

Aerogel: Synthesis and applications in engineering

Aerogel: síntesis y aplicaciones en ingeniería

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ABSTRACT

Keywords:

Aerogel, Nanomaterials,
Silica, Sol-Gel Synthesis.

Aerogels are ultralight and highly porous nanomaterials developed since the 1930s, which have evolved into key materials for science and industry. Their nanoporous structure and very low density provide exceptional properties, including low thermal conductivity, making them useful in sectors such as aerospace, construction, electronics, and energy. This article presents a comprehensive overview of aerogels, describing their synthesis and industrial applications. The synthesis is mainly carried out using the sol-gel technique, with precursors such as silica, and sodium silicate, catalysts, and various drying methods, with supercritical drying being the preferred method to preserve the nanoporous structure. Despite their advantages, aerogels face challenges such as fragility and high production costs. However, advances in more sustainable methods and the use of recycled materials aim to overcome these limitations. It is concluded that aerogels are modern and promising materials with high potential to revolutionize multiple industries through innovations in synthesis and processing.

RESUMEN

Palabras clave:

Aerogel, Nanomateriales,
Sílice, Síntesis Sol-Gel.

Los aerogeles son nanomateriales ultraligeros y altamente porosos desarrollados desde la década de los 30, que han evolucionado hasta convertirse en materiales clave para la ciencia y la industria. Su estructura nanoporosa y su muy baja densidad otorgan propiedades excepcionales, entre ellas una baja conductividad térmica, que los hacen útiles en sectores como la aeroespacial, construcción, electrónica y energía. Este artículo presenta una visión integral sobre los aerogeles, describiendo su síntesis y aplicaciones industriales. La síntesis se realiza principalmente mediante la técnica sol-gel, con precursores como sílice y silicato de sodio, catalizadores y diferentes métodos de secado, siendo el secado supercrítico como método preferido para conservar la estructura nanoporosa. A pesar de sus ventajas, los aerogeles enfrentan desafíos como la fragilidad y el alto costo de producción. Sin embargo, los avances en métodos más sostenibles y el uso de materiales reciclados buscan superar estas limitaciones. Se concluye que los aerogeles son materiales modernos y prometedores con alto potencial para revolucionar múltiples industrias gracias a innovaciones en síntesis y procesamiento.

1. Introduction

In recent decades, aerogels have attracted considerable attention due to their unique properties and potential for application in advanced technologies that seek energy efficiency and sustainability. Their ultralight nanoporous structure not only offers excellent thermal and acoustic insulation capabilities, but also opens up new possibilities in fields such as electronics, environmental protection, and medical engineering. Constant innovation in synthesis methods and the development of

hybrid aerogels with controlled properties position these materials as key to the transition toward more sustainable, multifunctional materials in modern industry.

1.1. Background

Aerogels were developed in the 1930s by Samuel Kistler by replacing the liquid in a gel with gas without collapsing its structure [1]. Since then, research has advanced to improve their thermal and mechanical properties, expanding their applications in the aerospace, construction, and energy

industries. Currently, there are inorganic, organic, and hybrid aerogels, which increases their versatility and industrial relevance [2].

These nanomaterials have exceptional properties. In the 1990s, NASA used aerogels as thermal insulators and to collect cosmic dust particles during space missions [3]. For example, on the Pathfinder Mars mission, aerogels protected the Sojourner rover, maintaining an interior temperature of 21°C despite nighttime temperatures on Mars reaching as low as -67°C [3].

Silica aerogels stand out for their very low thermal conductivity, which varies between 0.015 and 0.02 W/m K, and very low densities, ranging from 0.003 to 0.5 g/cm³ [4] [5], making them ideal for applications that require lightweight materials and high thermal insulation properties.

The aerogel family expanded with the addition of chalcogels made from sulfur, selenium, and cadmium, capable of absorbing heavy metals and water pollutants such as mercury and lead [6]. Techniques have been developed to encapsulate aerogel particles in epoxy resins in composite materials without infiltrating them. This process strengthens the particles and reduces their weight without compromising the structure [7].

