Egyptian Journal of Chemistry

http://ejchem.journals.ekb.eg/

Silica Aerogels and their Applications in Textile Industry

Ahmed G. Hassabo [a]*, Sohaila Shaker[b] Neaama A. Abd El-Salam [b], Nourhan A. Mohamed [b], Nehad Z. Gouda [b], Nadeen Khaleed [b], and Hanan A. Othman [b]

[a] National Research Centre (Scopus affiliation ID 60014618), Textile Research and Technology Institute, Pretreatment and Finishing of Cellulose-based Textiles Department, 33 El-Behouth St. (former El-Tahrir str.), Dokki, P.O. 12622, Giza, Egypt

[b] Benha University, Faculty of Applied Arts, Printing, Dyeing and Finishing Department, Benha, Egypt

Abstract

The coating of various textiles, including 3D weft-knitted spacer fabrics (92% polyester - 8% spandex), polyester, and cotton, is presently seen to be a great use for silica aerogels (SA). They may impart and improve various attributes to the aforementioned fabrics thanks to their exquisite porous structure, large surface area, and superior permeability. They are primarily created from three different types of precursors, namely water glass (Sodium silicate), alkoxysilanes, and orthosilicates, to produce silica, which has the chemical formula O-Si-O. They follow a conventional sol-gel manufacturing process, going through three stages: gelation, aging, and drying. They are coated onto cloth and give self-cleaning, superamphiphobicity, chemical protection, thermal insulation, and thermal comfort qualities.

Keywords: Silica Aerogels- Thermal insulation- Heat comfort- Superamphiphobicity- chemical protection – Self-cleaning.

Introduction

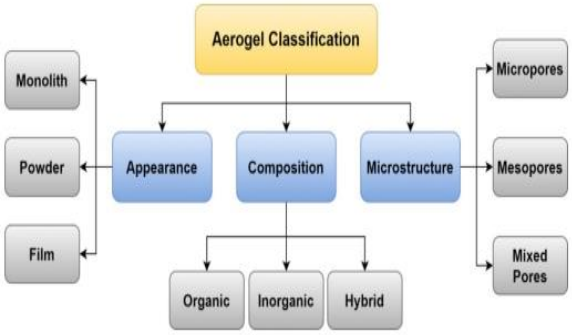
Aerogels are primarily mesoporous, access-cell materials featuring considerable inner porosity as well as low density. Aerogel's distinctive characteristics, including its substantial surface region, high mesoporosity, and extremely poor ability to conduct heat, are mostly a result of its micro-structure instead of the particular substance constitution of the nanoparticles which form the aerogel [1]. Extremely low levels of density are produced by the pores, which may cover over ninety percent of the substance's capacity. The very large specific surface areas are a result of the pores' very small (2–50 nm) size [2]. The arrangement and connectivity of the particles, known as the micro-structure, have a significant impact on the substance's general characteristics.

Aerogel, for instance, may provide a large surface area and high mesoporosity by organizing its particles in a tortuous network structure, making it a powerful absorbent for both gaseous substances and fluids. Parallel to this, aerogel's extremely poor thermal conductivity results from the arrangement of the particles, which forms an arrangement of holes that lock in air and reduce the passing of heat throughout the substance [1]. Aerogels may not only possess mesoporous, but also, microporous or mixed pores depending on their form. based on the synthesis techniques, the sort of catalyst used, as well as the kind of sol produced [3].

Of all extensively studied aerogel, the silica-based one is the most intriguing. Silica is a plentiful, inexpensive substance that may be used to create substances for a variety of uses. A structure composed of interconnected chains comprised of spherical nanoparticles forms a silica aerogel [3]. Sol-gel technique is used to produce silica aerogel. The starting materials might be alkoxysilanes based on organic solvents or sodium silicate based on aqueous solutions (water glass). Emulsified silica particles are created by condensing processes following the creation of silicic acid oligomers (from sodium silicate) or silicic acid oligomers that have undergone insufficient esterification (from alkoxysilanes). Then comes the Ostwald ripening, which includes gel synthesis, possible aging, alterations to the surface,

*Corresponding author e-mail: aga.hassabo@hotmail.com; (Ahmed G. Hassabo)
Receive Date: 11 June 2023, **Revise Date:** 03 August 2023, **Accept Date:** 07 August 2023,
First Publish Date: 07 August 2023
DOI: 10.21608/EJCHEM.2023.216963.8119

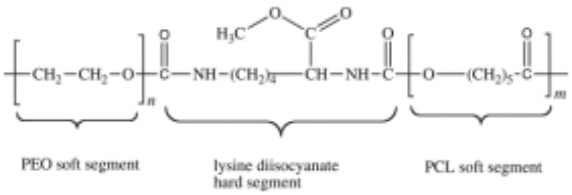
and being dried, as well as the creation of a 3D gel network. Given the manufacturing method, the final material can take on zero-dimensional (0D). e.g., monoliths, films, or powdered silica aerogel [4]. Additionally, (**Scheme 1**) provides an overall categorization for aerogels. [3].



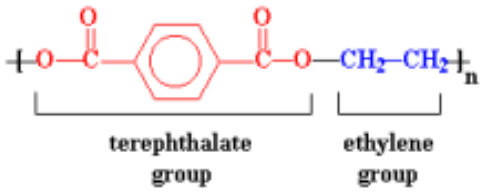
***Scheme 1**: Categorization of aerogels [3].*

Since the beginning of time, people have dressed in textiles. Yet, because of their useful qualities, their significance and utilization in different fields, like clothing that is protective, have grown gradually [5]. Silica aerogels appear to be among the greatest candidates for the use of safety garments in light of this. By utilizing several coating techniques, such as the knife-over roll coating technique [6] or dip-pad-cure procedure [7]. Both of these are regarded as printing techniques of some sort. Moreover, silica aerogels have properties that allow them to be used on textiles for a variety of purposes, including thermal insulation, water, and oil-resistant functions, chemical protection, and self-cleaning functions. Also, these coating techniques of silica aerogels are employed on three types of fabrics and they are: 3D weft knitted spacer fabrics, polyester fabrics and cotton fabrics.

A particular kind of textile blend that comprises polyester and spandex (92%-8%) is called 3D weft knitted spacer textiles. The 3D knitted fabric called a spacer cloth has two outer layers joined via a center core made of spacer yarns. The knitted structure of its sandwich form allows for exceptional air permeation, moisture transmission, and breathability. And this cloth has flexibility thanks to the spandex component in the mix [8] The structure of this blended fabric depends on the way the polyester yarns have been spun together. The spandex utilized in this fabric blend also consists of polyurethane, a long-chain polymer that is produced when polyester as well as di-isocyanide combine. Its chemical composition is likewise depicted in (**Scheme 2**) [9]. On the other hand, a fabric made from polyester is a class of polymers that mostly consists of ethylene and terephthalate moieties as well as having an ester functional group in its primary chain. And (**Scheme 3**) depicts its chemical composition [10].

