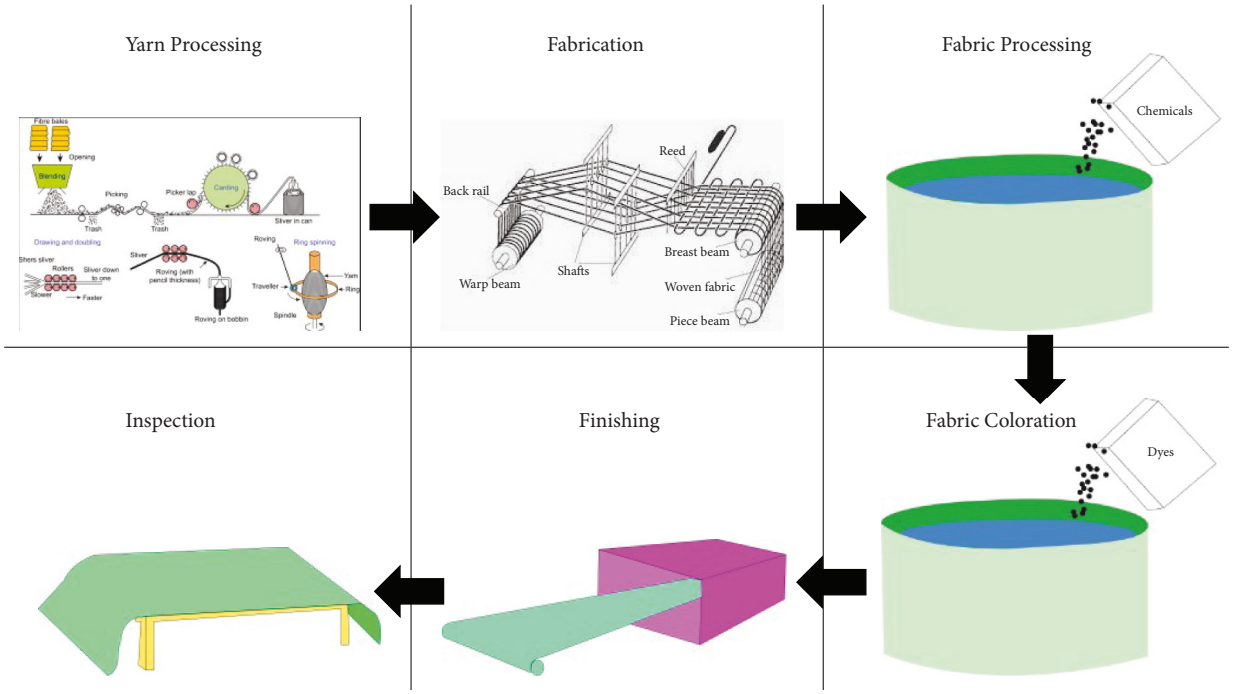


Figure 1: Flowchart of production of textile fabrics.

fabrication to change the feel, appearance, and performance or a combination of these properties. Finishing usually utilizes chemicals that can be damaging to the environment or the fiber/fabrics. Primarily, fiber processing is completed. After yarn processing followed by fabric creation, bleaching is almost always performed on the fabrics before dyeing. The production sequence of textile fabrics is given in Figure 1 [21–23].

2.1. Structure of Textile Assemblies

2.1.1. Fibers. There are two types of fibers, staple fibers and filament fibers. The length of staple fibers ranges from 0.8 to 18 inches (2 cm–46 cm). All-natural fibers are obtained in the form of staples except for silk. Long continuous fibers having an indefinite length are called filament fibers. The diameter of the fiber directly impacts the performance of the fabric [24]. Fibers with more diameters are called coarser fibers which are stiff, crisp, and rough. Fibers with smaller diameters are called fine fibers which are pliable and soft. Coarser fibers are used in producing luggage and book bags while finer fibers are used for comfortable and softer products. The drape of the fabric produced from the finest fibers is good and more comfortable. Fineness is measured in micrometers. The range of diameter of the natural fibers is 10–20 micrometers for cotton, wool, flax, and silk. For regenerated fibers, the diameter can be controlled. The cross-sectional shape of the fiber has an impact on different properties like bulk, hand, body texture, and luster [15]. The cross-sectional shapes of various fibers are given in Figure 2.

2.1.2. Woven Fabrics. Fabric weaving is the most extensively used textile manufacturing technique. There are two sets of yarns in the woven fabric interlaced mutually in the fabric structure. The yarn running along the length of the fabric is called warp yarn, and that running along the cross direction of the fabric is called weft yarn. These yarns interlaced into the fabric in different ways are called weave structures. The simplest weave structure is the plain weave in which warp yarns alternatively lift and go across the weft yarn and vice versa. Twill and satin weaves are also common weave structures. Diagonal lines can be seen on the face side of the twill weave fabrics which can be S and Z twill depending upon the direction. In satin weave, the binding places are arranged to develop a smooth fabric. The interlacement points must be prepared randomly to avoid twill lines. The smallest repeat of the twill weave is 5 [25]. Some weave structures are given in Figure 3.

2.1.3. Knitted Fabrics. Loops are the basic units of knitted structures. There are two main technologies for the construction of knitted fabrics such as warp knitting and weft knitting. The loops in one row of the weft-knitted fabric are produced from the same yarn. The horizontal row of the loops in knitted fabric is called a course, while the vertical row is called wales. The loops are formed along the fabric width in weft-knitted fabrics. The simple structure of the weft knitting is the plain knit structure, also called jersey knit. A rib structure is produced using needles of both beds that have the same appearance at the face and backside of the fabric [27]. Both structures are given in Figure 4.

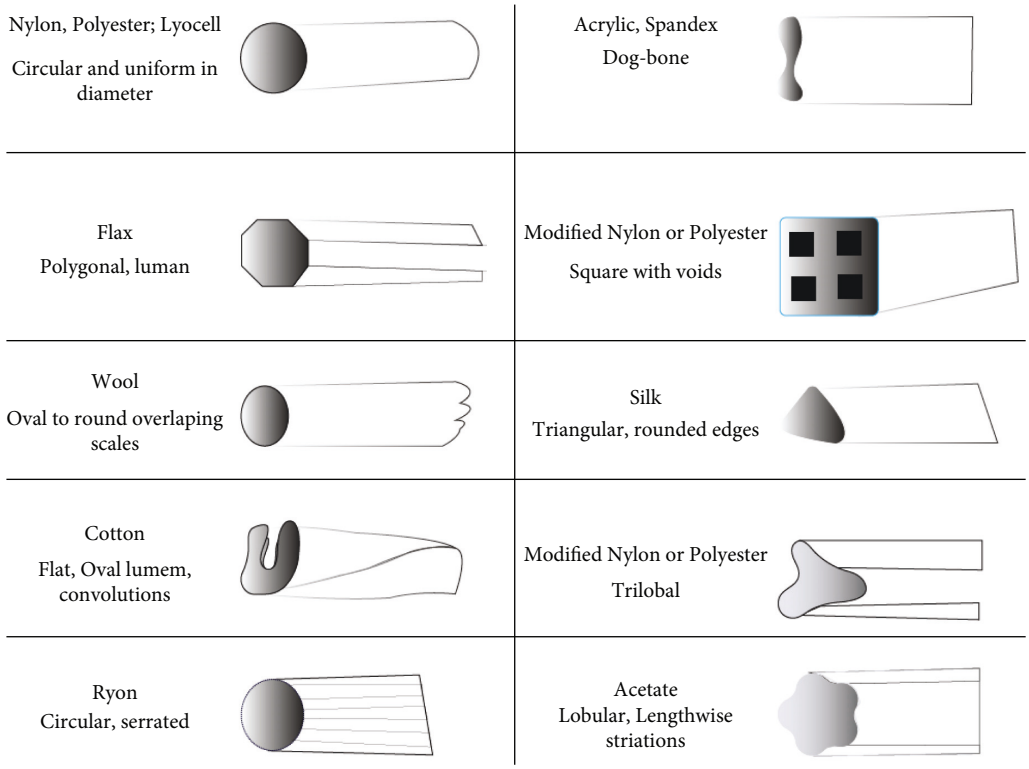


Figure 2: Cross-sectional shape of different fibers [15].

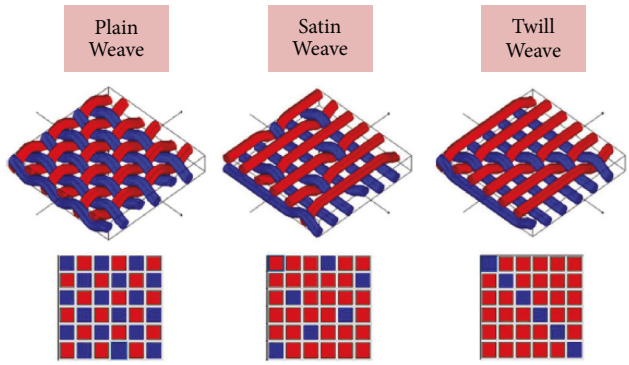


Figure 3: Schematics for different weave structures [26].

The second technology to produce knitted fabrics is the warp knitted technology in which every loop is formed from a separate yarn to produce the fabric structure. While weft knitting technology is usually used in clothing, warp knitting technology is used in technical applications [27].