The global aerogel market is growing at a compound annual rate of 10-12% for the next decade, driven by sectors such as automotive, aerospace, construction, and energy. Emerging applications in electric vehicle batteries for thermal management and fire prevention are noteworthy [8]. In addition, innovations in manufacturing methods seek to reduce costs and improve scalability, facilitating industrial adoption [9].

1.2. Limitations

Despite their advantages, the industrial use of aerogels faces challenges such as their fragility, high production cost, difficulty in processing, and scaling up for commercial applications. These limitations have restricted their widespread adoption, although recent advances in synthesis and the use of recycled materials seek to overcome these obstacles.

1.3 Scope

This article aims to provide a clear and concise description of aerogels, including their main properties, synthesis process, and applications in current engineering. The article discusses research and development achievements, as well as trends that will influence the future of the industry.

1.4 Problem Relevance

The growing demand for efficient, lightweight, and sustainable materials in modern industry makes aerogels a strategic alternative for improving energy efficiency, reducing environmental impact, and enabling new technologies. Their potential to revolutionize sectors such as construction, electronics, and energy highlights the importance of understanding and disseminating their functioning and applications.

1.5. Premise

Thanks to their unique structure and properties, it is assumed that aerogels can be adapted and optimized to solve current technological challenges, if their technical and economic limitations can be overcome.

1.6. Objective

The objective of this article is to present a comprehensive overview of aerogels by defining them, explaining their synthesis, detailing their properties, and analyzing their main industrial applications, in order to highlight their relevance and potential as modern materials.

2. Development

2.1. Aerogel

Aerogel is an extremely light and nanoporous nanomaterial, formed by a three-dimensional structure of solid particles connected by fine strands measuring just a few nanometers.

Its composition can contain up to 99.98% air, giving it an extremely low density of 0.003 g/cm³ and an ethereal appearance [2] [4]. It is also known as "blue smoke" or "transparent foam" [10].

Aerogels are generally manufactured from silica, and their properties can be customized for specific applications [11]. Because there is no single type of aerogel or formula, aerogels encompass a wide variety of compounds with different structures and geometries.

It is notable for its variety of properties, such as its very low thermal conductivity. Aerogels are

produced using the sol-gel technique, which involves replacing the liquid in the gel with air under controlled conditions to prevent the structure from collapsing [12].

Despite their advantages, silica aerogels present several challenges, including fragility, volumetric shrinkage during production, processing difficulties when combined with other materials, and, most importantly, high production costs [12, 11]. However, they are useful in specialized applications, such as catalytic supports, supercapacitors, acoustic barriers, and thermal insulators [4].

2.2. History and evolution

The term “aerogel” was coined by Samuel Kistler in 1931, who developed the supercritical drying process to replace the liquid in a wet gel with air without collapsing its porous structure [1]. Kistler also synthesized aerogels of alumina, tungsten oxide, and ferric oxide, laying the foundation for large-scale production [10].

In the 1990s, NASA used aerogels to capture cosmic dust and for thermal insulation in space missions, highlighting their technological importance [3]. Since 2000, polymer-based aerogels and hybrid composites have been developed [13]. In 2013, aerogel was recognized as the world's lightest solid [14].

Recently, research has focused on making aerogels more cost-effective and sustainable by improving their flexibility and mechanical properties [15], which has expanded their applications in aerospace engineering, construction, and environmental protection.

2.3. Classification

Aerogels can be classified according to their form (monoliths, powders, panels or blankets), their production method (aerogel, xerogel or cryogel), their microstructure (micropore, mesopore or mixed) or their chemical composition. The latter is the most useful for analysing and understanding their properties [10]. Although they are traditionally made from silica, advances in synthesis have made it possible to develop aerogels with a wide variety of chemical structures (see Figure 1), including:

2.3.1. Inorganic. These include metal aerogels (silver, gold, platinum, aluminum) and metal oxide aerogels (alumina, titanium dioxide, zinc oxide, zirconium oxide), which are useful in high-temperature storage, catalysis, and insulation [10].