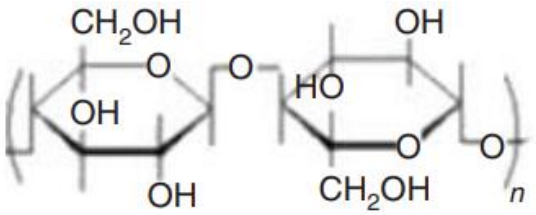


***Scheme 2**: Spandex's chemical composition [9].*



***Scheme** 3: the polyester's chemical composition [10]*

Additionally, cotton is one of the textiles that are most frequently used when covering with aerogels. 90% cellulose, 7-8% moisture, wax, fat, refined cotton, or absorbing cotton, which is completely cellulose and has a moisture content of only 6-7%, are the primary components of unprocessed cotton. Cellobiose, a unit that repeats itself consisting of a pair of glucose units and is found in cotton, is a long-chain polymer. The most significant groups in the polymer are the -OH and hydroxymethyl groups (CH2OH), and (**Scheme 4**) depicts the polymer's chemical structure [11]. And in this study, numerous coating applications for silica aerogels are reviewed.



***Scheme** 4: The cotton fiber's chemical structure [11]*

1. Synthesis of Silica Aerogels

In a procedure that involves dehydrating and the sol-gel processes, silica aerogels are frequently created using a wet chemical technique. The fundamental silica aerogel manufacturing method, known as the sol-gel procedure, includes the water-based hydrolysis and condensation reaction of the silica precursor, which is catalyzed by acidic compounds or bases, to produce a sol, that is then aged to produce a liquid gel [4]. The sol-gel procedures' primary benefits include sustainability, reduced chemical consumption, cooler temperatures processing, minimal harm to individuals, preservation of the natural qualities of textile fibers, the ability to customize coating dimensions, and the durable characteristics of coated textiles [12]. Additionally, post-modifications could be possibly

added to the as-produced silica aerogels to provide a particular performance, based on the intended functions [4]. And the subsequent procedures were followed in the production of the silica aerogel substance:

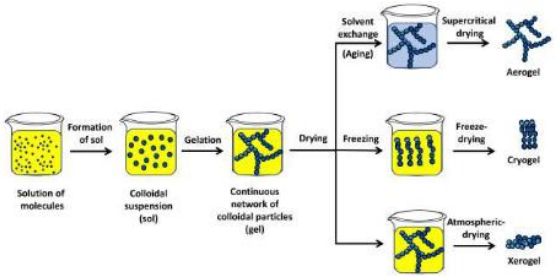
1.1. Sol-gel chemistry and gel formation methods (gelation)

Z. Mazrouei-Sebdani et al. were able to create a silica gel when a silica sol, or a stable colloidal solution of silica nanoparticles, is destabilized by the inclusion of a gelation catalyst to modify pH and subsequently its surface charge. The formation of the parent particles, their subsequent agglomeration into smaller secondary particles (clusters), and their eventual interconnection in a necklace made of pearls shape occur throughout the sol-gel shift as presented in (**Scheme 3**). The sort of drying technique has an impact on the sort of aerogel generated, as shown also in the figure. Precursor substances of silica that are useful for the industry include silicon alkoxides, water glass, and ion-exchange water glass [1].

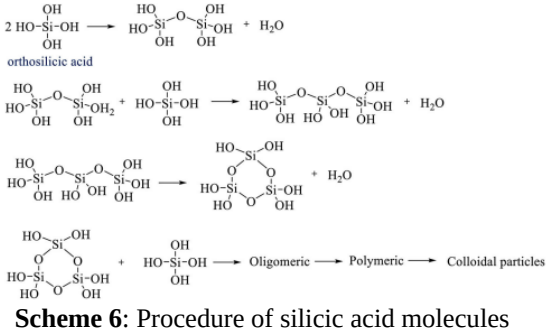
A suspension of sodium silicate (Na_2OnSiO_2) within water that has a Na/Si molar proportion greater than 1.5 is known as water glass. The silica exists as monomers and oligomers at such high Na/Si ratios that it is tetrahedrally organized by 4 oxygen atoms (sp^3 hybridized). As observed in (**Scheme 4**), they have a negative electrical charge on the quasi-bridging molecules of oxygen that are counterbalanced by Na+ cations in the water phase. The chemical reaction of acids and bases causes basic sodium silicate to gel [4], indicating that it's able to gel when acid is added (partial neutralization). Possibly the least pricey silica precursor is water glass. The microstructure and characteristics of water glass are capable of being strongly and negatively impacted by the sodium ions present in it. As a result, a different typical precursor is ion-exchange water glass, a silica acid mixture created, for example, by transferring water-glass liquid within an ion-exchange polymer. [1].

In comparison to quasi-ion-exchanged water glass, the researchers, Z. Mazrouei-Sebdani et al. could make ion-exchanged water glass also be gelled through the incorporation of bases (partial neutralization), but the ion-exchange phase imposes a significant expense. fortunately, ethanol is capable of being included to serve as another solvent, and single-step transfer has been established, the gelation solvent for each conventional and ion-exchanged water glass is usually water, which might demand extra solvent transfer throughout the following processing steps [1].

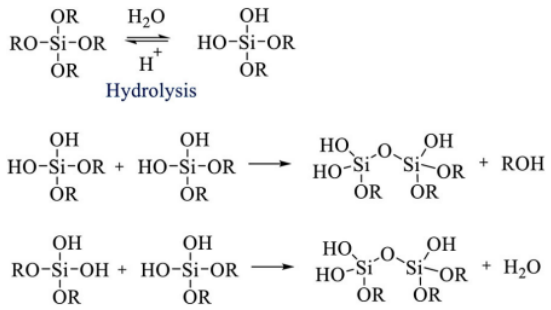
Additional chemical precursors, including silicon alkoxides, especially tetraethyl orthosilicate (TEOS) and tetramethyl orthosilicate (TMOS), whose use has revolutionized the aerogel sector, may additionally be employed by Z. Mazrouei-Sebdani et al. to create silica aerogels. According to (**Scheme 5**), alkoxide-based silica sols can be generated by the process of hydrolysis with water/alcohol condensing [1]. Additionally, C. LI et al. found out that, in contrast to the chemical formula of water glasses, alkoxysilanes undergo a hydrolysis process that produces Si-OH compounds along with being triggered by pH hifts when water is present. However, there are many additional types of alkoxysilanes known as organotrialkoxysilanes. Organotrimethoxysilanes include methyltrimethoxy silane (MTMS), vinyltrimethoxysilane (VTMS), and methyltriethoxysilane (MTES). Silicon alkoxides often undergo incomplete hydrolysis when hydrolyzed in a solution consisting of water and alcohol. just before the entire hydrolysis to o-silicic acid takes place, silica oligomers can be generated [4]. The traditional method for making alkoxide-based silica aerogels involves a two-stage acid-base synthesizing process that isolates the structure's creation from the hydrolysis as well as the condensation procedures. The two-step technique offers a greater degree of control to produce excellent-quality silica aerogels with characteristics of minimal density, uniform pore arrangement, and good light transmission when contrasted to the one-step method catalyzed using acid or base [4]



Scheme 5: Aerogel, cryogel, and xerogels synthesis [2]



Scheme 6: Procedure of silicic acid molecules condensing to produce silica structures.



Scheme 7: Alkoxysilanes are hydrolyzed and then condensed to produce silica nanostructures [4].