2.1.4. Nonwoven Fabrics. Nonwoven fabrics are defined as the web structure or sheet of entangled fibers bonded either by thermal, mechanical, or chemical means. A sheet is developed by randomly or directionally oriented fibers bonded together by adhesion, friction, or cohesion. Both natural and artificial fibers can be used to form the sheet. These sheets are formed to achieve specific properties like resilience, softness, strength, absorbency, usability, liquid repellency, antibacterial activity, filtering, and cushioning [29]. A schematic for a basic nonwoven structure and SEM image of electrospun nanofiber web is given in Figure 5.

2.1.5. Braided Fabrics. Braided fabric is also a textile assembly that is formed by the interlacement of two or more yarns resulting from the carriers rotating counterclockwise or clockwise direction [32]. These textile structures can be manufactured by interlacing orthogonally or intertwining two or more yarns to form a tubular structure. One yarn set is called the braided yarn while the other is called the axial yarn [33]. There are three typical braided structures, namely, regular, diamond, and Hercules, as shown in Figure 6.

2.2. Structure-Property Relationship of Textile Assemblies. Textiles have various properties like flexibility, strength, stiffness, durability, elasticity, water absorbency, heat insulation, dyeability, and resistance to chemicals. These properties are mainly dependent upon the physical and chemical properties of the fibers. Crimp, fineness, surface roughness, diameter, and all other properties of the fiber contribute to the mechanical properties of the fabric [34, 35]. Fiber's diameter has a main impact on the handle and the stiffness of the fabric. The fabric handle relies upon the fiber's cross-sectional shape [36, 37]. The softness and deformation of the fabric depend upon the space ratio in the fiber cross section [38]. Fiber diameter defines the thickness of the yarn that is produced in spinning. Finer fibers increase the yarn strength because of an increased number of fibers in the yarn with the same thickness. Thy also have an impact on the comfort properties of the apparel as thicker fibers are

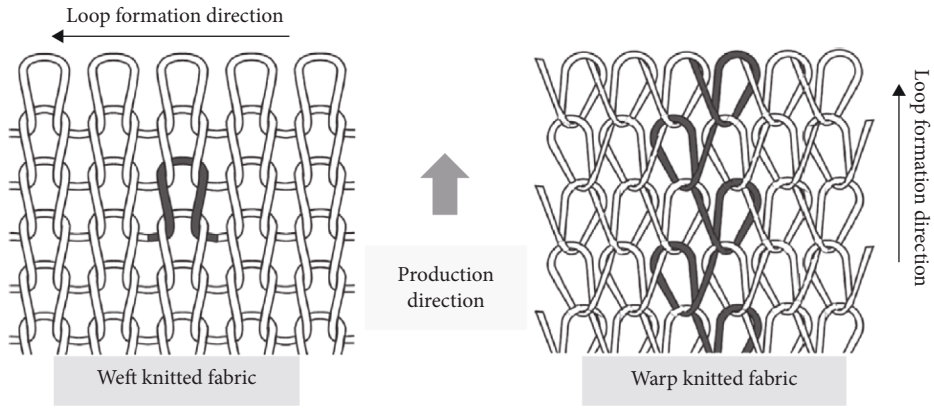
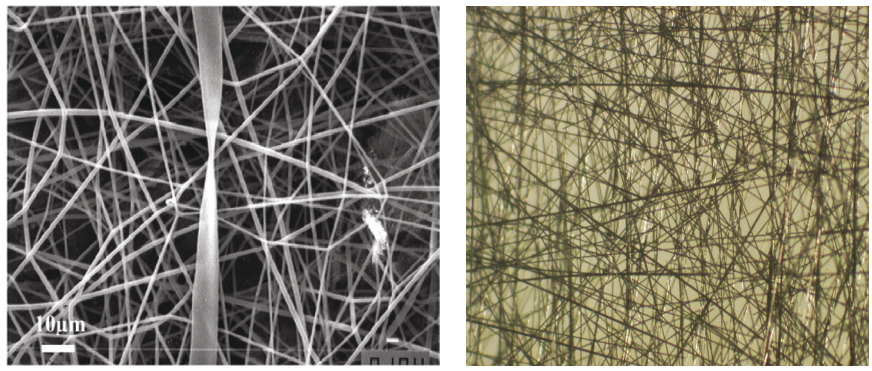


Figure 4: Schematic diagram for weft-knitted structures [28].



SEM image of Electrospun Nanofiber web

Microscopic image of nonwoven fabric

Figure 5: Nonwoven fabric images of electrospun nanofibers web [30] and nonwoven felt [31].

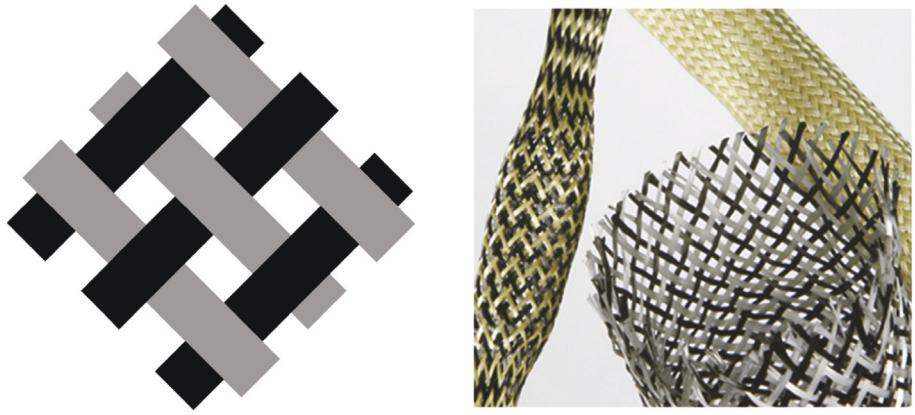


Figure 6: Schematics for braided structures [28].

irritating when in contact with skin [39]. Fiber length directly affects the yarn strength because longer fibers have more contact points to provide friction between the individual fibers than shorter fibers. The fibers having a length of less than 12 mm are not suitable for the spinning process. The degree of hairiness also increases with the increase of fiber length, which then causes difficulty during weaving, knitting, and sewing [40].

Tensile strength, elongation, and elastic recovery of the fiber are the mechanical properties defining the strength, stretchability, durability, and ability to return to the original shape of the final product. Crimp is a property, mostly present in natural fibers, which can be defined as the waviness of fibers along the length. Fabric quality is correlated with the fiber crimp [36, 37]. Fiber crimp is directly related to the fabric thickness, which

ultimately affects the total handle value of the fabric. Man-made fibers are crimped to improve the fiber handle. The friction coefficient is another property of the fiber to ensure the fiber cohesion to control the fiber slippage within the yarn and makes the yarn stronger. Moisture regain is another important property of the fibers depending on the fiber chemistry, temperature, and relative humidity of the atmosphere. It helps in dissipating electrostatic charge [41].

Besides the fiber properties, yarn structure is the most important factor affecting the properties of the fabric. The properties of the fabric are significantly influenced by yarn twist, linear density, and other processing parameters. Courser yarns increase the cover factor of the fabrics which ultimately increases the stiffness of the fabric. The hard twist of the yarn increases its packing density, which in return increases the stiffness of the fabric. Yarns have different structures depending upon the spinning technique like ring spinning, rotor spinning, MVS (Murata Vortex Spinning), and air jet spinning. Yarn properties also depend upon its structure. The physical and mechanical properties of the fabric are significantly affected by the fiber assembly in the yarn [37, 42–44]. Woven fabric produced from open-end spinning has greater thickness and coefficient of friction than ring-spun yarn [45]. Fabric made from core spun yarn has high bending rigidity and is resilient to compressive and tensile deformation. This fabric made up of core spun yarn also provides good values for hand qualities linked with summer suit applications for men [46–49]. Core wrap yarn developed from an air jet spinning technique gives less strength and a rigid feel in handling. The yarn produced by this technique is less bulky and hairy as compared to the ring-spun yarn.

The parameters of the fabric construction like weave, fabric set, and cover factor prominently change the fabric's performance. The cover factor is directly related to the stiffness of the fabric. Fabric constructed using a plain weave technique has higher shear rigidity and more compact structure than other weave fabrics because of the greater yarn-to-yarn interlacements in the fabric [50]. The twill weave fabric has more extensibility, compressibility, and smoothness as compared with plain weave. The bending property of the fabric is directly affected by the crimp of the fabric. The dimensional properties of the fabric such as real density and thickness play an important role in determining the fabric handling [44].

2.3. Porosity of Textile Assemblies with Applications. Porosity is defined as the ratio of free space to fibers in a given volume of fabric [51]. One of the many properties of fibers is that it provides interstices and greater surface area to the end products. Since the cross section of the fibers is very small, it can provide a greater number of overlaps. Porosity is the inherent property of the fibers that can be used to provide various properties such as insulation, comfort, and filters [52]. On the other hand, synthetic fibers can be produced on circular or any desired cross section depending on the spinneret type [53].

Fibers have porous structures depending upon the source and the production method. While regular fibers have pore sizes ranging from 35 μm to 66 μm, the pore size of micro-denier fiber ranges from 12 to 25 μm. The micro-denier fibers can provide better filtration and thermo-physiological comfort properties as compared to conventional fibers. The process of converting fibers into yarn is spinning. This process contains various operations, among which the ring frame is the last operation whose input is roving. It is a bulky strand of fibers that are twisted together. Thus, this roving can be wounded in a specific pattern to attain the porous structure [11].