2.3.2. Organic. It is based on polymers, such as polyimides and resorcinol-formaldehyde, which are used in industrial applications as binders and insulators [10] [5].

2.3.3. Hybrids. These combine organic and inorganic materials, integrating polymers, metals, and additives to improve physical and mechanical properties. Notable examples include aerogel composites with carbon nanotubes, graphene, or gelatin, which expand their range of applications and overcome traditional limitations [10] [11].

2.3.4. Chalcogels. Made from sulfur, selenium, and cadmium, they stand out for their ability to absorb contaminants from water [10] [6].

2.3.5 Bio-based. They are derived from cellulose and proteins, making them sustainable and useful for clean technologies and capturing pollutant gases. [10].

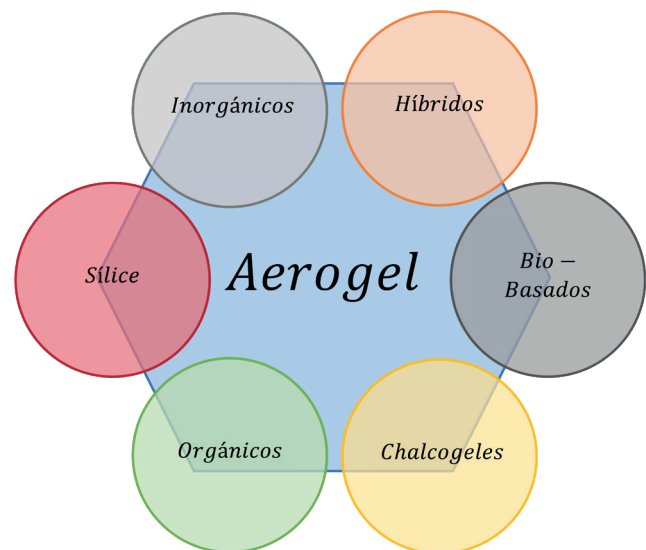


Figure 1. Chemical composition of aerogel

The development of new formulations and compounds, such as silica gelatin aerogels (GSA), has made it possible to overcome technical challenges and expand the applications of aerogels in various technological fields [11].

2.4. Properties

Silica aerogels are amorphous, ultralight materials formed by a three-dimensional network of interconnected solid particles containing up to 99.98% air inside. This structure gives them an extremely low density of up to 0.003 g/cm^3 [2] [4], and a texture similar to polystyrene foam, although much more fragile. With a pore volume of 90%, this property makes them ideal for applications that require lightness and high porosity [5]. Therefore, silica aerogels have exceptional properties such as (Table 1):

Table 2. Typical properties of silica aerogels

Propiedades	Valor
Densidad bruta (g/cm^3)	0.003-0.5
Conductividad Térmica (W/mK)	0.015-0.021
Densidad de la red (g/cm^3)	1.7-2.1
Área superficial (m^2/g)	100-1,600
Porosidad (%)	80-99.8
Diámetro medio de poro (nm)	20-150
Diámetro de partícula primaria (nm)	2-10
Índice refractivo	1.007-1.24
Módulo de elasticidad (MPa)	0.002-100
Impedancia acústica ($\text{kg/m}^2\text{s}$)	$\times 10^4$
Coefficiente de expansión térmica	$2.0\text{-}4.0 \times 10^{-6}$
Constante dieléctrica	1-2
Velocidad del sonido (m/s)	100

Fuente: [2] [4] [5]

2.4.1. Structure and porosity. Aerogels are typically mesoporous with interconnected pores ranging from 5 to 100 nm in size. Their average pore diameter is between 20 and 40 nm, giving them a high specific surface area of 250 to $800 \text{ m}^2/\text{g}$ or more [5]. This structure can be adjusted during the sol-gel process to adapt the final properties of the aerogel to the application.

2.4.2. Chemical properties. After synthesis, aerogels have functional groups such as silanol (Si-OH) on their surface, which determine their “hydrophilic” or “hydrophobic” behavior [12]. Through chemical treatments, it is possible to modify their surface to make them water-repellent, ideal in applications where moisture absorption is to be avoided [5] [12].