1.2. Solvents' influence and aging

The supply of water and alcohol are fundamental elements of hydrolysis and condensation, and solvent-polymer connections have an important role within the stage separation procedures which define the distinctive dimensions in alkoxysilane-based aerogels. C. LI et al. demonstrated the various functions that solvents serve throughout the production procedures of aerogels. The quantities utilized identify the solid content within the solution, and therefore the ultimate aerogel density as well. Various precursors demand various treatments and gelation solvents. Tetra(m)ethyl orthosilicates require alcoholic solvents, while sodium silicate just requires water as a solvent. Also, methyltrimethoxy silane (MTMS) could be synthesized by using both aqueous and alcoholic solvents [4]

Initially made gels are often fragile, nonetheless when stored in the original liquor, they gradually become stronger. The molecular structure of the colloid ought to be explored to comprehend these modifications. Interparticle necks in colloidal matter are frequently reinforced throughout the stages of aging, and these are just point connections at the moment of gelation [13]. Aging might be followed by roughening or microscopic separated phases of the gel phase, according to the precise circumstances. However, when done properly, the aging procedure has little effect on the gel's mesoporous structure and surface area while increasing its durability and ultimate rigidity. It is caused by the presence of remaining soluble silicates within the mother fluid soon following gelation. And The primary elements affecting wet gel's aging process are pH, temperature, as well as duration [4].

1.3. Post-functionalization

Post-treatments, such as rinsing and solvent swaps, are frequently necessary to remove remains to produce extremely pure gels or to make the solvent easier to integrate alongside the future stages of manufacturing. C. LI et al., for example, replaced the water-based solvent with ethanol to permit further supercritical CO_2 dehydration. This chemical alteration could take place at numerous periods throughout the manufacturing process, as illustrated by the examples below [4]:

The initial strategy: Pre-gelation functionalization:

Organosilane precursors can serve as the base compounds in this technique. Since they do not necessitate any extra procedures for processing, this approach is effective. It can only be probable if the organosilane is introduced into the solution and has no effect on gelation or structure development [4].

The second approach:

This method modifies the exteriors of wet gels post-gelation yet before being dried throughout the wet-surface alteration process. [4].

The final approach:

The gel surfaces may be altered in this process after or throughout drying within a gaseous stage, a fluid stage, or a supercritical state. [4].

Investigations were additionally conducted on the hydrophobic alteration of the silica aerogel exterior. The hydrophobization differs based on the silylation compound used, such as hexamethyldisilazane (HMDZ) or trimethylchlorosilane (TMCS). If an excessive amount of hydrophobic chemicals is used, the resultant aerogels exhibit comparable waterproof behavior. before, while, or following drying, hydrophobization procedures may be applied, such as via chemical vapor deposition (CVD) of alkylchlorosilanes upon a dehydrated aerogel. The majority of hydrophobization occurs during the wet stage before drying for silica aerogels, but, in practical terms. The modification after-synthesis procedure has the potential to become simpler in producing silica aerogels via more adaptable pore sizes and greater uniformity in the distribution of pore sizes than the co-precursor technique when combined with silicon sources featuring groups that are hydrophobic throughout the formation phase [4].

1.4. Drying procedures

Drying is the final but critical step in silica aerogel production. In a nutshell, drying replaces the liquids in the wet gel with air, which is quite tricky for aerogels because the small size of the pores leads to very large capillary forces when gas-liquid interfaces are present. Typical drying protocols are supercritical fluid drying (SCD), APD, and freeze drying (FD) [4].

The secondary pore structure may be adjusted using different freeze-drying (FD) techniques and solvents, which are mostly used on macroporous structures made of polymers. The method damages the basic mesoporous microstructure [4]. Nevertheless, (FD) is uncommon for silica aerogel since it is difficult

to produce silica aerogel monolith using FD [14]. SCD and APD methods, on the other hand, are thought to be superior methods for creating different kinds of silica aerogel. APD necessitates hydrophobic surfaces, i.e., enough trimethylsilyl (TMS) groups on the pore surface to avoid silanol condensation reactions and long-lasting disintegration throughout drying, to successfully produce excellent quality, minimal-density aerogels, indicating that this drying technique demands a significant amount of surface alteration. And based on the drying liquid, such as alcohol or CO_2, supercritical fluid drying was divided into high-temperature and low-temperature methods of drying [4].

The aerogel's main drying process at the moment is SCD_{CO2}. This process necessitates pricey supercritical drying machinery, which not just requires a lot of time, resources, and work but also presents substantial financial difficulties for massive-scale manufacture. The SCD is also a batch process, therefore reducing the products that may be produced on a big scale for business purposes. The SCD technique has the benefit of using less TMS hydrophobization, which could increase the silica aerogels' fireproofing [4]. The APD procedure, on the contrary, might be an additional advantageous method because of its relatively cheap manufacturing expenses, continuous and quick operations, and effective reduction of the size of necessary facilities (apart from high-pressure machinery) [14].

Applications of silica aerogels on textiles

1. Silica aerogels for chemical protection and breathability of textiles

1.1. Silica aerogel integrated with polyurethane applied on cotton fabric

An alternate method for creating breathable chemical protective clothing (CPC) with permeability is suggested. This outer coating integrates porous silica aerogel with polyurethane (PU). The two primary aims of the utilization of chemically protecting fabrics and silica aerogel are both to shield the individual wearing them from chemical threats and to allow the transmission of sweat vapor generated by human beings through garment materials for thermo-physiological comfort. So, a specific kind of fabric barrier had been developed. This particular kind of cloth is designed to be comfortable thanks to the coating layer that offered the chemical protection property. Cotton fabric was chosen as the material to be coated, and PU and silica aerogel particles were the ones utilized within the layer employed on the fabric's surface [15].

A commercial silica aerogel (SA) called Enova with 20 nm-diameter holes and a particle size range of 2 to 40 µm was utilized in an experiment conducted by M.A. Rahman Bhuiyan, et al., and coupled with a 100% cotton fabric that had been scoured and bleached. A thick white liquid paste with a water content of 40 to 70 percent was also utilized as a polyurethane binder. After that, the researchers used a knife-over-roll coating technique via laboratory coating equipment to cover the cotton fabric with polyurethane-silica aerogel at various concentrations (0.5%, 1%, 2%, and 3% on the total amount of adhesive). Additional cotton cloth had been employed as an equivalent and just the PU binder paste was placed upon it. The coated fabric samples were subsequently dried for 30 minutes at 60 °C and then cured for 5 minutes in the laboratory curing equipment [15].

The PU-aerogel-coated cotton textiles that were produced were then examined by the researchers. Substantial bonding among cotton fiber and PU adhesive was observed during the chemical evaluation of the coated samples, leading to an enduring coating on the fabric exterior. Aerogel particles were found distributed haphazardly in the coating upon the outermost layer of PU-aerogel-coated textiles, according to the surface characteristics of those materials. When it came to chemical durability against liquids, the majority of the chemicals became embedded in the porous aerogel layer, preventing liquids from penetrating the garment. As the amount of aerogel particles within the PU-aerogel coating rises, water-vapor transmission and airflow gradually improve, indicating increased thermal comfort. Less sweat accumulation is anticipated on the human body's skin or inside PU-aerogel-coated garments. The coated samples' unaltered moisture control characteristics following the incorporation of aerogel particles showed that liquid solutions might not pass through the coating, but vaporized moisture may penetrate through the aerogel pores without PU covering. The study's overall findings point toward the possible use of silica aerogel particles combined with PU coating as a novel method for creating protective apparel that is breathable for wearer comfort and offers improved chemical resistance [15].