Woven fabrics are produced by the yarn interlacement using a weaving machine. The weave structure depends on the type of interlacement to produce a plain or twill weave. There are other weave structures such as satin, sateen, basket weave, and matt weave. The thread spacing is another parameter of the fabric which can be expressed as ends per inch (EPI) for warp yarn and picks per inch (PPI) for weft yarn governing the openness of fabric structure. The pore size in the woven fabric structure depends upon the interlacements, yarn count, and thread spacing. Knitted fabrics are the structures formed by the interloping of the yarns. The pore size is not confined to the knitted structure because it undergoes expansion to take up the pressure fluctuations [12].

Nonwoven fabrics are produced directly using fibers without converting them into yarns. The fibers are bonded within the structure using chemical, mechanical, or thermal techniques based on the fiber type. Different machines have been developed for different bonding techniques. One of them is a needle punching machine that is used to mechanically interlock fibers. While spun bonding nonwoven machine is used to thermally bond thermoplastic polymer fibers, a wet-laid nonwoven machine is used for the chemical bonding of fibers. Fabrics have a bulkier and thicker structure for a given GSM than interlacement fabrics due to the poor compact binding of fibers, and this also makes the structure porous due to the creation of free spaces. The pore size of the nonwoven generally varies from 1 μm to 500 μm [13]. Due to its porous structure, it can be used as filter media and insulation media [12].

3. Methods to Develop the Nanoporous Structure of Textile Assemblies

Fabric porosity primarily depends upon the construction of fabrics. The closer the yarns of knitted and woven fabric, the lesser the size of the pores. The spaces between the yarns are more in knitted structure than in woven structure. But still, micropore size can be achieved using these textile structures. Moreover, there are various techniques such as controlled stretching of thin polymeric films, phase inversion, interfacial polymerization, and electrospinning through which nanopore size can also be achieved. The membranes produced from these techniques are categorized based on average pore size. Microfiltration pore size ranges from 0.1 to 5 mm, ultrafiltration pore size ranges from 0.01 to 0.1 mm,

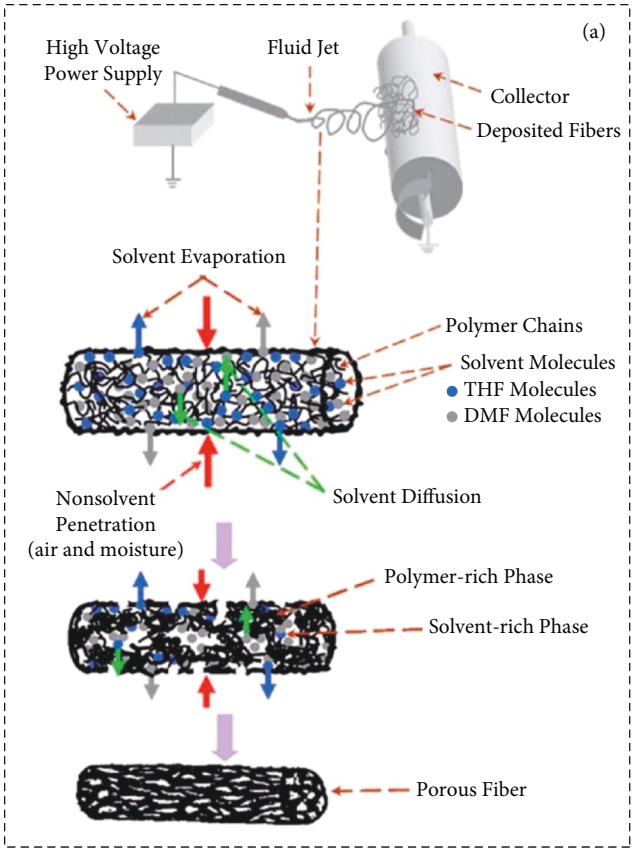


Figure 7: Schematic diagram illustrating the formation process of porous fibers during electrospinning [55].

and nanofiltration and reverse osmosis range from 1 to 10 nm and 0.1 to 1 nm, respectively [54].

Among the methods used for the fabrication of polymer-based porous membranes, electrospinning is the easiest and most efficient technique. It is the process that can be used to develop porous structures of nanofibers with diameters of 10 nm to a few micrometers by carefully controlling processing conditions as shown in Figure 7. Interconnected pores having uniform size distribution can also be produced via the electrospinning method [14, 54]. Fibers made by this technique can be used for the filtration of polluted air and water [56, 57]. Membranes made up using the electrospinning technique have various advantages due to their high porosity of around 80%. The conventional electrospinning technique involves a high voltage source, a syringe to feed polymer solution, spinneret, and ground collector [58]. The rheological interactions and electrohydrodynamic of polymer solution are critical parameters to be used in this technique [59]. The properties of the fibers mainly depend upon the polymer solution parameters (viscosity, conductivity, and concentration), processing parameters (feed rate, air gap, and voltage), and environmental parameters (temperature and humidity).

All categories of pore sizes can be achieved using this technique, but it has a serious disadvantage; that is, it exhibits poor mechanical properties because of weak fiber-to-fiber entanglements. Thus, researchers have investigated several approaches such as surface chemistry manipulation, nanomaterial incorporation [60], and using biobased polymers [61–63] to overcome the shortcomings of electrospinning. Qin and Wang [64] prepared a multilayered electrospun membrane using nanowhiskers and biobased nanoparticles to overcome the aforementioned drawbacks and improve the filtration efficiency of the nanofiber web using crosslinked PVA nanofibers.

Multilayer fibrous membranes have been developed to impart strength to membranes for filtration application. A schematic diagram for multilayer electrospun nanofiber membrane is given in Figure 8. One layer is fabricated to achieve the desired surface properties and the pore size [66–68]. Commercialization of the electrospinning technique is a versatile method for practical applications, but weak mechanical characteristics are still an issue [59]. Some researchers developed layered electrospun nanofiber membranes to overcome the shortcomings via the addition of nanomaterials to the dope solution [69]. But the addition of these materials created problems in the process and compromised the properties of the nanofibers [70]. Recently, in some studies, a composite membrane has been fabricated with the combination of electrospinning with electrospraying on the electrospun membrane which then improved the properties compared to adding particles to the solution [71]. Various attempts have been made to overcome the shortcomings of the electrospinning technique, but improvements were limited. Recently, aerogel, a new nanostructured material which is also called 21st-century material, has been developed to prepare textile reinforced aerogel composites exhibiting good mechanical properties as compared to nanofibers.

3.1. Aerogels. Aerogel is a highly porous (>95% porosity) artificial solid material firstly created in 1839 by Kistler [72]. The word aerogel was derived from a gel in which liquid components are replaced by a gas. It has an ultralow density and very low thermal conductivity due to its 3-dimensional nanoporous structure. These materials are very similar to hydrogels which are also prepared by the 3D network formation of organic polymers, inorganic materials, and composites [73]. The main difference between these two structures is the drying method. The use of supercritical drying in the synthesis of aerogels avoids the liquid-gas surface tension and liquid-solid adhesive forces arising during the process and results in compact gel structures.

Recently, advances in aerogel science have attracted increasing attention. The aerogels' high porosity, large surface areas, and low densities as well as adjustable network structures with the modification of synthesis conditions offer various advantages for the use of these intriguing materials. These structures are investigated for various applications such as sound absorption, energy conservation, thermal insulation, purification, and biomedicine [74, 75]. Along with inorganic aerogels such as silica, alumina, or titania, various organic aerogels were also synthesized due to their additional desirable properties such as biocompatibility and

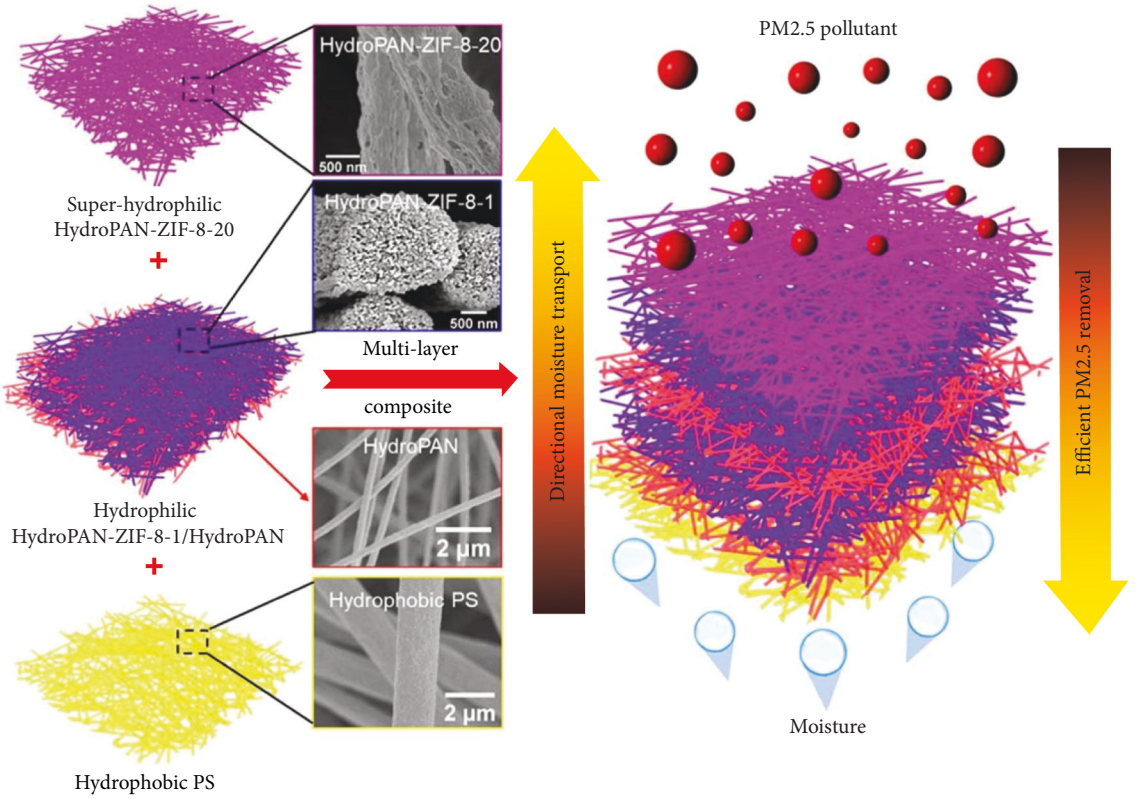


Figure 8: Schematic diagram for multilayer electrospun nanofibers [65].