2.4.3. Thermal conductivity. One of the most notable properties of silica aerogels is their very low thermal conductivity, which varies between 0.015 W/m K and 0.02 W/m K , comparable to or lower than that of air, which is approximately 0.025 W/m K [4] [5]. This characteristic makes them the best known solid thermal insulators. As they are non-flammable,

they offer greater safety. Heat transfer in aerogels occurs mainly by conduction and radiation, since convection is practically non-existent due to the nanometric size of their pores [16]. Thermal conduction is divided into two phases: “gas thermal conduction,” which refers to heat transfer through gas trapped in pores, and “solid thermal conduction,” which refers to heat transfer through the solid structure. As for thermal radiation, it is affected by absorption and scattering as it passes through the porous structure [17] (Figure 2). According to the theory of heat transfer at the nanoscale, pore size and the rarefied gas effect limit the thermal conduction of the gas, while photon scattering affects thermal radiation [18]. In addition, aerogels are highly permeable to near-infrared radiation, especially in the wavelength range of $3\text{-}8 \mu\text{m}$, which at high temperatures increases their thermal conductivity and reduces their effectiveness as insulators [17].

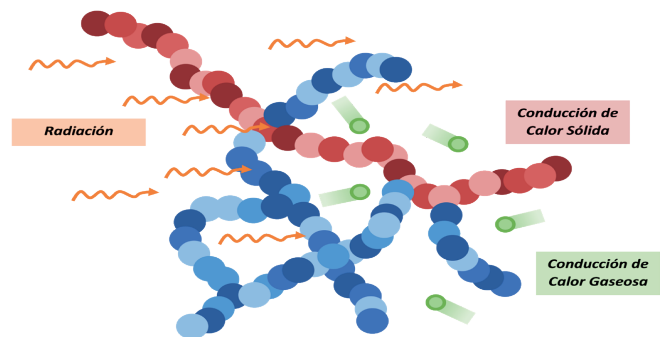


Figure 2. Heat transfer in aerogel

2.4.4. Optical properties. Aerogels can be transparent or opaque and have high visible light transmittance, allowing them to be used in insulating windows and optical devices [19]. However, they tend to scatter light, generating a yellowish coloration and a bluish tint when viewed against a dark background, which affects optical quality in certain applications [4].

2.4.5. Acoustic properties. Their properties are related to the thermal insulation of aerogel and depend on the nature and pressure of the gas in its pores, its density, and mainly its texture. Acoustic waves passing through aerogel decrease in amplitude and speed as energy is gradually transferred from the gas to the solid network [4]. With a sound velocity of around 100 m/s and a porosity of 90%, aerogels are effective acoustic insulators [5].

2.4.6. Mechanical properties. Although very light, silica aerogels are fragile and have low mechanical strength [5]. However, their compressibility and energy absorption capacity make them useful in applications requiring shock absorption or low shock impedance [20]. Hybrid and reinforced versions have significantly improved these properties [4].

2.4.7. Dielectric properties. Silica aerogels have a very low dielectric constant, around 1.1 [2] [12], making them ideal as insulating materials in advanced electronics, integrated circuits, and other high-tech devices [4]. Their dielectric strength, which indicates the maximum electric field they can withstand without becoming conductive, is approximately 128 kV/cm [21]. Additionally, there is a significant correlation between the dielectric constant and thermal conductivity of aerogels, both of which are impacted by their porous structure. High porosity implies low thermal conductivity, which affects the dielectric properties since the dielectric constant varies with the density of the aerogel [21].

2.5 Precursors, Solvents, and Catalysts Silica aerogels are mainly synthesized using the sol-gel technique, employing silicon alkoxides as precursors, such as tetramethoxysilane (TMOS) and tetraethoxysilane (TEOS).

Derivatives such as polyethoxydisilane (PEDS) and methyltriethoxysilane (MTES) are also used [11] [22]. The purity of these compounds is essential as it affects the final properties of the aerogel [5]. However, their high cost and handling risks (they have the potential to cause blindness) limit their commercial application [11].