2. Silica aerogels application for textiles' self-cleaning

Fabrics ought to be able to resist fluids to provide extra protection and maintain their pristine condition towards rain, toxic liquids, and other pollutants [16]. And here is where silica aerogels come into play, because they may provide textiles with great self-cleaning properties that enable the outer layers of the materials to remain clean, much like the self-cleaning phenomena of the lotus flower [7]

2.1. Silica aerogel's impact on the self-cleaning ability of 3D weft-knitted spacer fabrics

The outermost layers of weft-knitted spacer fabrics (92% polyester/8% spandex) WKSFs, which are employed in space suits, protective aims, absorbent

material and cozy clothes among other things, have been frequently improved with silica aerogels. To incorporate some type of self-cleaning capabilities [17]. Silica aerogels (SAs) were produced from tetraethylorthosilicate (TEOS) by the sol-gel process and subsequently coated upon the 3D weft-knitted spacer textiles [18].

Initially, silica aerogels were made by Islam, S.R., et al. by the two-step process of acid-catalyzed TEOS hydrolysis followed by base-catalyzed gel formation. The 3D weft-knitted textiles were next separated into squares and submerged in silica solution for 15 minutes. EtOH was employed to wash the wet-gelled 3D WKSFs for 8 hours. By switching the n-hexane, this EtOH rinsing was carried out three times. The wet 3D WKSFs were once more rinsed with n-hexane to get rid of excess ethanol-containing solution. Those wet 3D WKSFs were then thoroughly left to dry in an oven at 40°C as well as 60°C for 5 hours, after which they were dried again at 100°C for 5 hours, accordingly [19]. The specimens were then obtained and further studied by the researchers after being coated.

The coated spacer textiles also had a compacted surface appearance as well as an intermittent structure, which contributed to a rise in the treated 3D spacer fabrics' roughness on the exterior, and this in turn affected their potential for self-cleaning, as further evidenced by the scanning electron microscope (SEM) photographs. To test the fabrics' ability to self-clean, the researchers added coffee bean powder to both the coated and untouched fabric specimens. It was discovered that the silica aerogel-treated 3D weft-knitted textiles had an elevated static contacting angle, which caused the coffee powder to be readily washed and rinsed using water, indicating that the specimens that were coated possessed an excellent ability for self-cleaning. However, due to its saturation and adhesion upon the exterior of the uncoated 3D weft-knitted spacer fabric, the powdered coffee was unable to be completely rinsed using water [18]. Thus, it can be claimed that the silica aerogel coating is successful in integrating self-cleaning properties onto the 3D weft-knitted spacer textiles.

2.2. Silica aerogel's application of self-cleaning on cotton fabric

Due to their porous design and excellent permeability, a particular class of superamphiphobic cotton textiles coated with silica aerogel showed significant self-cleaning capabilities. They exhibit durability against stains as well as possible self-cleaning characteristics. To improve the properties of the finished fabric, the outermost layer of the cotton fabric is not only coated with silica aerogels but also blended with polydimethylsiloxane (PDMS) and 1H, 1H, 2H, 2H-perfluorooctyltriethoxysilane (PFTES) [7].

L. Xu et al. produced superamphiphobic cotton textiles by treating them with a silica aerogel. They originally used Methyl trimethoxy silane (MTMS) as a precursor and an acid-base sol-gel process which baked at ambient pressure to make the SiO_2 aerogel particles. They acquired the silica aerogel particles and then applied them to cotton textiles during treatment. The silica aerogel particles (4%) were dissolved in isopropyl alcohol while being swirled for 5 minutes. Polydimethylsiloxane (PDMS) (4%) and the curing component (10:1) were then mixed and mixed via ultrasonic vibrations for two hours to create the PDMS/SiO_2 coating treatment. Furthermore, the pH was brought down to 4 using acetic acid, and 5% of the chemical 1H, 1H, 2H, 2H-perfluorooctyltriethoxy silane (PFTES) was introduced to the ethanol. The solutions were continually stirred for an hour, then left aside for a further hour. The hydrolysis of PFTES led to the production of fluoroalkylsilanol solution [7].

The procedure of dip-pad-cure was then employed to generate cotton textiles that were superamphiphobic. The woven cotton textiles had initially been submerged for 10 minutes in a solution of 3-aminopropyltriethoxysilane (APTES) dissolution in ethanol (APTES, ethanol, with water were incorporated in 4:15:1). Subsequently, within an oven, they were left to dry at 60 ˚C. The thus produced pretreated cotton textiles were submerged in the aforementioned PDMS/SiO2 dip coating solution for 10 min. After that, they were squished using an automatic padder with a nip pressure equal to 3 kg/cm^2, baked in an oven, and finally cut into smaller pieces. Further, after being coated with PDMS/SiO_2 and drying, the textiles were compressed after spending an hour in the fluoroalkyl silanol solution. The generated textile was designated as PFTES/ PDMS/ SiO_2@Cotton immediately following being dried at 80°C for 10 min [7].

The manufactured coated cotton fabric underwent additional analysis and inspection for the purpose to evaluate its capacity for self-cleaning. To confirm the latter trait, the researchers tested it in some way. The cloth, which was mounted on a clear glass slide with a slight rotation, was covered with a thin coating of methyl blue particles. Drops of water on clean cotton fabric surfaces may rapidly disperse whenever water is repeatedly dripped upon specimens of dirty cotton fabric because uncoated textile surfaces have an abundance of hydroxyl groups. The particles of methylene blue dissolved but remained on the spotless cotton material. whereas, the drops of water put upon the outermost layer of PFTES/PDMS/SiO2@Cotton fabric rapidly glided off and transferred the dispersed methyl blue granules away without producing any trace, creating a clean cloth exterior. The PFTES/ PDMS/SiO2@Cotton fabric has a lesser surface tension over water. The PFTES/PDMS/SiO2@Cotton fabric surface allowed drops of water to slide off with ease, gathering up impurities in the process. This

demonstrated that the fabric made of PFTES/PDMS/SiO_2@Cotton has outstanding self-cleaning properties [7].

3. Superamphiphobic characteristics of silica aerogels

Overall, materials that reject water while maintaining an angle of contact with water of no less than over 90 degrees Celsius are referred to as hydrophobic or water-repellent surfaces [20]. Fabrics are one type of material. By lowering the energy of the surface while raising the roughness of the surface, it is possible to create a coating that is superhydrophobic upon fabric surfaces [21]. Fabrics with repellency to oils have also gained a lot of attention and the combination of both water and oil resistance qualities have grabbed even more attention. Yet, since oil has less surface energy than water and because superhydrophobic substrates cannot always resist oils, superoleophobic substances can be considerably more challenging to create than super water-resistant ones [22]. Nevertheless, textiles nowadays can be treated with silica aerogel to create hydrophobic and oleophobic (superamphiphobic) materials. This is a result of its abundance of pores, which enable it to contain water and oil.

