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# OVERVIEW OF MULTIFUNCTIONAL (ULTRA-)LIGHTWEIGHT MATERIALS FOR A SUSTAINABLE FUTURE

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***Abstract:*** *In line with the ongoing advancement of high-performance materials that are multifunctional and environmentally friendly, this paper provides an overview of recent developments in lightweight and ultra-lightweight multifunctional materials. We primarily examine the various types of low-density multifunctional materials, their production techniques, and their applications within the context of a sustainable future. From a structural point of view, ultra-light materials are classified into three main groups: aerogels, foam, and micro/ nanolattice. In terms of composition, they can be derived from ceramic, metallic, or polymeric materials. This overview pays particular attention to silica, carbon and composite aerogels, as well as metal, ceramic (carbon), and polymer foams.*

***Keywords:*** *Multifunctional materials, Aerogels, Foams, Ultralight materials, Micro/Nanolattices*

## 1. INTRODUCTION

Due to the alarming increase in waste resulting from energy-intensive technologies and fossil fuels, coupled with poor management of household and industrial waste, there is an urgent need to unite the efforts of people, especially scientists, to find solutions for pollution reduction or elimination.

One promising approach involves rethinking the product and its functions, using "eco" technologies, or developing a variety of new advanced materials, such as multifunctional (ultra-)lightweight materials [1-8].

In the last decades, lightweight and ultralight multifunctional materials have been a current and growing field of study in materials science and engineering. [9, 10]. There are a multitude of applications in the transport industry, building industry, healthcare, energy, etc., including applications for sustainable and healthy environment, such as: (i) green energy generation, transmission, and distribution, (ii) storage of electrical and chemical energy, (iii) energy efficiency and improved energy management systems, (iv) reducing carbon emissions, and (v) air and water purification [1- 11].

Multifunctional materials are any material or material-based system designed to perform multiple tasks, integrating different functions in one material through judicious combinations of structural and non-structural functions [5-12].

The structural functions include fracture toughness, tailored strength, stiffness, and damping, which can be combined with non-structural properties, such as the capability to noise and vibration control, to have antibacterial, self-cleaning, self-repair, thermo-chromism properties or electromagnetic interference shielding and/or structural health monitoring [11].

## 2. MULTIFUNCTIONAL MATERIALS FOR SUSTAINABLE FUTURE

Multifunctional lightweight materials (density less than 4 $g/cm^3$) [2, 3] have excellent specific strength, specific stiffness, heat resistance, and good structural and physical-chemical properties [3-11].

Multifunctional ultra-light (density less than 0.01 $g/cm^3$) [4-7] materials have unique functional properties, such as outstanding shock and energy absorption and buffering performance, noise reduction, sound absorption, shielding performance, and ideal filtering or adsorption performance [7-11].

These materials are designed for structural and environmental uses, such as energy generation and storage [3, 4, 6, 7], sensors and actuation devices, thermal insulation, battery electrodes, and biomedicine applications [1- 12]. The next sections will synthesize different types of multifunctional materials and recent advances in multifunctional ultralight materials, as sustainable green alternatives.

## 2.1 Multifunctional Materials Type

The existing ultra-lightweight materials can be classified according to their structures, in silica aerogels (density, ρ ≥ 0.001 g/cm$^3$[12], carbon aerogels [4, 5] (carbon nanotubes aerogels, ρ ≥ 0.005 g/ cm$^3$, graphene aerogels ρ ≥ 0.003 g/ cm$^3$, ) [12, 13], composite aerogels [7, 14, 15], metal foams (ρ ≥ 0.001 g / cm$^3$) [4,6, 8, 16] polymer foams ( ρ ≥ 0.008 g /cm$^3$) [17, 18], ultra-light ceramic foams ( ρ ≥ 0.0016 g /cm$^3$) [19-21] and ultralight cellular materials (micro or nanolattices) [22-26]. Ultra-light materials are classified from a structural point of view into three main groups (aerogels, foams, and micro/ nanolattices), and, from the point of view of composition, they can be based on ceramic, metallic, or polymeric materials [27-49].

Figure 1 illustrates different types of multifunctional ultralight materials.


**Figure 1. Different types of multifunctional ultralight materials**

Aerogels, foamed materials, and cross-linked materials are all porous materials. Porous materials are a typical ubiquitous structure in biological materials and play an irreplaceable biological role in animals, plants, and other organisms. Materials with natural porous structures such as common wood, cork, corals, and bones can withstand huge loads for a long time.

Porous materials are composed of a solid skeleton and many pores, of different shapes and sizes [6, 8-10, 12]. Porous materials are divided into two types according to the degree of structural regularity: one type is disordered porous materials, such as aerogels [5,7,13,15] and foam materials [16, 20], and the other type is materials with ordered porous structures, such as lattice materials [22-26]. In the process of developing ultra-light materials, aerogels appeared first.