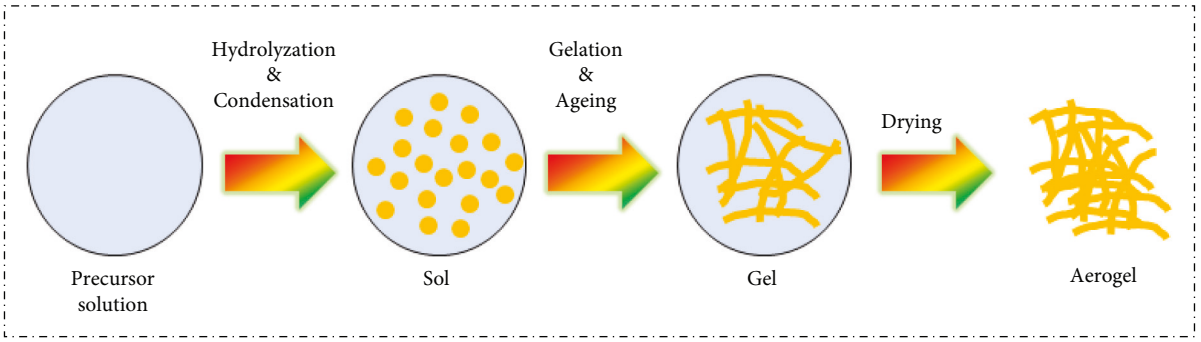


Figure 9: Schematic diagram of a sol-gel method for aerogel formation.

biodegradability. In the case where properties of only types of aerogels are not sufficient, composites are also synthesized to meet the necessities of the required application. These nanostructured materials can be synthesized in different monolithic forms depending on the shape of the mold that is used during the gelation process. Moreover, membranes, sheets, beads, spheres, and blankets can also be prepared based on the selection of the synthesis method [76]. If the resulting aerogel is desired in the form of particles, the dripping method [77], emulsion polymerization [78], and spraying [79] can be used.

3.2. Preparation Methods of Aerogels. Aerogels can be prepared by using different methods. Among those, sol-gel polymerization is widely used to synthesize inorganic aerogels like silica aerogels as shown in Figure 9. The sol-gel method consists of several steps such as the formation of the sol, gelation, and drying [80, 81]. Precursors are primarily subjected to hydrolysis, the rate of which can be accelerated by the addition of suitable catalysts. Subsequently, molecules resulting from hydrolysis reactions undergo condensation reactions to form a network. Consequently, the mixture forms a gel. These gels are then subjected to aging processes where the purpose is to improve their mechanical strength. The next step is to perform solvent exchange to replace the liquid within the pores and to remove any impurities with a solvent which is usually alcohol. The final step that is performed in the aerogel synthesis is drying these wet gels, also called alcogels, without damaging their structure. For this purpose, ambient pressure drying, supercritical drying, or freeze drying are used [82].

3.2.1. Supercritical Drying. Kistler first dried the silica aerogels using high-temperature supercritical drying in 1931 [83]. Ethanol or methanol was used as organic solvent, and drying was carried out in an autoclave at high temperature and pressure. The pressure during drying was kept above the critical pressure of the organic solvent, and the solvent was expelled out at a constant temperature. After that, the autoclave was cooled to room temperature after reaching the normal pressure [84–87]. This method has the serious disadvantage of fire hazards because of drying at high temperatures [87]. There is an alternative method that can be employed at low temperature; i.e., liquid CO_2, which has critical point close to ambient pressure, is used. This method is less expensive as compared to high-temperature drying [88].

3.2.2. Freeze Drying. This drying method includes freeze drying at low temperature and sublimation of the solvent under vacuum. Aerogels of various materials such as cellulose, graphene, clay, silica, carbon, and alginate have been synthesized using the freeze-drying method. Various studies have reported drying silica aerogels at −50°C to −80°C under vacuum [89–91]. Although it is cheaper than supercritical drying, the crystallization of the solvent within the pores produces cracks. That is why it is not widely used in the drying of aerogels [92, 93].

3.2.3. Ambient Pressure Drying. Supercritical drying, which is energy intensive and expensive method, is mostly used in the synthesis of aerogels. The ambient pressure drying method is cheaper than supercritical drying and so can be used as an alternative drying method. This method comprises surface modification, network strengthening using a silylating agent, and contact angle manipulation [94–96]. Si–OH group is substituted by the alkyl group in the silylation process followed by the introduction of the trimethylsilyl group which causes shrinkage of gel at ambient pressure. Ambient-pressure-dried aerogels show better properties like density, porosity, and thermal conductivity than high-temperature supercritical drying [95–97], but the processing time of this method is 4–7 days, which makes it too costly for industrial production.

Among those, supercritical drying is the most used and preferred one as the use of this method prevents the formation of the vapor-liquid interface in the pores resulting in intact porous structures at the end of drying as well as being suitable to use at large-scale production.

Along with inorganic aerogels, organic and even composite aerogels are also prepared via similar techniques depending on the requirements of the intended application area. As composite aerogels can be synthesized with two different aerogels [98, 99], a substrate can also be used onto which aerogels will be synthesized [100–103]. In addition, aerogels can also be prepared using polymer nanofibers without the gelation of sol but using nanofibers as building blocks for a network of aerogels via crosslinking and entanglement [104]. This method is called the gelation-free method which greatly simplifies the production of aerogels on a large scale.

3.3. Aerogel Integration into Textiles. Among the interesting features of aerogels, low thermal conductivity attracts a lot of attention from various industries. Incorporation of those porous structures into windows, doors, roofs, terraces, ducts, ceilings, hot water pipes, etc. was found to be very successful [105]. Along with those industries, the textile industry has also recently started to investigate aerogels to improve the thermal insulation properties of their products. As one of the drawbacks of those nanostructured materials is their brittleness, it is difficult to combine aerogels with textile end products. However, their incorporation into textiles was also shown to increase their strength [106]. The most commonly used textile reinforced aerogels are reinforced with nonwoven fabric due to their properties like moderate strength and stability, lightweight, low cost, and high production rate [104, 107]. There are generally different ways to develop aerogel-incorporated textiles.

3.4. Aerogel-Incorporated Textiles. The first method to prepare aerogel-incorporated textiles is that both the textiles and aerogels are separately produced and then combined using various methods.

3.4.1. Padding. It is the traditional method to apply the desired material to a textile substrate. In this method, the textile material is firstly dispersed in the liquid and then applied to the textile substrate using a padder. Some researchers have applied aerogel particles on the nonwoven sheet to develop aerogel textiles [108]. Jin et al. [108, 109] used this method to pad D50 nanogel, purchased from Cabot Co. (USA),having particle size of 7 to 11 μm and applied it on nonwoven fabric sheet , and reported that the thermal protective performance of the fabrics has been increased by applying aerogel particles. However, the water vapor permeability of the fabrics was decreased. It is a very simple technique, but currently, there is no data present about the flexibility of the product produced using this method.

3.4.2. Thermal Bonding. In this method, aerogel particles are entrapped inside the fiber network of nonwoven fabrics using heat. The heat melts the adhesive (a part of the fiber in nonwovens) which attaches aerogel particles in the nonwoven structure. Frank et al. [110] developed an aerogel nonwoven using this method. A web was produced using two different types of polyester fibers having different melting points in which the low melting fiber acted as the resin to hold the granules or particles of aerogels. The resulting web was compressible and bendable with a weight of 1.2 kg/m^2 and a thermal conductivity of 28 mW/mK. Xiong et al. [111] used this method to prepare another aerogel nonwoven. Aerogel particles were thermally bonded with low melting powder between the two layers. The first layer was needle-punched nonwoven, whereas the second one was an electrospun nonwoven. The thermal property of

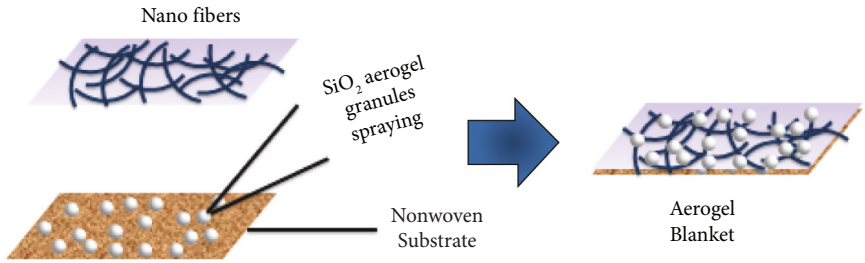


Figure 10: Schematic diagram for the lamination method.