3.1 Silica aerogel's superamphiphobic application on polyester fabrics

From outdoor as well as workwear to the home goods market, there is an ever-increasing need for polyester textiles with water and oil-resistant qualities. Consequently, sustained hydrophobicity of fabrics made of polyester requires a large decrease in surface energy. To achieve this, silica aerogel (SA) was added to the polyester fabric to impart the material's outstanding soil-releasing and hydrophobic qualities as silica aerogel's wetting characteristics (contact angle) and surface tension (surface energy) and their buildup exhibit an oleophobic and water-resistant effect on fabric [23] Pelin Altay et al. experimented by padding textiles with silica aerogel before analyzing the finished fabrics to evaluate the influence of the silica aerogel on the resulting fabrics [**24**].

Rem Aerogel-W, a nanoporous aquatic silica aerogel exhibiting exceptional insulating properties, was the aerogel paste that the researchers employed. Due to its water-based construction, this form of silica aerogel is additionally convenient to work with nevertheless recyclable, harmless to humans, and dust-free. Furthermore, they employed Aerocoat-120, a commercial two-component aquatic silica aerogel material, as a binder. The 100% scoured polyester was subsequently treated with SA. Water was incorporated gradually after the silica aerogel binder and paste were made in five distinct quantities by intense stirring. Utilizing a traditional padding mangle at room temp as well as squeezing equipment, silica aerogel was carefully impregnated into the fabric made of polyester. Each solution sort received five specimens. The specimens were subsequently dried for 10 minutes at 105 degrees Celsius [24].

The results of the investigation revealed that all treated textiles had varying degrees of hydrophobic and soil-releasing properties, depending on the amounts of binder and silica aerogel paste utilized. Among the samples treated with various quantities of silica aerogel, the specimen coated with 0.5g of SA paste and 0.5g of SA binder had the least wetting and the highest water-resistant qualities with a contact angle of 170.43. Additionally, it demonstrated soil release characteristics having a stain rating of 3 to 4, which means that the 0.5 g of SA paste and 0.5 g of SA binder enable simple dirt cleanup throughout washing. These findings and analysis showed that silica aerogels possess an impact on 100% polyester textiles because they can offer them water and soil resistance qualities when impregnated with these substances in a single step at the lowest temperature, without the issue of dusting, making the resulting fabrics suitable for applications such as outdoor clothing as they can resist water, soil, oil, and grease [24].

3.2. Silica aerogel's superamphiphobic application on 3D weft-knitted fabrics

The surrounding ecosystem, aquatic life, as well as human health, have all suffered as a result of effluents from factories containing harmful chemicals used in dyeing and printing [25]. As a consequence, the application of silica aerogels for coating-resistant fabrics has attracted a lot of interest. A 3D weft-knitted spacer fabric (92% polyester/8% spandex) is a representation of a fabric with multiple applications. This category of fabrics is thought to offer the greatest substitute for cotton and other conventional moisture-sensitive textiles since it generally possesses hydrophobic properties. It also offers better strength, strong planar flexibility, good longitudinal compression, and the ability to be reused. Nevertheless, they need to increase their hydrophobic and oleophilic characteristics, which is where silica aerogels come into effect [26].

As the procedure was completed in two steps, Islam et al. created the silica aerogel using the sol-gel technique. Initially, acid-catalyzed Tetraethyl orthosilicate (TEOS) hydrolysis with the assistance of dissolved HCL in water and afterwards, base-catalyzed gel formation with the assistance of NH_4OH. Subsequently, by treating the 3D weft-knitted spacer fabric specimens for 24 hours at 20°C as well as 65%

humidity level, the researchers were able to create the treated specimens. Following that, the specimens were split into 35 cm × 35 cm squares and submerged in silica sol for 15 minutes. After that, the specimens became firm and were placed in a container that was carefully capped. Wet-gelled specimens of materials were held at 25 °C for an additional 24 hours following the creation of the gelled coating (20 min) to preserve the gel network in the fabric structures. For eight hours, ethanol was used for washing the wet-gelled specimens. 3 further cycles of rinsing followed by an n-hexane exchange were performed. The ethanol-containing solution was eliminated from the wet-gelled films by washing it off using n-hexane lasting a period of eight hours. All of the specimens were carefully dried out using an oven at 40°C as well as 60°C for 5 hours, before being further cured for 5 hours at 100°C [26].

When 3D weft knitted spacer materials had been examined alongside untreated 3D weft knitted spacer materials, the specimen with the greatest number of silica aerogel particles showed the greatest water-resistance as well as oleophobic features among all the coated specimens, according to the evaluation of the coated materials. As the contact angle increases with increasing silica aerogel particle concentration, this coated specimen's hydrophobic properties improved by 57.78% as compared to an untreated specimen. Additionally, the coated sample's oleophobicity was evaluated in contrast to an untreated one. According to the investigation, the oleophobic properties of oils like vegetable oil increased by 37.79%, whereas those of oils such as motor oil were enhanced by 35.97% [26].

Because both sorts of oils possess distinct viscosities, their absorption rates vary. Vegetable oil's thin consistency made it possible for it to enter a capillary network of sorbents or specimens quickly. However, throughout the absorption process, the capillary system was considerably impacted by the exceptionally high viscosity of engine oil. Vegetable oil also has a greater density and surface tension than motor oil. Overall, 3D weft-knitted spacer textiles' hydrophobicity, as well as oleophilic qualities, have been greatly enhanced, making them suitable for usage in manufacturing uses such as space suits and protective clothes. Additionally, the modified textiles might be utilized in harsher conditions thanks to the silica aerogels as well as weft-knitted spacer fabrics' modifying properties [26].

3.3. Silica aerogel's superamphiphobic application on cotton fabrics

Several benefits of superamphiphobic materials are flexible nature, permeability, and low weight, alongside structure that contains a lot of pores. In addition to attempting to create such textiles, SiO2 aerogels were applied to them. This was done because of their re-entrant rough structures as well as the ability to store a great deal of air, which creates ideal circumstances enabling the creation of superamphiphobic surfaces. To create these textiles, a protective layer made mostly of silica aerogel particles, polydimethylsiloxane (PDMS), and 1H, 1H, 2H, 2H-perfluorooctyltriethoxysilane (PFTES), is capable of being used [7]

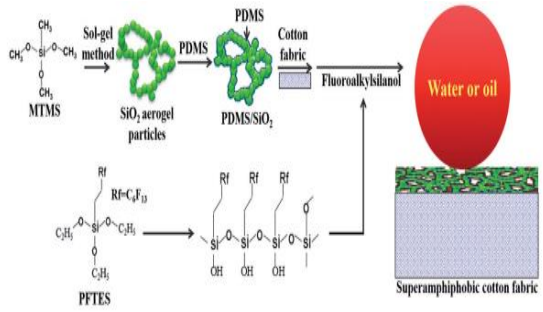
Through the use of a silica aerogel coating, L. Xu et al. were able to create superamphiphobic cotton textiles. They first created the SiO_2 aerogel particles using Methyl trimethoxy silane (MTMS) as a precursor and an acid-base sol-gel technique that dried at ambient pressure. They obtained the silica aerogel particles and used them for treating the cotton textiles. They whipped for 5 minutes while dispersing the silica aerogel particles (4%) in isopropyl alcohol. Then, for generating the PDMS/SiO_2 coating treatment, polydimethyl siloxane (PDMS) (4%) and the curing component (10:1) were combined and agitated using ultrasound for two hours. Furthermore, acetic acid was utilized to adjust the pH to 4 as well as 1H,1H,2H,2H-perfluoro-octyltriethoxysilane PFTES (5%) was included in the ethanol. The mixes were strongly agitated for 1 hour and then left alone for 1 hour. Fluoroalkylsilanol solution was created by the hydrolysis of PFTES [7].