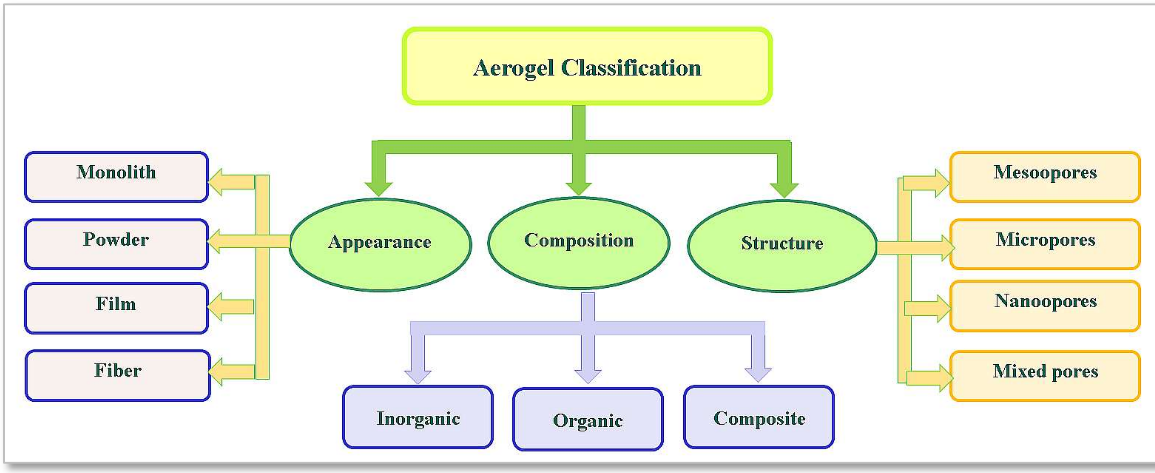
***Aerogel*** is a lightweight meso/micro/nanoporous material filled with 99% air, typically synthesized by a sol-gel process**.** Another definition of aerogel is "a gel comprised of microporous, mesoporous and/or nanofibril solid in which the dispersed phase is gas" [34]. Due to its foam-like structure, the aerogels are also known as "frozen smoke" [27-49].

Karamikamkar *et al.* [28] and also Sonu *et al.* [49], classified the aerogels by appearance, composition, and structure (see Figure 2a).

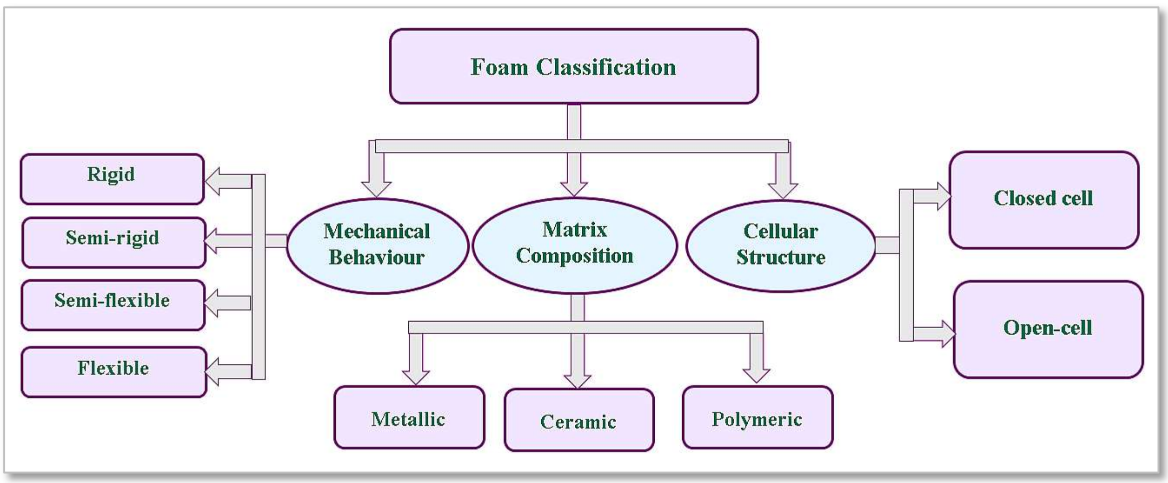
In terms of appearance, aerogels are a monolith, powder, film, or fiber type; after composition, aerogels are classified into inorganic (ceramic or metallic-based aerogels) [31-39], organic (synthetic or natural polymers) [40-43,49] or hybrid/composite [14,15] and, after structure, the aerogels are with mesopores, micropores, nanopores or mixed-size pores [28, 34].

Depending on how aerogels are obtained, they are divided into aerogel, xerogel, cryogel, or hydrogel [34].

The second type of ultralight material is ***foam***, which is also a porous material/substance, formed by trapping gas pockets in a liquid or solid. The foams are rigid, semi-rigid, flexible, and semi-flexible and can be metallic, ceramic, or polymeric [16, 20].




**(a)**




**(b)**

**Figure 2. Classification of ultralight porous materials. (a) aerogel classification, adapted after [28] and [49]; (b) foam classification depending on mechanical behavior, matrix composition, and cellular structure**

Foams contain disordered pores and can be divided according to the shape of the pores [4, 16-21] into open-cell foam (with interconnected pores) and closed-cell foam, as illustrated schematically in Figure 2b [27-49]. Open-cell foam refers to the communication between pores, while closed-cell foam means that the surface of the pores is closed, and the pores are separated by a solid skeleton.

The last type of materials considered as part of the category of ultralight materials are micro or nanolattices.

The ***microlattice*** is an ultra-light material, with a structure consisting of a connected network of struts, when the struts surround tiny spaces. Compared to aerogels and foams, the microlattices are periodically ordered porous materials, also made from metallic, polymeric, or ceramic materials and they are obtained from various methods, like 3D printing technology, wire-woven method, electroless plating, etc. [2, 22, 26].

### 2.2. Ultralight Multifunctional Aerogels

The first aerogels were produced nearly a century ago, by Kistler *et. al.* [40]. In the process of preparation of aerogel (condensation, transforming in gel, aging, and drying of the gel), Kistler and Charles studied and managed to replace the liquid in the gel with gas without changing the solid structure. Kistler and his team [40] found the solution to the problem of shrinkage and structural collapse of the solid, which occurs when the liquid in a gel is separated from the solid by direct evaporation, using supercritical alcohol drying technology. In this way, the world's first aerogel, silica aerogel, was born. After this discovery, other types of aerogels are synthesized, such as cellulose, gelatine, agar, albumin aerogels, and so on.