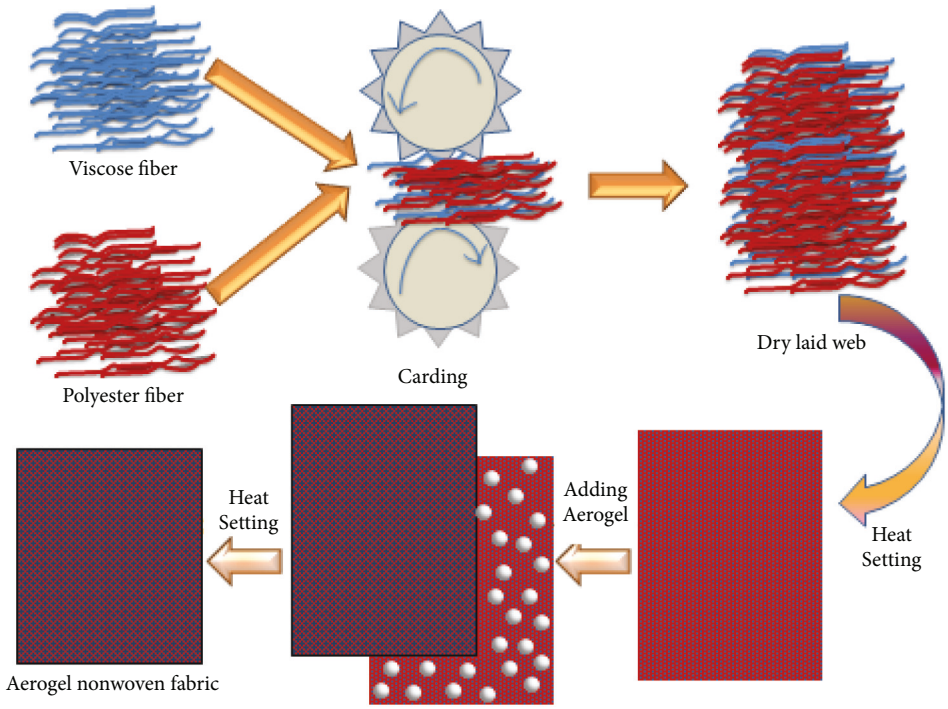


Figure 11: Schematic diagram for the development of aerogel nonwoven composite.

the fabric was enhanced by the addition of aerogel particles, but the effect on the air permeability and the water vapor permeability of the fabric was insignificant.

3.4.3. Lamination. In this method, aerogel particles are sprayed upon the nonwoven fabric surface, and then a nonwoven layer or mesh of nanofibers is hot-pressed on the surface of the nonwoven fabric. The schematic diagram for the lamination method is given in Figure 10.

Xiong et al. [111] developed a blanket by spraying SiO_2 aerogel granules to form a layer on the surface of needle-punched polyester nonwoven fabric. Subsequently, a layer of PAN nanofibers was hot-pressed to cover the granules. Based on the results, an excellent thermal resistance ($0.031.94^{\circ}m^2$-K/W) was obtained for the blanket. Some researchers have developed the blankets using aerogel beads in their structure. The beads were incorporated into the nonwoven fibrous structure to enhance the thermal characteristics of the aerogel composite blankets [101, 112]. In another study, Bhuiya et al. [113] produced an aerogel-incorporated nonwoven by integrating silica aerogels (purchased from Cabot Corporation) for thermal and chemical protection. The size of the powder aerogel particles was 100 to 120 micrometers with 120–150 Kg/m^3 particle density and 20 nm pore size. The first step was to produce a dry-laid web of polyester and then blend it with a viscose fiber using a carding machine. Consequently, this web was converted into a nonwoven sheet by heat setting. Aerogel particles were then sprayed using a perforated roller, and a fusible lining was placed on the fabric to fix the particles. This way, a layered structure, in which the aerogel particles were sandwiched in the nonwoven structures, was formed as shown in Figure 11. The chemical resistance and thermal resistance of the fabrics were improved by incorporating aerogels.

Xiong et al. [114] prepared a three-layered structure of aerogel-based nonwoven composite. The first layer that is also called the support layer was treated with a laser to produce holes. Then, a thin fabric layer was connected to one side as a second support layer. The holes were then filled with aerogel granules, and another layer of the fabric was placed

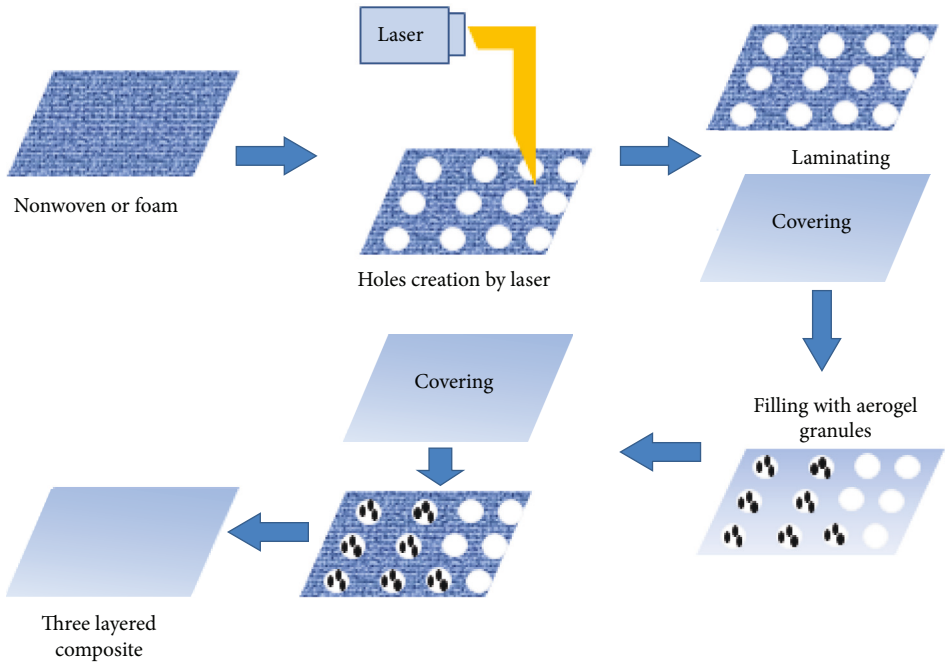


Figure 12: Schematic diagram of the three-layered aerogel nonwoven composite.

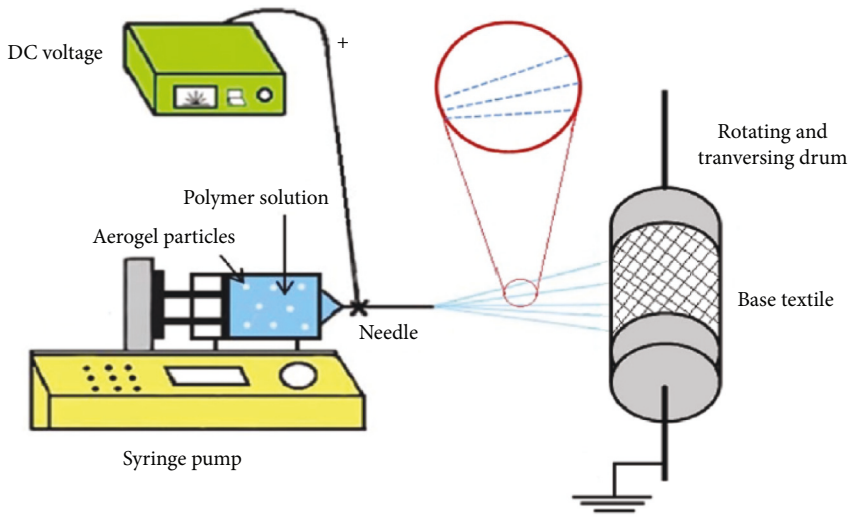


Figure 13: Schematic diagram for the electrospraying of aerogel particles on the textile substrate [115].

on the other side to prevent the loss of aerogel granules as shown in Figure 12. Finally, both sides of the support layer were covered with soft fabric to achieve a closed system. It was found that the layered aerogel composite has more thermal resistance, but less compression resistance, as compared to regular nonwovens.