The cotton-based materials were coated by the researchers using a dip-pad-cure method. The fabric made from cotton was initially submerged for 10 minutes in a solution of 3-aminopropyltriethoxysilane (APTES) mixed with ethanol (4:15:1) before being dried at 60°C in an oven. The cotton textiles that had been prepared were dipped in the PDMS/SiO_2 coating solution for 10 minutes, and pressed through an automated padder at 3 kg/cm^2, followed by being dried inside an oven. Furthermore, upon being coated with PDMS/SiO_2 as well as drying, the textiles were compressed after spending an hour in the fluoroalkylsilanol solution. The generated fabric was given the label PFTES/PDMS/SiO_2@Cotton following being dried at 80°C for 10 minutes as well as curing, respectively. And the whole process of producing superamphiphobic cotton fabric is illustrated in (**Scheme 6**) [7].

The high-magnification Scanning Electron Microscope (SEM) visuals of the generated cotton fabrics showed the presence of almost spherical SiO_2 aerogel particles that complied with one another and were encapsulated at the same time by silicone elastomer PDMS binding agent's layer as well as thick PFTES film, this was discovered whenever the produced coated cotton fabric had been inspected and analyzed. It was also determined that the cotton fabric had been

effectively treated with an outer coating of coarse permeable SiO_2 aerogel particles and PDMS and PFTES that had minimal surface energy which is the reason for the cotton's superamphiphobic characteristics. It appeared that a layer of air cushion was encased by coarse nanostructures created by SiO2 aerogel particles, generating a liquid-air-solid barrier and successfully shielding cotton fabric substances from water or oil absorption [7].

The amount of time required for curing additionally dictated if the superamphiphobic coating was enough or not, although prolonged curing did not improve the properties of the coated cotton cloth. Once the cure period exceeded 60 minutes, coated textiles' oleophobicity was somewhat altered. As a consequence, 60 minutes was chosen as the appropriate time for curing. The produced superamphiphobic cotton fabric additionally possessed outstanding resistance to 1500 rubbing cycles as well as prolonged UV light. In summary, these resistant superamphiphobic materials have a wide range of possible applications and therefore show bright futures [7].



Scheme 8: Superamphiphobic cotton fabric manufacture procedure [7]

4. Thermal insulation and/or heat comfort characteristics of silica aerogels

For the majority of polymeric substance uses, fire remains a significant problem. In actuality, these substances rapidly ignite whenever subjected to flames and can produce hazardous fumes [27]. Protective apparel is often designed to reduce the possibility of harm to the user while providing reliable shielding from the surroundings and other dangerous elements [28] such as the previously mentioned dangerous fumes. Particular compounds known as flame insulators or flame suppressants are substances that are created and added to a variety of polymeric materials, including textiles [29]. Due to its relatively low heat conductance, silicone-based aerogel is one of these substances that has been extensively utilized as a form of thermal insulation agent.[30, 31].

4.1. Silica aerogel's thermal insulation application on weft-knitted spacer fabrics

Among the several kinds of aerogels, silica aerogel possesses several intriguing qualities. Silica is non-combust and under the same conditions, its heat conductance is considerably less than that of air [32]. As a consequence, silica aerogel offers a promising future in the field of fabric protection from heat and flames. Weft knitted spacer fabric (92% polyester + 8% spandex) is a form of material that has multiple advantages, including outstanding parallel compressibility and high flexibility, making it a prime candidate to be modified using silica aerogels [19].

First, Tetraethyl Orthosilicate (TEOS) was employed as a precursor in a typical sol-gel process by Islam, S.R. et al. to create the silica aerogel. The synthesis of the sol-gel was performed within two steps: first, acid-catalyzed TEOS hydrolysis, then base-catalyzed gelation. The squares weft-knitted spacer textiles were then coated by the researchers by submerging them in a silica solution lasting 15 min. The specimens were cured and placed in a container that was completely closed off. The wet-gelled specimens were held at 25°C for an additional 24 hours following the creation of the gelled layer (20 minutes) on the fabric specimens to preserve the network of gel constructions. The wet-gelled specimens underwent an 8-hour ethanol rinse. Three times laundry was done while being exchanged into n-hexane. The ethanol-containing solution was removed from the wet-gelled films by washing them in n-hexane for eight hours. The material was subsequently repeatedly dried for 5 hours in an oven at 40°C as well as 60°C, and finally dried again for 5 hours at 100°C [19].

The researchers carried out a study of the finished coated cloth. It was discovered that the application of silica aerogel (SA), which produced a SiO_2 network on the specimens of weft-knit spacer material, proved its efficiency. Additionally, every specimen had both a high thermal resistance and a low conductivity to heat. According to the quantity of silica aerogel utilized, coated weft-knitted spacer textiles with silica aerogel likewise demonstrated significant porosity ratios with percentages ranging from 85.67% to 90.33%. The substantial porosity of the fabric allows for greater air trapping, which warms the body. Following receiving the silica aerogel treatment, the spacer textiles' ability to penetrate air was somewhat reduced, but their density grew. Upon being treated with silica aerogel, the spacer textiles likewise didn't alter in terms of thickness of fabric or yarn angle organization [19].

As silica aerogels were produced employing the sol-gel process and then added to the fabric specimens, the specimen that had a 62% addition of silica had the greatest heat resistance of all the weft-knitted spacer fabric specimens. This might be explained through the

thermodynamic interaction between the Si-OH in silica particles along with the fibers (through hydrogen as well as dipolar-dipolar interactions). The dipolar-dipolar association led to an increased additional percentage of silica on the specimens because of the polar chain arrangement of polyester (PET) fibers' primary difficulty with hydrogen. The creation of hydrogen bonds with spacer fabric specimens along with silica nanoporous was ascribed to the outermost hydroxyls by the strong bonding between SAs collections and fabric constructions. It was shown that specimens' heat resistance increased with silica addition percentage. This particular specimen furthermore possessed the lowest fabric weight, the largest number of pores (90.33%), and the greatest penetration of air. As a result, it works best in applications in industries that require strong insulation, such as space suits, down jackets, along with cold-weather protective clothing. Therefore, weft-knitted spacer textiles' characteristics may be improved or altered using SAs, and the materials or clothing might be utilized in tough situations [19].