In addition, solvents such as ethanol, methanol, and acetone are used to facilitate gel formation and stabilization. The process also requires the addition of acid or base catalysts to control the gelation rate and final structure of the aerogel [11].

The combined use of acid-base catalysts (two stages) allows materials with greater porosity and better pore distribution to be obtained [5]. Alternatively, sodium silicate (Na_2SiO_3 —soluble glass) is used as a precursor in commercial methods to reduce costs and facilitate large-scale production [5] [11].

3. Synthesis

Silica aerogels are synthesized using the sol-gel process, which is valued for its simplicity, low cost, and effectiveness in producing high-quality aerogels. This process consists of three main stages: (1) wet gel formation, (2) gel aging, and (3) gel drying [11] (Figure 3).

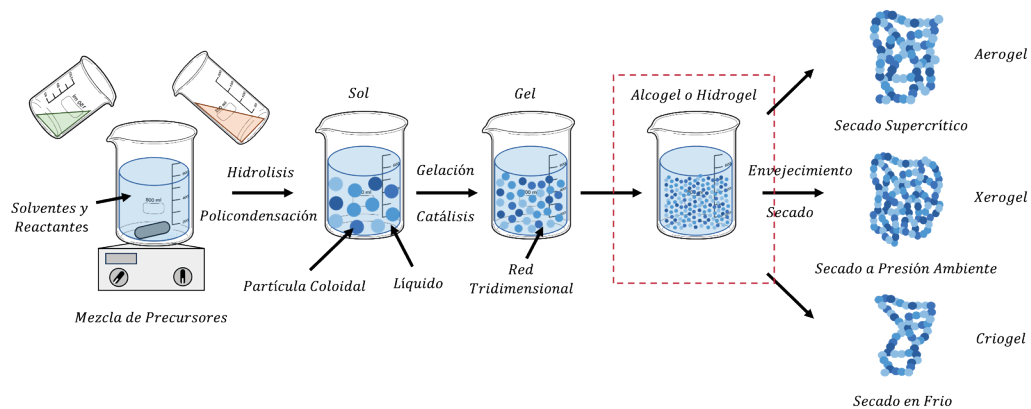


Figure 3. Sol-gel process

3.1. Wet Gel Formation (Sol-Gel).

This process involves several stages: mixing precursors, hydrolysis, polycondensation, gelation, and other steps as appropriate. It begins by mixing the precursors (TMOS, TEOS, Na_2SiO_3) with solvents, catalysts, and water, which initiates hydrolysis and polycondensation to form colloidal

nanoparticles (sol) smaller than 1 μm .

These particles bind together to form an open three-dimensional network (gel) [7]. When the gel contains a lot of liquid, it is called an alcogel. If natural precursors are used, it is called a hydrogel, which contains much more liquid [12]. Both are considered intermediate stages before the final dry

material.

Subsequently, gelation continues, involving the continuous transition of the sol through the formation of siloxane bonds (Si-O-Si). If this transition is abrupt, it is known as a "sol-gel transition." The type of catalyst (acids or bases) affects the texture and density of the gel: acid catalysis produces less dense and more porous gels, while base catalysis produces less porous and denser gels [7].

Factors such as solvent type, catalyst concentration, pH, and water-precursor ratio affect the final nanostructure, including size, pore distribution, and texture [7].

3.2. Gel Curing

The wet gel matures through the Ostwald mechanism, which reinforces the fragile solid network through particle bonding and growth, improving mechanical stability and porosity [22]. Proper control during this stage can improve properties such as elastic modulus, thermal conductivity, flexural strength, optical transmittance, density, strength, and stiffness [12].

3.3. Gel Firing

This final stage is critical, as it determines the finished properties of the aerogel. Firing drying, capillary forces can cause cracking and shrinkage, although silica gels are more resistant to these effects due to their siloxane bonds [12]. There are three main drying methods (see Figure 3).