3.5. Electrospraying of Solution Containing Aerogel Grains Mixed with Polymer. Another method to produce aerogel-incorporated textiles is the mixing of aerogel granules with a polymer solution or with its molten state via the electrospinning technique as shown in Figure 13. In a study reported by Bhuiyan et al. [116], silica aerogel granules were deposited on the viscose fabric using polyacrylonitrile electrospun fibers. Primarily, silica aerogel particles were milled to reduce their particle size to the micron range. Subsequently, these silica aerogel particles were mixed with polymer (polyacrylonitrile) solution, and finally, this solution was added to an electrospinning pump to obtain nanofibers of polyacrylonitrile containing silica aerogel particles. Then, this nanofiber layer was placed between two layers of viscose nonwoven fabric to develop a layered structure. Xiong et al. [117] used needleless electrospinning to embed aerogel particles in the polymer and then sprayed it on the fabric. Silica aerogel in the form of a powder was added to the polytetrafluoroethylene solution. This solution was then sprayed on the polypropylene sheet to form a

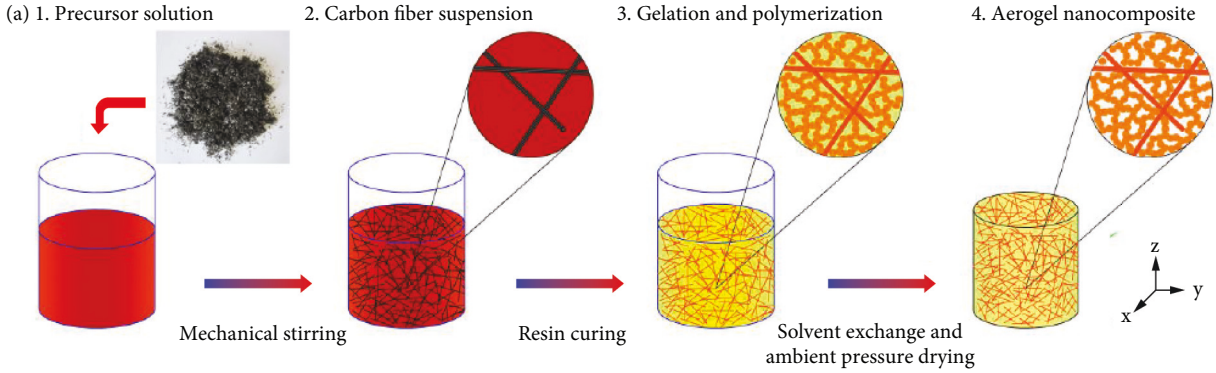


Figure 14: Schematic diagram for the preparation of fiber reinforced aerogel [122].

microporous structure. Ghahfarokhi et al. [115] also sprayed the aerogel particles with an impregnated polymer solution on the polyester woven fabric. Firstly, the aerogel powder was mixed with fluorocarbon solution and then sprayed on the woven polyester fabric to create a hydrophobic fabric.

3.6. Incorporation of Textiles into the Aerogels. The third method to incorporate aerogels in textiles is to combine them during the synthesis stage. This way, various properties can be imparted to the aerogels such as flexibility, mechanical strength, and conductivity. Moreover, some properties of the textiles can also be improved like thermal insulation [103], filtration efficiency [118], and antibacterial properties [119]. Fibers or fabrics can be added to the sol before gelation of the aerogel. Different natural and synthetic fibers have been added to the aerogel sol to produce the textile-incorporated aerogels [101, 120].

Various researchers have worked on fibers incorporated within aerogels. Some of them added nanofibers [121] or chopped fibers [122]. In some other studies, a nonwoven sheet of the fibers was added to the solution of aerogel precursors before gelation as shown in Figure 14 [122]. An aerogel composite was synthesized by reinforcing SiO_2 aerogel with electrospun polyvinylidene fluoride (PVDF) webs via electrospinning and sol-gel processing. The synthesized aerogel composite exhibited improved strength, flexibility, and hydrophobicity but low thermal resistance (0.028 $Wcm^{-1}cK^{-1}$) as compared to pure nanofiber web [121]. Natural fibers such as silk, bamboo, ramie, hemp, and soy silk were added to the precursor solution of aerogel by Finley et al. [123]. Moreover, jute fibers [124], cotton linters [125], and recycled cellulose [126] have also been added to the aerogel precursor solution to prepare textile-incorporated aerogels. The modified composite aerogel kept good heat insulation at 0.026 W/mK. Inorganic fibers like glass and ceramics have also been used in aerogels [127]. Wang et al. [128] and Zhihua et al. [129] used ceramic fibers in the synthesis solution of aerogels. The resulting material had better strength (4.8×10^4 Pa) than aerogels (1.6×10^4 Pa), but its thermal conductivity increased from 0.023 W/mK (pure aerogel) to 0.026 W/mK (silica aerogel composite). Kim et al. [130] and Liao et al. [131] added glass fibers to the silica aerogel solution to form a composite structure. The prepared nanocomposites had a low thermal conductivity of 0.026 W/mK, which is very promising for their use in thermal insulation applications. In another study, An et al. [132] prepared ceramic aerogel-aramid fiber textile composite by in situ crosslinking reaction, and it was found that the composite had an excellent thermal insulation conductivity (as low as 0.034 W/mK) with high compressive strength (1.1 MPa). The composite textile has shown promising performance under harsh environments with varying temperatures, for example, from −196°C to 400°C. Zhang et al. [100] added the polypropylene nonwoven in the aerogel solution to form a nanocomposite structure. The specific surface area of the silica aerogel composite was 700 $m^2 g^{-1}$, and the pore volume was 3.04 $cm^3 g^{-1}$. Aerogel-fiber composites have better adsorption capacities compared with activated carbon fiber (ACF) and granules of activated carbon (GAC) and have much better mechanical properties than thaose of pure silica aerogel. Boday et al. [133] added polyaniline nanofibers to the aerogel precursor solution before the gelation. The prepared aerogel was found to be electrically conductive with a 900 m^2/g surface area. From this discussion, it can easily be said that textile fibers can be incorporated into aerogels to enhance the characteristics of both constituents, aerogels and textiles. The preparation of aerogel textile composites decreases the thermal resistance of the aerogels to some extent but imparts strength to aerogels for commercial applications like blankets and clothing. On the other hand, the properties of the textiles such as thermal resistance, porosity, filtration efficiency, and hydrophobicity can be enhanced by incorporating textiles into aerogels.

Various nonwoven fabrics have been incorporated into aerogels for commercial thermal applications. Ahmad et al. [103] synthesized a new composite of alginate aerogel with polyester (PET) nonwoven by a sol-gel method. This approach is the direct insertion of the fabric into the solution of the aerogel precursor. The composite system then undergoes hydrolysis, gelation, aging, solvent exchange, surface modification, washing, and drying and finally forms a soft aerogel/nonwoven composite. The composite had a higher thermal resistance and also a higher tensile strength than the pure PET nonwoven. Mazraeh-shahi et al. [134] and Oh et al. [101] both immersed the polyester nonwoven sheet in the sol of aerogel precursor. The contact angle of the PET nonwoven was improved from 89° (pure PET nonwoven) to 98° (PET

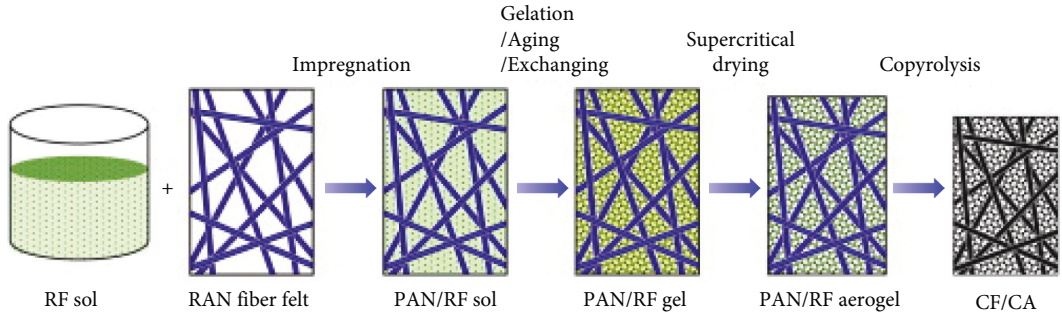


Figure 15: Schematic illustration for the synthesis of aerogel [135].

nonwoven reinforced aerogel). Feng et al. [135] dipped polyacrylonitrile nonwoven into the resorcinol-formaldehyde sol to prepare an aerogel composite as shown in Figure 15. Many woven fabrics have also been used to produce textile-incorporated aerogels. Wang et al. [136] and Schmitt et al. [137] placed the woven carbon fabric between the glass plates, and then the aerogel precursor solution was poured to produce an aerogel composite. These were used to build button cell supercapacitors with a capacitance of about 11 F and a serial resistance of about 170 mΩ. The resulting carbon aerogel showed significantly better results than the commercial materials.

Islam et al. [138] prepared aerogel-incorporated textiles using three-layered weft-knitted spacer fabrics with different thicknesses and silica aerogels to study the thermal performance of the resulting materials. The fabrics were cut and then placed in the silica sol to create a gelled layer on the fabrics with the gelation. SEM images revealed the silica network on the surface of treated fabrics even though more magnified images were also needed to see the structure of aerogels. The incorporation of silica aerogels in those fabrics decreased the thermal conductivity of the native fabrics depending on the thickness of the fabric that was used.

3.7. Aerogel Fibers. Many currently available aerogels are in the form of particles or monolithic block materials, but their low drapability makes their applications limited. Drapability is the drawback of monolithic aerogels or particles, so to overcome this issue various methods have been developed. The incorporation of aerogel particles in nonwoven structures or textile-incorporated aerogels is a method to overcome the drapability issue. The drapability issue has been resolved by this method, but the thermal conductivity becomes compromised [139]. In addition, fiber reinforcements in aerogels lower the thermal insulation properties of the aerogels as explained in Section Therefore, to increase the thermal insulation properties, even more, nonwovens made up of aerogel fibers would be favorable. There are only a few studies on the production of aerogel fibers, and some of them are discussed here.