4.2. Silica aerogel's thermal insulation application on polyester fabric

The most basic mechanisms by which heat is transferred are conduction and thermal radiation. Aerogels' poor thermal conductivity inhibits heat transmission by conduction, plus their very porous nature, offering few places for moving air atoms, reduces fanning thermal transfer. It is possible to coat fibers using such kind of porous material. However, the fiber-reinforced aerogel materials have to remain hydrophobic to provide outstanding thermal insulation, especially in a damp climate. Furthermore, a technique that involved electro-spraying silica aerogels with a fluorocarbon finishing agent had been utilized to create such thermally insulating fabric. In this procedure, the fabric used is polyester woven fabric [33].

To get rid of any conceivable contaminants, F. Shams-Ghahfarokhi et al. prepared the polyester textiles first by rinsing them using a non-ionic soap before letting them air dry. The scientists took advantage of a silica aerogel that dried at atmospheric pressure while being synthesized from a water glass, a readily accessible and safe precursor. The resulting water-glass-based silica aerogel powder had a packing density of 0.05–0.07 g/cm^3, an average particle diameter of 6.6 µm, as well as a degree of porosity of over 90%. The scoured polyester textiles were further processed by being electro-sprayed using a combination of 3% (w/v) silica aerogel in 20% (w/v) fluorocarbon material, RUCO-COAT FC 9000. After diluting the C6-based fluorocarbon compound in pure water, the aerogel powder was carefully included while being vigorously stirred. For improved dispersion, a small quantity of emulsifying substance was employed. The viscosity was gradually raised by adding aerogel powder to the fluorocarbon solution [33].

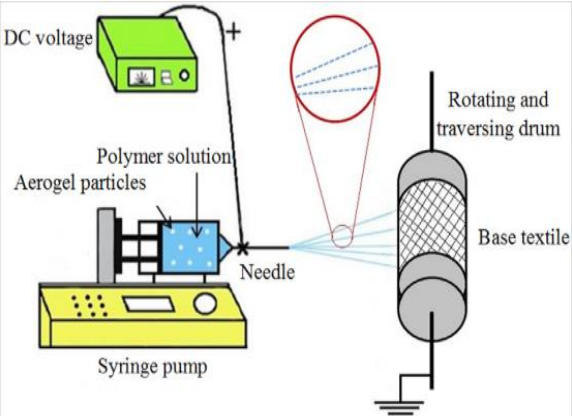
Using a stirrer with a magnet, the aerogel/fluorocarbon solutions were whisked around for 12 hours. The most important electro-spraying procedure variables included 0.85 mL/h flow rate, 17 kV voltage, and 5 cm between the tips of the needle to the collecting device, respectively. A pointed tip needle that had a 0.6 mm inside diameter was employed to electrospray the specimens. The treated textiles were followed by curing in a lab dryer for 2.5 min at 170 °C after getting dried for 5 min at 100 °C. And (**Scheme 6**) illustrates the fundamental configuration of the electro-spraying apparatus employed. The features of the coated polyester samples' thermal insulation were afterward examined [33].

The electro-sprayed samples of aerogel/ fluorocarbon demonstrated strong insulating qualities, high water resistance, and minimal dust-releasing activity. The specimen that was electro-sprayed for 24 hours displayed the lowest heat transfer amount, with the thermal transmission % trending downward concerning the aerogel concentration of the coated surface. Aerogel electro-sprayed textiles' structure may have reduced permeation of air due to the aerogel particles' existence upon the top layer of the textile materials, which results in fewer inner-fiber gaps. Thus, the major causes of the decreased airflow and subsequently poorer thermal conductivity of the aerogel-fluorocarbon electro-sprayed specimens are both aerogel particles as well as their impact upon the structural features of textiles. Additionally, this innovative spraying technique overcomes the primary flaw of aerogel-textile composites—dust release—with a reduction in weight value of below 5 %. This is a result of the aerogel particles being successfully trapped within the fluorocarbon film layer. Therefore, thinly sprayed advanced substances with insulating and water-resistant qualities have the potential to be applied in the field of protective clothes [33].

4.3. Silica aerogel's thermal insulation application on the commercial fabric nomex and flame-retardant cotton

Being involved in an overheated workplace is frequently accompanied by excessive heat brought on by both the extreme temperatures as well as the worker's heightened activity level. Employees are subjected to hot variables while at work in the manner of direct heat, thermal radiation, and flame. Due to the heated environment, protective apparel, and expended physical activity, there is a detrimental thermal state beneath the garment, leading to distress. The aerogel layer, which may be applied as an additional coating to already thermally protective clothing to improve its effectiveness, is a potential alternative for heat insulation as well as protection to lessen this sensation. The second aim of this treatment is to improve the

thermal insulation property while also reducing the thickness of the multilayers used in these protective clothes. Before the use of aerogel as a coating, thick layers were required to improve the thermal insulation characteristic of these protective garments [34].



Scheme 9: The diagram shows the essential layout of the electro-spraying apparatus [33]

Mikiewicz, P. et al. used cotton fabric coated with a flame-retardant finishing chemical in addition to the commercial fabric Nomex® (93% m-aramid, 5% p-aramid, 2% antistatic fibers). They additionally employed the commercially available aerogel Enova®. The specimens of each kind of material were initially prepared by the researchers, who warmed them to a temp of 20±2°C plus partial dampness of 65% 5%. Following that, utilizing two distinct proportions of silica aerogels—45 weight percent and 60 weight percent—and a particle density of 120 kg/m^3, researchers developed the coating combination, that was composed of silica-based aerogel, adhesive material, as well as flame suppressant. Furthermore, the proportion of the flame retardant to adhesive material was 75:25. The coating solution's three components were incorporated into the container till a homogenous mixture had been created. A wooden spatula was employed to spread the solution across the samples' surfaces. The drying procedure took place for 20 minutes at a temperature of 40°C [34].

According to the examination performed by the researchers, all of the altered specimens had better heat resistance. The flame-retardant cotton fabric (CA), whose durability against thermal radiation (relative heat transfer index, or RHTI), was 19.93 s whereas that of the modified Nomex® fabric was 18.13 s, represented the best specimen in terms of shielding from both contact as well as thermal radiation. This cotton fabric had been treated with the combination that beheld silica aerogels at a weight percentage of 45 wt%. This prescribed amount of aerogel proved to be adequate for the specimen to attain the highest level of efficacy of protection from contact along with thermal radiation. Furthermore, the coating combination stuck to the cotton fabric more effectively than Nomex fabric since Nomex® fabric absorbed more of the coating solution than cotton fabric, whose coating layer remained thick and wasn't even entirely absorbed. Because of this, silica aerogels have demonstrated their effectiveness in improving the thermal insulation qualities of protective textiles [34].

Conclusion

In conclusion, it was found that the use of silica aerogel coating successfully improved the performance of the three types of fabrics: 3D weft-knitted spacer fabrics, polyester, and cotton fabrics, as well as gave them additional features like superamphiphilia, chemical resistance, thermal insulation, and self-cleaning properties. It was discovered that because of their porous nature, they may trap liquids and air inside their mesoporous structure. Through the use of a sol-gel technique and a precursor of one of the three types—water glass, alkoxysilanes, or orthosilicate—silica aerogel particles were effectively created. The textiles were submerged in solutions containing silica aerogel particles, electro-sprayed, or coated with a silica aerogel film using an adhesive such as polyurethane. Fabrics now have a lot of promise in the field of protective textiles because of all these successful attempts to cover them with silica aerogels.