Aerogel exhibits extraordinary insulation and structural properties and has a large specific surface area [13,15, 28,32,33] (500–1200 $m^2/g$), the thermal conductivity of 0.005–0.1 $W{\cdot}mK^{-1}$[28,32,33], high porosity (up to 99.8%) low dielectric constant (k = 1.0–2.0), and low refractive index (1.05) and adsorption characteristics [27-50]. Aerogels are attractive materials for sensors due to their large surface area, porosity, and ability to be functionalized with biological molecules.

Among the *inorganic aerogels*, we mention the ceramic ones based on carbides, nitrides, oxides, and metallic ones (aerogels made of a web of metallic nanoparticles).

Over the years, the most studied carbide-based aerogels [5, 7, 13, 14] were silicon carbide, carbide-derived carbons [31-39, 45-50], and molybdenum carbide aerogels [49].

The nitride-based aerogels include boron nitride aerogel, carbon nitride, and aluminum nitride aerogels [49].

Metallic aerogels appear as a group of materials for various applications (scaffolds for energy storage and electrocatalysis, etc.) since they exhibit the merits of both metal and aerogel [47-50].

Polymeric organic aerogels are for instance polysaccharide-based aerogels, phenolic-based, polyol-based, protein-based, and carbon-based aerogels (the carbon resulted from biological sources that are pyrolyzed or combusted to produce carbon-based aerogel) [27, 49, 51]. Table 1 summarizes different inorganic aerogels' composition, structure densities, and synthetic methods [31-39, 45-50].

**Table 1. Properties and synthesis methods of different types of inorganic aerogels**

| Type | Density, g/cm$^3$ | Synthetic method | Properties | Reference |
|---|---|---|---|---|
| Silica aerogel | 0.163 - 0.036 | Two step (acid–base) sol–gel process | absorbent for organic solvents and oils | Bhagat *et.al.* [31] |
| | 0.128 | Sol-gel and supercritical drying processes | good transparency, homogeneity | Błaszczyński *et.al.* [32] |
| | 0.0023 | Alcohol supercritical drying | thermal insulation | Kocon *et.al.* [33], Dorcheh *et.al.* [34], |
| Flexible silica aerogels | - | Condensation-dehydration reactions of the hydrolysis products for obtaining a silicone skeleton structure | oil-water separation excellent mechanical properties | Li *et.al.* [35] |
| Carbon aerogel | 0.00016 -0.0224 | Sol-gel | oil absorption, elasticity responsive conductivity | Sun *et.al.* [36] |
| Graphene aerogel | - | Ice-templating freeze-casting | good thermal stability | Li *et.al.* [37] |
| | 0.0044-0.0079 | Freeze-drying | Fire-resistant, good compressibility and variable electrical resistance | Li *et.al.* [38] |
| | ≥0.0032 | Self-assembly | binderless composite monolith electrodes for supercapacitors | Qian *et.al.* [39] |
| Aerographite | ≥ 0.0002 | Chemical vapor deposition growth by zinc oxide template | Electrode Materials for Lithium-Ion Batteries | Mecklenburg *et.al.* [45] |
| Carbon aerogel | ≥ 0.008 | Cycling freezing-thawing | Super water absorbs and shape memory capacity | Jiang, *et.al.*, 2014 [46] |
| Nobel metal gels (Ag, Au) | ≤ 0.0088 | Reducing metal salts to metallic nanoparticles | plasmonic properties, catalytic activity, and electrical conductivity, large specific surface area, porous network, and monolithic structure | Jiang *et.al.*, 2021 [47] |
| Nickel nanowire aerogel | 0.02 | magnetic-field-assisted gelation | highly compressible, elastic, air-dryable used in energy storage and electrocatalysis as electrode scaffolds | Pan *et.al.* [48] Sonu *et.al.* [49] |
| Gold aerogels | 0.04-0.043 | template-free method for the 3D assembly of Au NPs | catalysis applications | Wen *et.al.* [50] |

***Silica aerogel*** mainly contains silicon dioxide, it is an extremely translucent material, and it has an amorphous, inhomogeneous structure, with porosities up to 99.8%, with internal surface area of 600–1000 $m^2/g$, apparent densities of 0.003–0.35 $g/cm^3$, and with low thermal conductivity values. It has different applications in buildings, transport vehicles, national military defense, optoelectronics, etc. as thermal and acoustic (sound) insulation materials, as well as for filtration or removal of oil or other lubricating substances from the surface of the water [31-35].

Silica aerogel could be obtained through the "sol–gel" process (gel preparation, aging, and drying of gels) followed by additional procedures, such as supercritical drying [31-34], the additional procedures are used to influence the structure of the final product. Bhagat *et al.* [31] obtained through the sol-gel process in two steps, hydrophobic silica aerogels, using low-cost precursors and methanol solvents, for oil/organic solvent absorption from water.

Błaszczyński, *et.al.* [32] prepared homogenous silica aerogel materials with transparent properties and with a density of 0.128 $g/cm^3$ by an improved two-step sol-gel process. Also, Kocon *et al.* [33] developed a sol-gel process in two-steps for supercritical drying with ethanol at a lower density (0.0023 $g/cm^3$) of silica aerogel.

***Carbon-based aerogels*** (e.g. carbon aerogel, carbon nanotubes aerogel, graphene aerogel, aerographite, etc.) have high surface area (>2400 $m^2/g$), excellent chemical, thermal, mechanical stabilities, good thermal stability good insulation properties [37], fire -resistant and super water absorbing capabilities [38], and have shape memory characteristics [45].
All carbon aerogels, featuring temperature-invariant (-190–900 °C) super-elasticity and ultralow density (down to 0.00016 g/ $cm^3$) were created by assembling graphene sheets that were chemically-converted with carbon nanotubes, taking advantage of the cooperative impact between large graphene cell walls and elastic carbon nanotube ribs [5]. For instance, Li *et. al* [38] created a reduction and self-assembly process in one-step of a fire-resistant graphene aerogels with ultra-light weight and compressibility properties. The hydrophobic nature coupled with high porosity of 99.6%, permits the compressive graphene aerogels to have be used in oil collection because it can absorb different organic liquids. This type of graphene aerogel holds good compressibility, variable electrical resistance, and fire-resistance characteristics Figure 3 shows the graphene aerogel obtained by Li and his team [38], before and after the flame treated.