3.3.1. Supercritical drying (SEF). This is the most effective method of preserving the porous structure because it removes the solvent at high temperatures and pressures (see Figure 6). This prevents the collapse of the porous structure by eliminating capillary forces [12], generating monolithic "aerogels" with low density and high surface area, ideal for thermal and acoustic insulation [11]. This method can be used with different solvents, although CO₂ is the most commonly used because it is the safest and most efficient option. Despite its effectiveness, the process can be costly and complex, and surface modifications are required to improve chemical durability [11].

3.3.2. Ambient pressure drying (CRF). This method is simple and low-cost, evaporating the solvent at normal temperature and pressure (Figure 6), making it suitable for industrial production [12]. However, it tends to produce aerogels with higher density and a risk of cracking [7]. Firing drying, a phenomenon known as spring back occurs, which recovers part of the gel's original volume after contraction caused by capillary forces during solvent evaporation, helping to preserve the porous structure [11]. Surface modification with silylating agents can reduce volumetric shrinkage and produce hydrophobic aerogels. However, there is still a risk of collapse due to internal stresses, which makes controlling the final dimensions of the aerogel difficult [11]. Although this process can be lengthy and consume large amounts of solvents, the use of co-precursors and optimization of the method have made large-scale production feasible [26].

3.3.3. Freezing drying (FF). This method involves freezing the gel and sublimating the solvent under vacuum (Figure 6), obtaining highly porous cryogels, which are useful for heat-sensitive materials and medical applications that require maintaining structural integrity. While safer and more environmentally friendly, this process is slow and costly, and solvent crystallization can damage the structure [12]. To minimize these problems, rapid freezing and the use of suitable solvents are recommended [7].

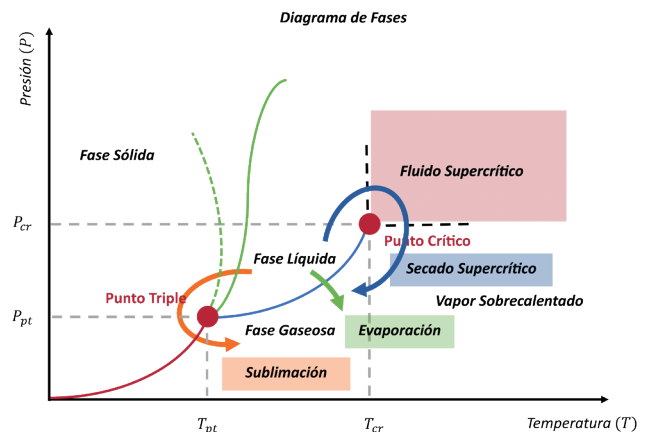


Figure 4. Phase diagram of the drying stages

4. Industrial applications

Aerogels, thanks to their low density, high porosity, and excellent thermal, acoustic, and chemical properties, have applications in various industries. They are particularly noteworthy in the following and other possible fields (Figure 5):

4.1. Thermal and acoustic insulation

4.1.1. Construction. They are used in windows, walls, and ceilings to improve the thermal and acoustic insulation of buildings, reduce energy consumption, and improve comfort [12] [25].

4.1.2. Transportation. Used in cars, trains, and planes to reduce weight, improve energy efficiency, and protect batteries from fire and heat [26] [27].

4.1.3. Petrochemical and Energy Industry. Used for insulation in pipes, tanks, and equipment at high temperatures, benefiting from its lightness and corrosion resistance [5].

4.2. Absorption and filtration

4.2.1. Environmental protection. Cellulose and carbon aerogels adsorb oils, organic pollutants, and heavy metals, making them useful in spill cleanup and wastewater treatment [6].

4.2.2. Particle capture. Used by NASA to capture cosmic dust and preserve samples on space missions [3].

4.3.1. Catalysts. Their large surface area and chemical stability make them excellent for use as catalysts in industrial processes and chemical synthesis [12].

4.3.2. Adsorbents and Extractants. Used for selective adsorption of gases, vapors, and toxic compounds in industrial and environmental processes [12] [10].

4.3.3. Luminescence. The combination with the optical and electronic properties of fullerenes enables multifunctional materials with visible light emission for optoelectronics and sensors [28].