Funds

There is no avelable fund

Acknowledgments

The authors are gratefully-grateful to acknowledge the Faculty of Applied Arts, Benha University. Furthermore, the authors are gratefully grateful to acknowledge the Central Labs Services (CLS) and Centre of Excellence for Innovative Textiles Technology (CEITT) in Textile Research and Technology Institute (TRTI), National Research Centre (NRC) for the facilities provided.

Author Declarations

The authors declare that the data supporting the findings of this study are available in the article

The authors declare that there is no conflict of interest.

Reference

1. Mazrouei-Sebdani, Z., et al., A review on silica aerogel-based materials for acoustic applications. Journal of Non-Crystalline Solids, 2021. **562**: p. 120770.
2. McNeil, S.J. and H. Gupta, Emerging applications of aerogels in textiles. Polymer Testing, 2022. **106**: p. 107426.
3. Akhter, F., S.A. Soomro, and V.J. Inglezakis, Silica aerogels; a review of synthesis, applications and fabrication of hybrid

composites. Journal of Porous Materials, 2021. **28**(5): p. 1387-1400.
4. Li, C., et al., Silica aerogels: from materials research to industrial applications. International Materials Reviews, 2023: p. 1-39.
5. Awgichew, D., et al., Experimental Study and Effect on Recycled Fibers Blended with Rotor/OE Yarns for the Production of Handloom Fabrics and Their Properties. Advances in Materials Science and Engineering, 2021. **2021**: p. 4334632.
6. Rahman Bhuiyan, M.A., et al., Polyurethane-aerogel incorporated coating on cotton fabric for chemical protection. Progress in Organic Coatings, 2019. **131**: p. 100-110.
7. Xu, L., et al., Preparation of durable superamphiphobic cotton fabrics with self-cleaning and liquid repellency. Journal of Adhesion Science and Technology, 2022. **36**(1): p. 1-20.
8. Yu, A., S. Sukigara, and K.-L. Yick, Curvature control of weft-knitted spacer fabric through elastic inlay. Textile Research Journal, 2022. **92**(19-20): p. 3826-3837.
9. Alam SMM¹, I.S.a.A.S., Reviewing the Production Process, Physical and Chemical Properties of Spandex Fibers. advance research in textile engineering 2020.
10. N, N., et al., Polyesters - A Review. 2017.
11. Kumar, P., et al., Synthesis of Cotton Fiber and Its Structure. 2022. p. 17.
12. Periyasamy, A.P., et al., Progress in Sol-Gel Technology for the Coatings of Fabrics. Materials, 2020. **13**(8): p. 1838.
13. Iswar, S., et al., Dense and strong, but superinsulating silica aerogel. Acta Materialia, 2021. **213**: p. 116959.
14. Smirnova, I. and P. Gurikov, Aerogel production: Current status, research directions, and future opportunities. The Journal of Supercritical Fluids, 2018. **134**: p. 228-233.
15. Bhuiyan, M.R., et al., Polyurethane-aerogel incorporated coating on cotton fabric for chemical protection. Progress in Organic Coatings, 2019. **131**: p. 100-110.
16. Li, H., et al., Durable superhydrophobic and oleophobic cotton fabric based on the grafting of fluorinated POSS through silane coupling and thiol-ene click reaction. Colloids and Surfaces A: Physicochemical and Engineering Aspects, 2021. **630**: p. 127566.
17. Islam, S.R., et al., The influence of silica aerogels on wettability, wicking, spreading, and self-cleaning ability of 3D weft-knitted spacer fabrics.
18. Islam, S.R., et al., Oil Swelling and Self-cleaning Ability of 3D Weft-Knitted Spacer Fabrics Integrated with Silica Aerogels by Sol-Gel Method. 2023: p. 62-71.
19. Islam, S.R., W. Yu, and T. Naveed, Influence of silica aerogels on fabric structural feature for thermal isolation properties of weft-knitted spacer fabrics. Journal of Engineered Fibers and Fabrics, 2019. **14**: p. 1558925019866446.
20. Xing, L., et al., Recent developments in preparation, properties, and applications of superhydrophobic textiles. Textile Research Journal, 2022. **92**(19-20): p. 3857-3874.
21. Zhu, J., et al., Preparation of superhydrophobic, antibacterial and photocatalytic cotton by the synergistic effect of dual nanoparticles of rGO-TiO2/QAS-SiO2. Industrial Crops and Products, 2022. **189**: p. 115801.
22. Chen, J., et al., Two-Step Approach for Fabrication of Durable Superamphiphobic Fabrics for Self-Cleaning, Antifouling, and On-Demand Oil/Water Separation. Industrial & Engineering Chemistry Research, 2019. **58**(14): p. 5490-5500.
23. Mazrouei-Sebdani, Z., et al., Sodium silicate based aerogel for absorbing oil from water: the impact of surface energy on the oil/water separation. Materials Research Express, 2019. **6**(8): p. 085059.
24. Altay, P., R. Atakan, and G. Özcan, Silica aerogel application to polyester fabric for outdoor clothing. Fibers and Polymers, 2021. **22**(4): p. 1025-1032.
25. Alassod, A., M.A. Abedalwafa, and G. Xu, Evaluation of polypropylene melt blown nonwoven as the interceptor for oil. Environmental Technology, 2021. **42**(18): p. 2784-2796.
26. Islam, S.R., et al., The study of hydrophobicity and oleophilicity of 3D weft-knitted spacer fabrics integrated with silica aerogels. Journal of Industrial Textiles, 2022. **51**(5_suppl): p. 8804S-8825S.
27. Vahabi, H., M.R. Saeb, and G. Malucelli, Analysis of Flame Retardancy in Polymer Science. 2022: Elsevier.
28. Bhuiyan, M.R., et al., Advances and applications of chemical protective clothing system. Journal of Industrial Textiles, 2019. **49**(1): p. 97-138.
29. Bifulco, A., et al., Flame retarded polymer systems based on the sol-gel approach: recent advances and future perspectives. Journal of Sol-Gel Science and Technology, 2022.
30. He, F., et al., Thermal Conductivity of Silica Aerogel Thermal Insulation Coatings. International Journal of Thermophysics, 2019. **40**(10): p. 92.
31. Shafi, S., et al., Improved heat insulation and mechanical properties of silica aerogel/glass fiber composite by impregnating silica gel. Journal of Non-Crystalline Solids, 2019. **503-504**: p. 78-83.

32. Shaid, A., L. Wang, and R. Padhye, The thermal protection and comfort properties of aerogel and PCM-coated fabric for firefighter garment. Journal of Industrial Textiles, 2016. **45**(4): p. 611-625.
33. Shams-Ghahfarokhi, F., et al., A new technique to prepare a hydrophobic and thermal insulating polyester woven fabric using electro-spraying of nano-porous silica powder. Surface and Coatings Technology, 2019. **366**: p. 97-105.
34. Miśkiewicz, P., M. Tokarska, and I. Frydrych, Application of coating mixture based on silica aerogel to improve thermal protective performance of fabrics. Autex Research Journal, 2022.