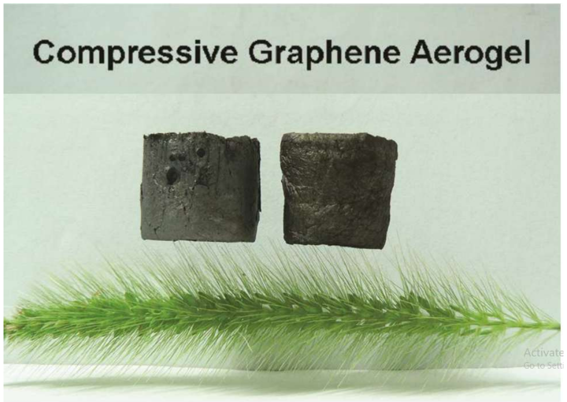



**Figure 3 shows the untreated aerogel (left) and a flame-treated aerogel (right) sitting on a green bristlegrass, obtained by Li and his team [38].**

Another type of multifunctional graphene-based aerogels was obtained by self-assembly between resol-type phenolic prepolymers and graphene oxide sheets (Figure 4) [39].

The unique properties of graphene-based aerogels, such as excellent electrical conductivity, remarkable elasticity and ultralow density [39], make them highly valuable for a variety of multifunctional applications.

***Aerographite*** is an ultra-lightweight (minimum density can reach 0.0002 $g/cm^3$) carbon microtube material. Even with its low density, the ordered structure delivers impressive characteristics such as optical, electrical, and mechanical.

Despite its low density, the hierarchical design produces remarkable mechanical, electrical, and optical properties. Aerographite or "*Flying graphite*", was obtained by Mecklenburg *et al*. [45], using chemical vapor deposition (CVD) with ZnO as a template. Using this method, larger carbon nanotube materials (several cubic centimeters) can be obtained.

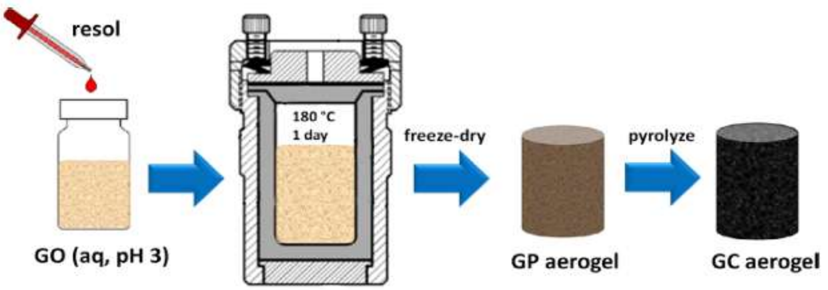



**Figure 4. Schematically presentation of multifunctional graphene-based aerogel fabrication [39].**

***Metallic aerogels*** represent a distinctive category of inorganic aerogels. They consist of a framework of metal nanoparticles that have undergone critical drying, exhibiting properties of both metals and gels.

Iron, gold, or silver aerogels can be obtained through different techniques [47-50], such as templating and dealloying methods.

***Polymeric organic aerogels*** are for instance carbon-based aerogels (the carbon resulted from pyrolyzed biological source) [27,34,49-51], polysaccharide-based aerogels [27,34,49-64], phenolic-based [59, 60], polyol-based [49], and protein-based [34, 50]. Table 2 summarizes different organic aerogels' composition, structure densities, and synthetic methods [7,41-43,61-64].

**Table 2. Synthesis methods and properties and of different types of organic aerogels**

| Type | Density, g/cm$^3$ | Synthetic method | Properties | Reference |
|---|---|---|---|---|
| Polymeric composite nanofiber aerogels | 0.02 | Self-assembled 3D networks | filtration membranes. wearable electronics, thermal stealth, and | He *et.al.* [7] |
| Organic composite aerogel (calcium alginate-intercalated polypropylene mask filters ) | 0.0694-0.02281 | Ice templating method | thermal insulation, absorption, fire repellent | Pornea *et.al.* [41] |
| Cellulose-based bioaerogels ("aerocellulose") | 0.06 to 0.3 | dissolution of cellulose in NaOH/water, gelation, cellulose regeneration, and drying in supercritical conditions | Adsorption and/or separation capacity | Gavillon *et.al.* [42] |
| Pectin aerogels | 0.04-0.11 | Chemical Vapor Deposition | thermal insulation low thermal conductivity | Effraimopoulou *et.al.* [43] |
| Cellulose based bioaerogels | 0.00508 | Facile freeze-drying process | Sustainable, reusable, and superhydrophobic Clean polluted water from oil and organic solvents | Zhou *et.al.* [61] |
| Polysaccharide-based superabsorbent aerogels (alginate aerogels) | - | Sol-gel and supercritical fluid technology. | water superabsorbent aerogels of saline (alginate aerogel absorbs 120 g of saline/gram) | Mallepally, *et.al.*[62] |
| Honeycomb polyimide aerogel | 0.195 | extrusion printing assisted by freeze casting, followed by assembly of building blocks | sound absorbing metamaterials | Gui *et.al.* [63] |
| Hybrid aerogel composite Phenolic Resin/Siloxane) (PR-Si) Aerogels | 0.312-0.356 g/cm$^3$ | PR-Si hybrid aerogels by vacuum impregnation Hybrid aerogels were obtained by sol-gel polymerization, along with ambient pressure drying and solvent exchange | insulative properties and good thermal ablative high compressive strength | Yin *et.al.* [64] |

***The polysaccharide-based aerogels*** are derived from a range of renewable sources, including carrageenan, chitosan, alginate, cellulose, pectin, and mucilage, and can be categorized as *bioaerogels* [27,34,49-51].