4.4. Electronics and energy

4.4.1. Electrical insulators. Their low dielectric constant makes them ideal for integrated circuits and advanced electronic components [4] [12].

4.4.2. Batteries and energy storage. They improve safety and thermal management in electric vehicle batteries [27].

4.4.3. Solar Cells. They serve as a porous, lightweight template that allows the manufacture of TiO₂ photoanodes to improve the performance of solar cells [12] [29] [30] [31].

4.4.4. Sensors and Detectors. Used in optical devices and sensors, such as Cherenkov detectors for particle physics [4].

4.5. Kinetic energy absorption

4.5.1. Damping. It is used as a material to lighten and dissipate energy. [32].

4.5.2. Ballistic and Impact Protection. Used in ballistic coatings to absorb impacts and vibrations [20].

4.6. Other applications

4.6.1. Textiles. Incorporated into extreme sports and protective clothing, providing thermal insulation with minimal weight [12] [26].

4.6.2. Agriculture and Pharmaceuticals. Used to improve food preservation, organic tissue growth, and controlled drug release [33].

4.6.3. Coatings. Added to paints and varnishes to improve insulation and surface protection [12] [34].

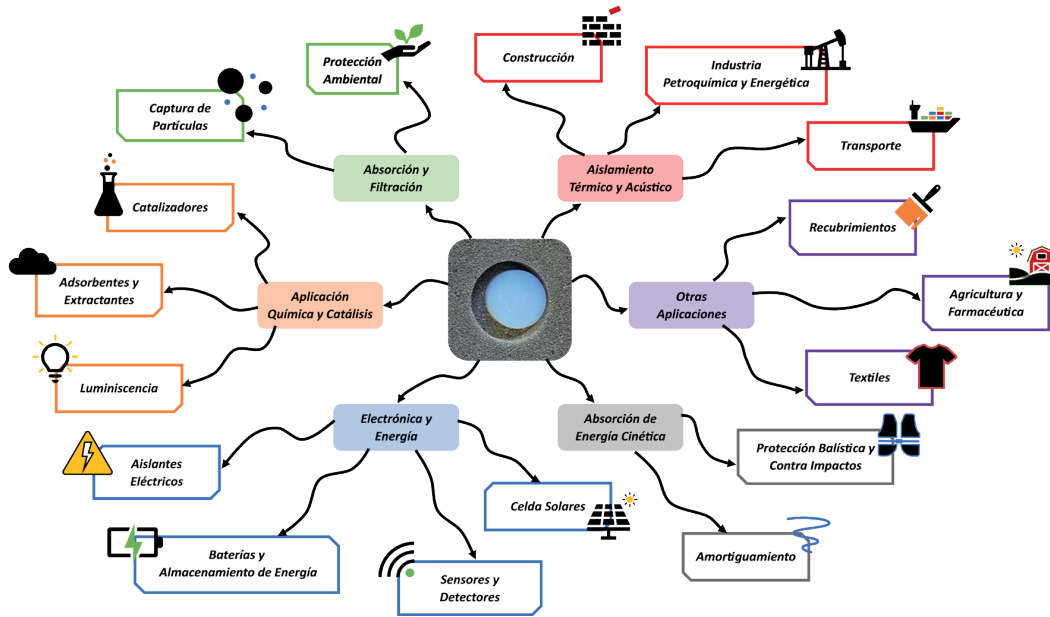


Figure 5. Fields of Application

5. Conclusions

Thanks to their nanoporous structure and low density, aerogels are unique materials with exceptional properties, especially as thermal insulators. This article provides information on what aerogels are, how they are synthesized, and the industries in which they are used, such as aerospace, construction, electronics, and environmental protection. It also highlights the increasing relevance of aerogels in industry and science.

Above all, the choice of drying method and synthesis conditions determines key properties such as density, porosity, thermal conductivity, and mechanical strength. Despite persistent challenges such as fragility and production costs, research is progressing toward more sustainable solutions through new synthesis routes and the use of recycled materials.

Finally, aerogels would position themselves as an innovative and promising alternative for the development of more efficient and sustainable technologies in the future.

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