Karadagli et al. [140] prepared a lightweight, thin cellulose aerogel fiber from microcrystalline cellulose. They prepared a dope solution for cellulose aerogel fibers by dissolving the cellulose in different amounts (0.5–6 wt%) in the melt of calcium thiocyanate tetrahydrate. When the dope solution got prepared, this viscous solution was transferred to a micro extruder (Xplore 15, DSM, Geleen, Netherlands) for the fiber extrusion as shown in Figure 16. A porous 3D aerogel structure was produced having pores in the nanometer range. The densities of the aerogel fibers obtained with 0.5–6 wt% concentration vary from 0.009 to 0.135 g/cm^3, respectively. The specific surface area was measured using nitrogen physisorption which was in the range of 120–230 m^2/g. The strength of the fiber aerogels was in the range of 4.5 to 6.4 MPa. The SEM images of the aerogel fibers are given in Figures 16(e)-16(f). There is one drawback of the cellulose aerogel fiber which is its lower tensile strength as compared to technical fibers.

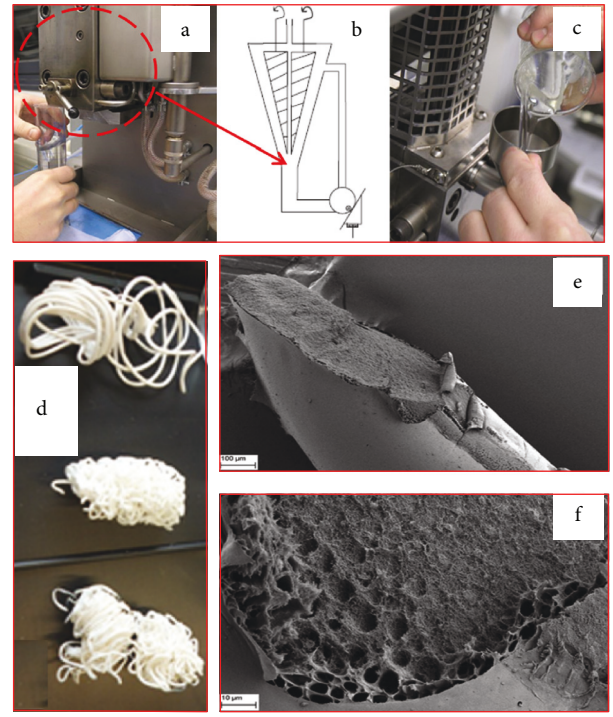


Figure 16: (a, b) Two conical, fully intermeshing corotating twin screws; (c) filling of a viscous cellulose-salt melt hydrate solution into an extruder; (d) cellulose aerogel fibers; (e-f) SEM images of 3 wt% cellulose aerogel fibers produced by twin screw extrusion exhibiting a mantle-core structure [140].

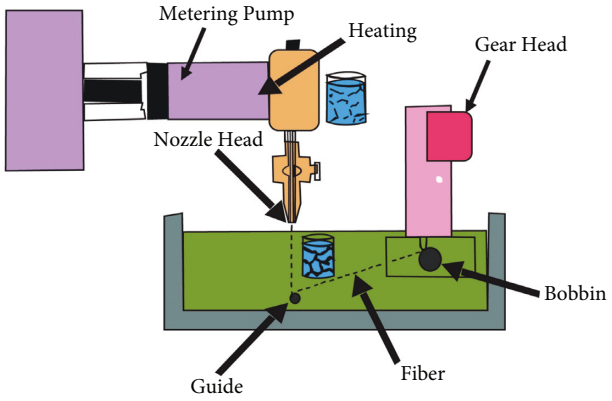


Figure 17: Schematic diagram for the laboratory spinning plant for the fiberization of silica wet gel.

Pico et al. [141] also prepared silica aerogel fibers using the sol-gel method followed by supercritical drying. Firstly, the sol was prepared separately, then forced by the metric pump via a nozzle into the coagulation bath to start the polymerization, and then continuously winded on the bobbin. Then, the fibers finally dried in supercritical carbon dioxide. The specific surface area which was measured by nitrogen physisorption was 755 m^2/g. The average pore size on the fiber surface was 6 nm.

Mroszczok et al. [139] developed cellulose aerogel fibers using the sol-gel method followed by supercritical drying. They used wet spinning to produce gel fibers. Aerogel fibers were extruded from the multifilament spinning nozzle with 100 holes having 15 μm diameter. A core-sheath structure of the fibers has been prepared as can be seen in Figure 17. In a recent study by Wang et al. [142], an aerogel textile woven with polyimide fibers was prepared by freeze-spinning. The synthesized fiber was shown to be mechanically strong with high porosity. Excellent thermal insulation properties were seen, especially at high temperatures. Along with other advantages of the polyimide fibers such as wearability and self-extinguishing properties, the prepared aerogel textile was suggested as a promising thermoregulating textile at high temperatures.

Different strategies for the development of aerogel-based textiles have been discussed, and it has been found that all strategies have improved the properties of both the textile materials and aerogel. However, every strategy has its advantages and limitations. In the first strategy, aerogel and textiles are produced separately and then combined to achieve the properties of both materials. This strategy enhanced the properties of the textile, but the weak interaction between them and rigidity are the drawbacks of this strategy. The second strategy is reinforcing fibers or fabrics in the aerogel structure which enhances the mechanical properties of the aerogel, but the thermal insulation of the resulting material is compromised. The second drawback of this strategy is its rigidity which limits its application in various fields. The third strategy is to develop aerogel fibers to overcome the rigidity of the aerogel textiles, but aerogel fibers have weak mechanical properties which restrict the fiber for further processing.

3.8. Thermal Insulation of Aerogel-Based Textiles. Thermal insulation is the promising property of aerogels with ultralow thermal conductivity (<0.1 W/mK). Total heat transfer of aerogels could be due to gas conduction, solid conduction, heat radiation, and gas convection through a gas flow [143]. Since aerogel is a 3D porous material, the contribution of thermal conductivity via the solid-solid interface or solid-gas interface will be reduced. The contribution of thermal convection is almost negligible due to the nanoporous structure of aerogels providing a very small area for heat transfer. The contribution of radiation to thermal conductivity under ambient pressure and temperature could be ignored [144]. Gas conduction has a major contribution to the thermal conductivity of aerogels which mainly depends upon the pore size in aerogel and the free path for moving air molecules [143]. So thermal insulation of aerogel materials is mainly dependent upon the presence of nanosized porous structure able to entrap air within the pores.

3.8.1. Thermal Insulation of Aerogel Blankets. One of the major applications of aerogel-based textiles is the aerogel blankets for thermal insulation. Because polyester reinforced silica aerogel blankets have low thermal conductivity, hydrophobicity, compression resistance, flexibility, and ease of usage. Aerogel blankets are capable of providing high thermal insulation at a fraction of the thickness of conventional insulation materials. The use of these materials for insulation of buildings can reduce the loss of energy by conserving interior space. The thermal performance of the aerogel blankets could be five times higher than the non-aerogel based insulation materials [145]. The blankets developed by reinforcing aerogel with fibers provide excellent thermal insulation properties. Aerogel blankets have a thermal conductivity of 0.011-0.015 W/mK for the temperature range betwwn 200°C-650°C. The thermal conductivity of air and polyurethane is half of the aerogel blankets. THis makes aerogel blankets useful forextremely cold and extremely hot environments [146].

Silica aerogel blanket Spaceloft® 3251 (Aspen Aerogels, USA) was implanted in polyester microfiber nonwoven to be used in textile. Silica aerogel produced dust by handling due to crushing of aerogel which gives an unpleasant feeling to the user. Therefore, the silica aerogel blanket was laminated with a laminate of breathable membrane, Platilone® M2234, made up of polyether block amide. The aerogel blanket was laminated on both sides to yield a five-layered structure [145]. Silica aerogel blanket Spaceloft® 3251 is a dark gray color flexible material with oleophilic and hydrophobic properties having 0.013 W/mK thermal conductivity [147]. The gray color of the blanket is due to the color of fibers and silica aerogel having metal particles to decrease the effect of thermal radiations from the environment. The laminated silica aerogel material is easy to cut and sew like nonwoven fabrics. Despite multilayer structure of the laminated silica aerogel blanket, it is a very light material with 0.205 g/cm^3 density, 2.51 mm thickness. ad 616 g/m^2 areal density, which

is suitable to use in garments for personal protection in extremely cold weather [145].

3.9. Commercial Scale Production of Aerogels. Aerogel production on a commercial scale is dominated by carbon and silica aerogels. The first industrial production of aerogels was started by Monsanto chemicals in the 1950s. Major manufacturers of aerogel on a commercial scale are American Aerogel Corporation, Cabot Corporation, Dow Corning, BASF, Svenska Aerogel AB, Aspen Aerogels Inc., Airglass AB, Active Space Technologies, and Acoustiblok UK Ltd. [83]. The market of aerogels was valued at $353.6 million in 2015 which is expected to rise and reach a valuation of $1100.2 million by the end of 2024. Aspen Aerogels and Cabot Corp. (USA) made insulation materials made up of silica aerogels have a substantial share in the market [148]. The bulk quantity produced of aerogel blankets has prices from $40/m^2 to $150/m^2.