These ***bioaerogels***, also referred to as synthetic lightweight porous materials, are created by replacing the liquid in hydrogel structures with gas [27, 30, 51-64]. The establishment and development of organic aerogels, especially *bioaerogels*, were determined by the need to obtain biocompatible aerogels. Bioaerogels are originated from natural, semi-natural, and synthetic sources. Initially, bioaerogels were studied for applications in biomedical fields [27, 51-55], for drug delivery and disease diagnostics (alginate aerogel [55], cellulose aerogel [53]), and tissue engineering [54].

But, in the context of environmental sustainability, to conserve natural resources and clean and protect global ecosystems, the researchers studied and developed advanced materials such as bioaerogels for bio-sensing [55, 56], for thermal insulators [43, 57], sound adsorption [41] (acoustic insulators), fire-repellent applications [41], $CO_2$ captures [58], catalyst supports [59], or oil/water separation [30,60,61]. The schematic presentation of three types of bioaerogels used as adsorbents for different water pollutants is shown by James *et al.* [30] and presented here in Figure 5. Most bioaerogels are prepared by polymer dissolution, solution, and drying which preserves the network morphology, usually with supercritical $CO_2$ [57].

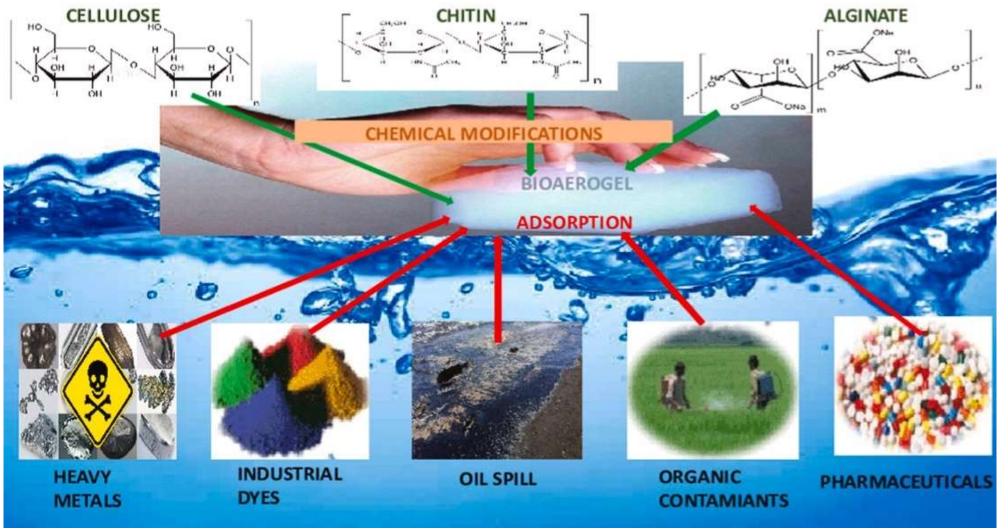



**Figure 5. Schematic presentation of the main types of bioaerogels, used as sustainable adsorbents for different water pollutants [30]**

All cellulose nanofibres aerogels with superior porosity (99.5%) and ultralow density (0.008 g/cm$^3$), have shown high water absorbency, high recovery rate of 4 s of the shape when contacted with water, and high number of reusability of at least 20 times [46]

***Phenolic-based aerogels*** are based on formaldehyde and resorcinol with basic and acid activators [59, 60]. The process of gelation takes place because of the phenolic furfural cross-linking. The phenolic resin aerogels display a series of excellent characteristics such as (a) large sound absorption, (b) low heat conductivity; (c) low density, (d) insulative properties [64], and obviously, as ultralight materials have (e) very low density [59].

***The protein-based aerogels*** are synthesized from plant or animal-origin proteins, like silk fibroin, collagen, gluten, albumin, etc., and are used in biomedical applications and the food industry [34, 50].

The other types of organic aerogels that were created using a polycondensation reaction, are aerogels that contain multiple hydroxyl groups and are called ***polyol-based aerogels***. They can be used in glaring system of double-glazed windows and sensors due to their transparency [34,49].

***Aerogels based on pectin*** are another bio-based aerogel, with high specific surface area and low density, 600 m$^2$/g and 0.1 g/cm$^3$, respectively, and excellent thermal insulation. The pectin aerogel was synthesized by Effraimopoulou *et al.* [43] by chemical vapor deposition (CVD). They studied the pectin-based aerogel and the development of the thermal conductivity in humid conditions, as well as the influence of processing conditions on the pectin aerogel's structure. They concluded that pectin aerogels are thermal super-insulating matters having thermal conductivities between 0.0148 and 0.0234 W m$^{-1}$ K$^{-1}$ [43].

### 2.3. Multifunctional Materials from Foams and their Applications

Like aerogels, they are foam materials from the category of porous materials that contain disordered pores. The difference between aerogels and foams is that they are obtained in different ways and have different properties. For example, a foam is a material in which pockets of gas are created in a liquid or solid, unlike aerogels which, as we have shown in the previous section, aerogels are obtained through the sol-gel process, followed by additional procedures to improve the structure and properties.

Many techniques exist to obtain metal, ceramic, or polymeric foams, depending on the required foam characteristics and applications [4,12,16-21]. The performance of foam materials also depends on the cellular structure [65-80].

***Metal foam*** [4, 65, 69-73] is a structural and functional material that developed rapidly in the late 1980s. This functional material is widely used, such as in the manufacture of automobiles and space industries, lightweight construction materials, heaters, and heat exchangers, but also has significant potential in the area of oil-water separation [67], air filtration, metal -ion sorption-dye absorption, and $CO_2$ sorption [65, 66].

Metal foam provides excellent protection against collisions because it absorbs a lot of energy while being a lightweight construction element, which further reduces fuel consumption and environmental impact.

*Open-cell metal foams* consist of sponge-like pores, which further allow the fluid to circulate between the pores. The hybrid open-cell metal foams offer a great advantage due to their bi- or multifunctionality.

Specific characteristics of open-cell foam material include a large surface area number of cells, high porosity, and a combination of mechanical properties, like strength or stiffness, with multifunctional ones, like good thermal or electrical conductivity of the Al or Cu matrix metal [4,65], liquid or gas permeability [73] good sound absorption [77] and good vibration reduction effect due to its structure [70]. The manufacture of open-cell metallic foams uses, for example, (i) the sponge replication technique [16], (ii) using powder metallurgy process, consisting of coating pure polyurethane foam with metal/alloy powder, using an organic binder solution, or (iii) electroless metal plating and removal of the template stages [4, 78].

The microstructures and fabrication schemes of open-cell metal (Ag, Ni, Cu, and Co) foams are presented in Figure 6 [4].

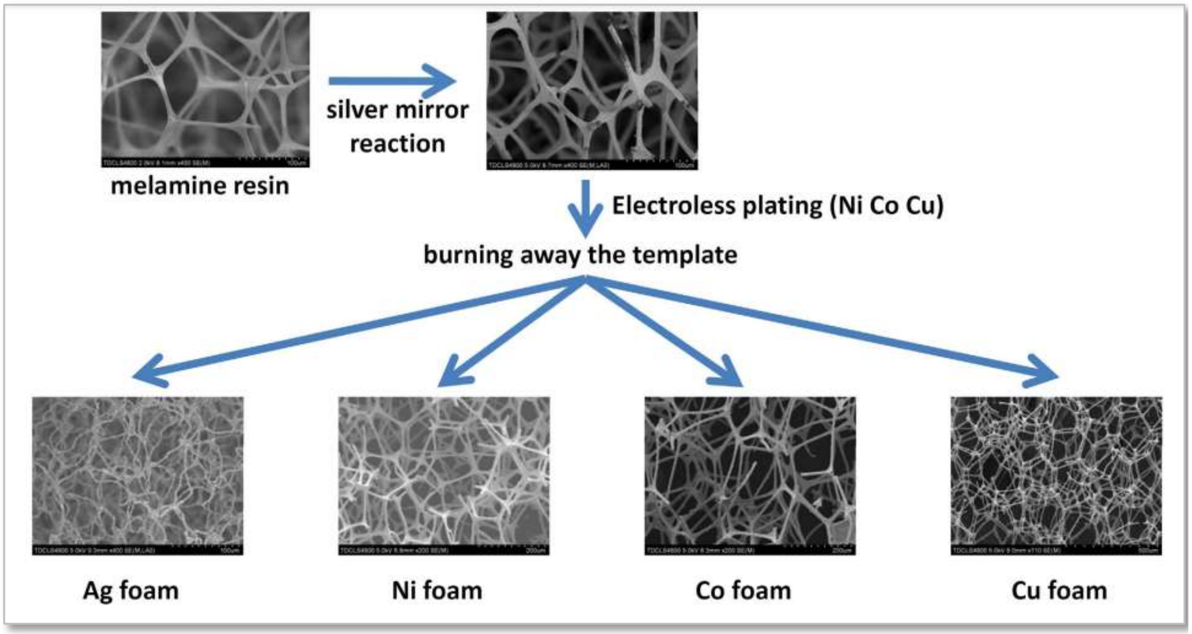



**Figure 6. Fabrication scheme of ultralight open-cell metal (Ag, Ni, Co Cu) foams [4]**

Badiche *et. al.* [76] obtained an ultralight (0.1335 - 0.4005 g/cm$^3$) highly conductive open-cell nickel foams through the electroplating method (Ni electroplating on the coated polyurethane template surface and then removal of the template). Jiang *et al.* [78] applied the same techniques of electroless metal plating to obtain open-cell Co/Ag composite foams. Characterization and analysis of the results led to remarkably low densities (≤ 0.0127 g/cm$^3$), high porosity (99.9%), and a stress-strain curve that was long and flat. To get *a closed cell*, the metallic foams are synthesized by liquid metallurgy route, powder route processing, or techniques based on self-propagating combustion synthesis [4,6, 16]. Tappan *et al.* [16], report a method to achieve ultra-low densities of 0.011 g/cm$^3$, and surprisingly surface areas as high as 270 m$^2$/g, for their nanostructured, monolithic, and transition-metal foam. Using self-propagating combustion synthesis, they produced monolithic nanoporous iron, cobalt, copper, and silver metal foams, utilizing transition-metal complexes with ligands containing nitrogen.

***Ceramic foams*** can be made from different techniques from modified replication techniques [79], direct foaming method or foam impregnation method [21, 80] to chemical vapor deposition (CVD) on metal template [81, 82]. Gui *et.al.* [82] produced carbon nanotube foams using chemical vapor deposition, resulting in a three-dimensional interconnected structure of self-assembled nanotubes. These sponges are exceptionally lightweight, highly porous, and hydrophobic in their unmodified state, allowing them to be elastically and reversibly shaped. They can float on water and effectively absorb extensive oil films, indicating potential for environmental applications [82]. Another application of ceramic based composites like alumina/ zirconia composite ceramic foam [80] or ceramic based on silicon oxide, crystalline cordierite and mullite) foam [21] as thermal insulation with also other functions like high porosity excellent specific compressive strength, are developed by Huo et al. [80].