Conventional silica aerogel production on a large scale was dependent on the cost and availability of the raw materials. The raw material for silica aerogel production was energy intensive as it is procured by reaction of sodium carbonate with quartz sand at high temperature [149]. Industrial grade fumed silica has $2.8–$5.5/Kg wholesale price range in the market. Silica ranging from 0.1 to more than 10 percent dry weight is pervasive across plants [150]. Except for water glass and organic silicates, different biowaste ashes such as bagasse, maize stalk, wheat husk, rice husk, and bamboo leaves have been used as the raw material for silica sources in aerogel production [151, 152]. Xu et al. [150] reported a review related to the silica production from lignocellulosic biorefinery feedstocks. They studied various feedstocks such as pearl millet, napier grass, switchgrass, and annual sorghum. The yield of silica from the feedstock ranged from 41 Kg/ha to 3249 Kg/ha. Among different biomass sources, rice comprises 19–22% of silica which is a higher quantity compared to any other biomass source [153, 154]. The company named Green Earth Aerogel has started the production of silica aerogel from rice husk on an industrial scale [151].

3.10. Applications of Aerogels. There are numerous applications of aerogels like thermal insulation, space suit components, pipeline insulation, acoustic application, filler and carrier material, supercapacitors, and absorbers. Applications of aerogels in textiles are discussed here.

3.10.1. Applications of Aerogels in Textiles

(1) Antibacterial Textiles. Antibacterial property is required in textiles to be used in medical applications. Aerogels can be used to acquire an antibacterial property in textiles. Mahltig et al. [119] achieved the antibacterial property by inserting the biocides in silica coatings and applying them to the textile fabric. In this study, silver nitrate, octenidine, cetyltrimethylammonium bromide (CTAB), and colloidal silver were added to the sol solution. Researchers have successfully produced antibacterial textiles and have found that CTAB and octenidine additives in the silica coating showed higher inhibition (90%) than colloidal silver and silver nitrate after 4 hours against fungi *Aspergillus*. Wu et al. [155] used recycled plastic bottles, oyster shell powder, and silica aerogel powder to develop a textile composite. The thermal resistance and the antibacterial property were improved by adding oyster shell powder and silica aerogel powder as compared to pure recycled polyester textile.

(2) Medical Textiles. Biopolymers in combination with siloxanes have been used for the synthesis of films for coatings and membranes. These synthesized hybrid materials can be used in various medical applications as bone substitutes, biocompatible materials, and cement for reconstruction or bone repair. The layers of biocomposites can be prepared from silica and bone-relevant proteins such as chitosan, gelatin, and collagen. These biopolymers are used as organic additives owing to their bioadhesive, biodegradable, and multifunctional properties [119, 156, 157].

Textile Engineering offers a toolbox in terms of fiber production method or textile fabrication process to develop nonwoven or woven aerogel composites exhibiting different mechanical and structural characteristics to overcome certain limitations such as the poor mechanical properties of polysaccharide-based aerogels. Cellulose aerogel fibers were produced using microcrystalline cellulose by wet spinning technique for drug delivery applications. Produced alcogel fibers were loaded with a drug before supercritical CO_2 drying [158].

(3) Insulating Textiles. The insulation property of the aerogels is extremely useful to develop lightweight and flexible textile materials for insulation purposes. Thermally insulated fabrics can be used in automobile industries as well as building and construction industries. The aerogel composites can be used as blankets for energy conservation in buildings to control heat loss. Aspen Aerogels has developed a product named Pyrogel insulation to be used as an underfoot barrier in extremely cold weather for climbers of Mount Everest [159].

(4) Intelligent Textiles. Li et al. [160] produced smart aerogel fibers by impregnating phase change materials into graphene aerogel fibers followed by coating with fluorocarbon resin. First, graphene aerogel fibers were prepared by wet spinning technique followed by subsequent reduction and supercritical drying. The resulting fiber exhibited a high surface area (548 m^2g^{-1}) and 2.27 $cm^3\,g^{-1}$ pore volume. The preparation of the fiber was then completed by a coating of fluorocarbon resin. The finished fibers were then twisted into yarn and woven into the fabric, exhibiting superhydrophobic properties for self-cleaning and multiple responsive properties to external stimuli with reversible energy conversion and storage. These smart fibers can be used in wearable electronics.

Li et al. [161] fabricated a core-shell yarn structure by dipping aerogel-spun carbon nanotube yarn in a PVA solution in which the core was made up of pure carbon

nanotube and carbon nanotube/PVA as a sheath. The produced yarn exhibited 447.1 S/cm electrical conductivity and linear piezoresistive response with a 2.36-gauge factor. The PVA-coated yarn improved the tensile strength, Young's modulus, and abrasion resistance by 71.8%, 157.3%, and 100%, respectively. The developed yarn structure was suggested to be used as a strain sensor in flexible intelligent devices.

(5) Flame Retardant Textiles. Aerogels have also been used to impart a flame retardant property to the fabrics by coating the aerogel on the fabric. Shaid et al. [162] produced a multilayered firefighting garment in which one layer was coated using silica aerogel particles and phase change materials to increase the ignition time of the firefighting garment. The ignition time of the firefighting garment has increased from 3.3 s to 5.5 s with the application of aerogel and phase change material. In another study, Shaid et al. [163] used aerogel nonwoven as batting material for the firefighting protective clothing. They have bought an aerogel nonwoven made of silica aerogel from Buyaerogel.com and used it as a layer between other layers of the firefighting suit. It was shown that the thermal resistance of the aerogel nonwoven was 8 times more than the commercially available simple nonwoven.

(6) Clothing, Apparel, and Footwear. Yang et al. [164] created a nano-cellular structure within the polyurethane foams by incorporating silica aerogels to improve the thermal and mechanical properties of footwear applications. They have incorporated silica aerogel particles manufactured by JIOS Aerogel USA into the foam. Thermal insulation of the foam has increased up to 45%. Moreover, mechanical properties were also enhanced by incorporating aerogels into the foam. In the research conducted by Zrim et al. [165], the properties of the laminated silica aerogels matting composites were evaluated. They have used commercially available silica aerogel composite Pyrogel 2250 manufactured by Aspen Aerogels Inc., USA. Laminated aerogel composite provides breathable and waterproof footwear with high thermal resistance at a lower weight and a lower thickness in comparison with other advanced materials.

4. Recent Developments and Challenges

At present, commercial corporations from all over the world that can develop outstanding-performance aerogels-based blankets are limited to a few known companies like Cabot Corporation and Aspen Aerogels. For various countries, the production cost of aerogel blankets is still high. So reducing the manufacturing cost of aerogel blankets with regular porous structures is the key to success. To take complete advantage of aerogel materials and to improve the opportunities, further research needs to be conducted in different areas. There are various challenges that should be addressed in future studies. Various aerogel materials should be synthesized by focusing on high-performance textiles. Research should be conducted specifically on manufacturing methods to reduce manufacturing costs by improving the process parameters. Commercially developed cheap aerogel materials still have a long way to go. But with the technological advancements and enhancement of energy conservation awareness on a global scale, new commercially available eco-friendly aerogel materials with good thermal insulation properties and at low cost will continue to grow. The demand for aerogels will increase in the future because of their use in industrial pipelines, heat insulation in ship hulls, safety protection in new energy vehicles, clothing for extremely cold weather, management of heat flow in semiconductors, Space Shuttle insulation materials, and building insulation materials.

5. Conclusion

Conventional, as well as modern, technologies to develop the micro and nanoporous structure in textiles were reviewed. In conventional technologies, different fabrication methods (weaving, knitting, and nonwoven fabric manufacturing) were used to obtain porous structures. Nonwoven fabrics were reported to show a better porosity among all the textiles produced using conventional fabrication technologies to achieve a microporous structure. The electrospinning technique was used by several researchers to produce a nanofiber web to obtain a nanoporous structure, but this nanofiber web has drawbacks because of its low strength and slow production. Some researchers have worked to overcome the drawback of the nanofibrous web, but they could achieve only limited results. Aerogel is a recently reported nanostructured material with ultralow density and high thermal insulation. However, pure aerogel has a stiff structure and low strength; thus, it cannot be used in various applications. Therefore, textile reinforced composites were developed to impart strength and flexibility to the aerogels, which in turn have nanoporous structures and high thermal insulation. In this review, three strategies have been discussed. In the first strategy, aerogels were produced separately and then deposited onto the surface of the fabrics. In this strategy, the thermal insulation of the fabric increased, but the comfort properties and flexibility of the textiles were compromised. The second strategy was to insert textile reinforcement into the aerogel during its manufacturing phase. The composite aerogel synthesized with this technique showed good flexibility and thermal insulation. However, the thermal insulation of the aerogel composite was less than that of the native aerogel due to the reinforcement within the structure. Consequently, in the third strategy, aerogel fibers were developed to overcome this issue. Aerogel fibers have very good thermal insulation properties as compared to aerogel composites, but their mechanical properties are poor, which should be investigated and improved in future studies. It can be anticipated that the demand for the textile composites with aerogels will focus on energy saving of special protective clothing in cold weather and high-temperature environment, new energy vehicles, ship hulls, semiconductor industries, and building insulation materials.

Data Availability

The data used to support the findings of the study can be obtained from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Authors' Contributions

Mr. Farooq Azam and Dr. Faheem Ahmad conducted the literature review. Dr. Zeynep, Dr. Abher, and Dr. Yasir helped in writing the manuscript. Dr. Sheraz, Dr. Sohail, and Prof. Can Erkey reviewed the manuscript and guided the overall project.

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