Chen *et. al* [81] developed a structure that was built on a nickel scaffold template for the growth of graphene foam and graphene/poly(dimethyl siloxane) composites with a very high electrical conductivity, flexibility. This material that can be used in electrical applications such as electrode materials for lithium ion batteries and supercapacitors, elastic and flexible conductors, high-performance electrically conductive polymer composites, etc.

Different types of foams, properties, and synthetic methods are shown in Table 3[4, 67, 75-87].

**Table 3. Properties and synthesis methods of different types of metallic, ceramic and polymeric foams**

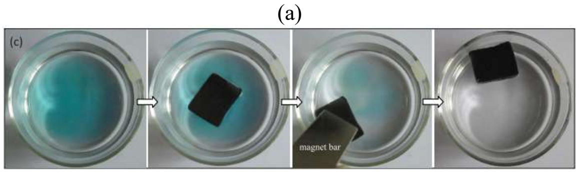
| Type | Density, $g/cm^3$ | Synthetic method | Properties | Reference |
|---|---|---|---|---|
| **Metallic based foams** | | | | |
| Closed-cell Al-based foams | 0.05–0.55 | treatment of the molten metal by direct gas injection | fire resistance, thermal insulation, energy and sound absorption; | Guner *et.al.* [75] |
| Open-cell nickel foams | 0.1335-0.4005 | Ni is electroplated on a polyurethane (PU) coated surface, before burning out the PU foam | highly conductive foam energy storage (battery) applications | Badiche *et.al.* [76] |
| Closed-cell Al-based foams | 0.18–0.24 | in situ gas generation | sound absorbers and shock absorption properties | Miyoshi *et.al.* [77] |
| Open-cell (Ag, Ni, Co , Cu) ultralight monolithic metal foams | 0.0074 | electroless plating (Ni, Co, Cu) of a polymeric template, followed by the removal of the template | acoustic, vibration, or energy shock damping, catalyst supports, thermal insulation, battery electrodes; | Jiang *et.al.*, 2015[4] |
| Open cell Co/Ag composite foams | ≤ 0.0127 | electroless metal plating and removal of the template stages | Ideal energy absorber long flat stress–strain curve high porosity (99.9%) | Jiang *et.al.,* 2016 [78] |
| Closed Cells Al-Based Foams | ≤ 0.03 | pore-forming method by insertion of transferable pattern design, followed by gas injection) | structural applications for automotive and aerospace fields; | Ubertalli *et.al.*/[87] |
| **Ceramic based foams** | | | | |
| Carbon-bonded alumina ceramic foam filters | - | modified replication technique based on the Schwartzwalder and Sommers process | refractory and steel melt filtration, good mechanical properties and cold crushing strengths | Emmel *et.al.* [79] |
| Alumina/ zirconia composite ceramic foam (closed pore structure) | 0.17 | direct foaming method | high-temperature thermal insulation,high porosity excellent specific compressive strength | Huo *et.al.* [80] |
| Graphene foam | 0.005 | Chemical Vapor d Deposition (CVD) by Ni foam template | supercapacitors | Chen *et.al.* [81] |
| Carbon nanotube sponge | 0.005-0.01 | CVD and ferrocene as catalyst | absorption capacity | Gui *et.al.* [82] |
| Ceramic (silicon oxide, crystalline cordierite and mullite) foam | 0.173-0.194 | foam impregnation method | as thermal insulation, adsorption, and environmental protection. | Cui *et.al.* [21] |
| Interconnected skeleton of magnetic composite ($Fe_2O_3$/C, Co/C, Ni/C) foams | 0.005 | calcinations of PU sponges, grafted with poly(metal acrylate) layers | ultralight oil–water separation | Chen *et.al.* [67] |
| **Polymeric based foams** | | | | |
| Polyethylene foam | 0.00823 | facile thermally induced phase separation method. | superhydrophobic and thermal insulation oil water separation | Su *et.al.* [83] |
| Closed cell polyurethane foam materials | 0.037-0.145 | exothermic reaction between a polyol and an isocyanate, mixed in specific volumetric proportions | packaging, cushioning, space filling (foundation remediation) insulation | Buzzi *et.al.* [84] |
| Polyurethane foams functionalized with graphite powder and magnetic nanostructures | - | coating base polyurethane sponge in the magnetic nanostructures/graphite nanocomposite slurry | nano-porous oleophilic, hydrophobic, and magnetic sponge absorption of oil-based compounds | Nandwana *et.al.* [85] |
| Polydimethylsiloxane (PDMS) foams | 0.18 - 0.75 | sugar-templating process | eco-friendly PDMS sponge, hydrophobicity and oleophilicity absorption of oil from water | Choi *et.al.* [86] |

***Polymeric foams*** consist of a gaseous phase dispersed in a solid plastic phase and the resulted material has the properties of both phases [61]. The multifunctional ultralight, superhydrophobic and thermal insulation polymeric foams have attracted the researcher's attention as a solution for application of them in reducing the effects of pollution, such as: absorption of crude oil or oil-based compounds from marine/lakes/rivers environment [83-86]. In the process of oil-water separation, adsorption is an important property, and the ability of porous materials to adsorb different types of oil becomes significant.

For instance, Su *et.al*. [83] developed an ultra-high molecular weight polyethylene (UHMWPE) foam with the secondary pore structure, with excellent adsorption performance and outstanding thermal insulation performance, for oil-water separation applications. The macro morphology and oil absorption performance on the water of one of the UHMWPE developed foams, are presented in Figure 7(a) [83]. They also managed to adjust the shape of the foam in the laboratory, which makes the production process controllable, and, in the future, open the possibility to the applied the synthesis process on a large scale [83].

An ultralight $Fe_2O_3$/C magnetic material was obtained from a commercial polyurethane sponge as a template, foam could be manipulated by a magnet bar for removal of lubricating oil from the surface of the water [67] (Figure 7b). The schematic presentation of multifunctional ultralight magnetic foams fabrication is shown in Figure 8.

(a)




(b)

**Figure 7. Oil absorption from the surface of water of different types of foams (a) UHMWPE foam [83]; (b) superhydrophobic $Fe_2O_3$/C foam under magnetic field [67]**

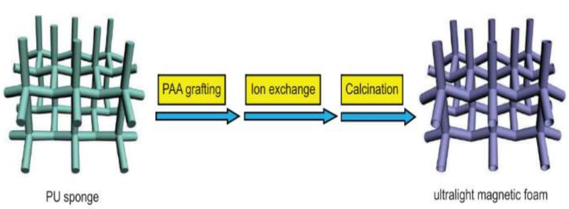



**Figure 8 Schematically presentation of multifunctional X/C (X= Fe2O3, Co, Ni) foam fabrication, from a polyacrylic acid (PAA)-grafted PU sponge [67]**

### 2.4. Multifunctional Materials from Micro or Nanolattices and their applications

***Microlatice material*** is an ultra-light material that has appeared in the last decades. The micro/nano lattice materials with ordered porosity can be metallic based [23, 88], polymeric based [89] and micro/nano-lattice ceramics [90]. Micro/nano lattice materials as cellular materials exhibit some outstanding multifunctional properties such as noise reduction, shock and impact energy absorption, lightweight and specific strength. They also showed excellent application potentials in machinery, biomedical, equipment, transportation, aerospace, national defense, energy, and other industrial fields [91].

Micro/nano lattice materials are highly compressible and can regain their original shape easily after high forces are applied. Ultralight cellular materials are suitable for acoustic, vibration, or shock energy damping, catalyst supports, thermal insulation, and battery electrodes.

The advanced engineered lattice materials for lightweighting spacecraft structures depending on cellular structure have different properties. For examples, the multifunctional open cell lattices that exploit anisotropy meet or exceed airplanes mechanical property objectives and provide novel thermal management and vibration damping control. The regular closed cell lattice (cubic and octet) for secondary space structures has exceptional specific stiffness and multifunctional debris protection and impact energy absorption properties.

***Metallic microlattice*** combines useful mechanical properties of metals [4, 6, 8, 22, 88, 92] with smart geometrical orientations providing greater stiffness [6, 8, 22, 88, 92, strength-to-weight ratio and good energy absorption capacity than other types of cellular materials [22, 88, 92] used in sandwich construction. In 2011, Schaedler *et al.* [22] prepared ultra-light porous nickel material ($\rho \geq 0.0009$ g/cm$^3$) in which became the "lightest material in the world" at that time, research on materials microlattice has grown. Metallic lattice could be made from stainless steel, Ti alloys like Ti-6Al-4V or Ni, Mg or Al based micro lattice material [88]. Ultra-lightweight sandwich panels based on ultra-stiff and ultra-strong nano-crystalline metals with ultra-light lattice core materials, with applications in aerospace vehicles and structures, are presented in Figure 9 [92].

**Figure 9 Ultra-lightweight sandwich panels based on nano-crystalline metals standing on the dandelion [92]**

Metallic microlattice materials are created using traditional manufacturing methods, including both woven and non-woven metal textiles, deformation forming, and investment casting. They can also be produced through additive manufacturing techniques such as self-propagating photopolymer waveguide processes, electron beam melting, selective laser melting, along with metal plating [93].

***Ceramic microlattices***. Porous ceramics have attracted significant interest for their lightweight nature, resistance to wear and corrosion, low thermal conductivity, and ability to withstand high temperatures. The 3D printable mullite-based porous ceramics offer advantages such as outstanding fire resistance, reduced thermal conductivity, and sound insulation [90]. The capacity to create both porous and robust structures is essential for the development of new applications involving porous materials. Mullite-based porous ceramic monoliths have been produced using a protein gelling technique with waste fly ash hollow microspheres [90].

Meza *et al.* [94] developed ceramic nanolattices from aluminum oxide, where the beams are engineered to stretch instead of bend. An important factor in the design of these lattices is the ratio of wall thickness to beam radius; when this ratio is sufficiently low, compressing the beams does not lead to fracture. This allows the nanolattices to endure significant compression while being able to return to a shape close to their original form once the stress is released.

Meza *et al.* [94] confirmed that nanoscale ceramic materials have the characteristics of ultra-light and high specific strength at the same time and can return to their original shape when the pressure reaches 50%.

Zheng *et al.* [95] obtained a cross-linked material with ultra-low density and strong mechanical properties comparable to the solid materials and they called this material a "metamaterial" to emphasize that the mechanical properties of this material are determined by the geometric structure rather than the composition of the material. The density of this material is between 0.00087~ 0.258 g/cm$^3$. The creation of these microlattices, using metals, polymers, or ceramics as base materials, has been enabled by additive micromanufacturing method, along with nanoscale coating and post-processing techniques. The resulting materials demonstrate exceptional stiffness over a wide range of densities, spanning more than three orders of magnitude, irrespective of the material used. [95].

## 3. CONCLUSIONS

Lightweight and ultralight multifunctional materials were reviewed in this paper focusing on their properties, production methods, and applications considering the demand for high-performance, environmentally friendly solutions.

As a result, three main categories of multifunctional ultralight materials such as aerogels, foams, and micro/nanolattices, and their applications for sustainable and healthy environments have been considered.

Ongoing research in the development of these lightweight and ultralight materials continues emphasizes several key areas: (a) leveraging the advantages of various materials to obtain ultralight composite structural materials; (b) functionalization of ultra-light materials, (c) developing new technologies, such as micro 3D printing, which allows the fabrication of porous materials with controlled porosity, such as micro or nanolattices, with smaller volume and improved strength. These innovations promise to significantly contribute to the reduction of harmful air emissions and pollutants in both terrestrial and aquatic ecosystems.

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