

Review

Tomy Muringayil Joseph*, Seithkan Azat, Ehsan Kianfar*, Kunnelveli S. Joshy, Omid Moini Jazani, Amin Esmaeili, Zahed Ahmadi, Józef Haponiuk and Sabu Thomas*

Identifying gaps in practical use of epoxy foam/aerogels: review - solutions and prospects

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Abstract: Epoxy foam/aerogel materials (EP-AGs) have potential in the aerospace, construction, and energy industries, allowing the development of lightweight high-performance products for a wide range of applications. Research interest in developing EP-AGs is increasing as it has the potential to create greener and more sustainable materials for making various products. Several commercial applications of EP-AGs and techniques for creating, processing, and drying them have already been reported. The introduction of EP-AGs into value-added materials is one of the most promising options but suffers from a lack of knowledge about the relationships between microstructure and properties. The current obstacles to their use in the industrial sector and for applications

and challenges related to factory scale-up are also taken into account. EP-AGs are hindered by critical gaps in applicational and processing complexity, such as scaling up from laboratory to large-scale production, optimizing synthesis and processing techniques, and developing standardized testing protocols. The review focuses on the processing complexities and further difficulties associated with EP-AGs to improve casting burdens, cost-effectiveness, and accessibility in various applications. This review also examines the challenges in synthesizing EP-AGs used to make special materials, their practices, and the technological barriers one would face.

Keywords: epoxy foam; aerogel; polymer processing; thermosets; crosslinking; technology

1 Introduction

Scientists of the Mobil oil company developed methods to synthesize the first mesoporous silica gels with ordered porosity in 1992, leading to an increase in research on porous materials and the development of Metal-Organic Frameworks to extend the nanoengineering of porosity to microporous regimes (Califano and Costantini 2020). Interest in porous materials has further increased over the past three decades, but nano-scale porous materials have been more interesting given the possibility of contributing more surface area and interactions (Jouyandeh et al. 2018; Tikhani et al. 2019). Materials are porous if they contain cavities, channels, or interstices deeper than wide (Rouquerol et al. 1994). Regularly arranged pores are common, but irregular pore structures are more common due to cross-linking, aggregation, or selective removal of elements.

Organic and inorganic porous materials are used in a variety of fields, like drug delivery systems (Mahmodi et al. 2020; Servatan et al. 2020). Porous polymers are being explored for applications in fuel cell membranes, electrode materials, gas storage, and sorption materials/chromatography (Jugjai et al. 2002; Moayed Mohseni et al. 2022). Porous materials have also been used in medical science for enzyme immobilization,

***Corresponding authors: Tomy Muringayil Joseph**, Department of Polymer Technology, Faculty of Chemistry, Gdańsk University of Technology, G. Narutowicza 11/12 80-233, Gdańsk, Poland, E-mail: tomy.muringayil@pg.edu.pl; **Ehsan Kianfar**, Young Researchers and Elite Club, Gachsaran Branch, Islamic Azad University, Gachsaran, Iran, E-mail: ehsankianfar775@gmail.com; and **Sabu Thomas**, School of Energy Materials, Mahatma Gandhi University, Kottayam 686560, Kerala, India; International and Inter-University Centre for Nanoscience and Nanotechnology, Mahatma Gandhi University, Kottayam, 686560, Kerala, India; and Department of Chemical Sciences, University of Johannesburg, Doornfontein, P.O. Box 17011, Johannesburg 2028, South Africa, E-mail: sabuthomas@mgu.ac.in

Seithkan Azat, Satbayev University, Satbayev Str. 22a, 050013, Almaty, Kazakhstan

Kunnelveli S. Joshy, School of Energy Materials, Mahatma Gandhi University, Kottayam, 686560, Kerala, India

Omid Moini Jazani, Department of Chemical Engineering, Faculty of Engineering, University of Isfahan, 8174673441, Isfahan, Iran

Amin Esmaeili, Department of Chemical Engineering, School of Engineering Technology, and Industrial Trades, College of the North Atlantic – Qatar, Doha, Qatar

Zahed Ahmadi, Department of Chemistry, Amirkabir University of Technology, Tehran, Iran

Józef Haponiuk, Department of Polymer Technology, Faculty of Chemistry, Gdańsk University of Technology, G. Narutowicza 11/12 80-233, Gdańsk, Poland

simulation, biological sensors (Rabiee et al. 2021), and controlled-release drug carriers (Rabiee et al. 2022) and also have been used for molecular sieves, catalysts, and thermal insulations (Chowdhury et al. 2019; Yadav et al. 2020). Thermal insulations are one of the earliest applications of porous nanomaterials, preventing heat loss by convection (Al-Homoud 2005). Porosity is the only alternative to achieve low dielectric constants, as pores decrease the number of polarizable molecules per unit volume reducing the materials ability to store electrical energy.

Polymers are increasingly used in specific applications other than commodities, creating new forms and structures (Joseph et al. 2023a, 2023c). Polymers are used in various industries, such as packaging, construction, automotive, electronics, textiles, and healthcare (Joseph et al. 2023b; K. I. et al. 2022; Muringayil Joseph et al. 2022). Recent advancements in polymer science (Thomas et al. 2023) include sustainable, functional polymers, nanotechnology-driven materials, additive manufacturing methods, smart polymer innovations, and recycling technologies to address environmental challenges and promote versatile applications.

Samuel Kistler invented aerogels (AG) which are low-density porous materials prepared by preventing the shrinkage caused during drying of gels which can be formed by combining a polymer and solvent (Yashim et al. 2021). Synthesizing an aerogel involves exchanging the solvent within the gel's pores with a gas while preserving the gel's solid network structure. AGs are nanoporous materials with extraordinary physical, chemical, and mechanical properties that are suitable for thermal insulation, chemical sensors, catalysis, acoustic transducers, environmental cleaning, water-repellent coatings, metal casting moulds, and energy storage devices which are formed in various materials with porosity ranging from 80 % to 99 % (Vinayakumar et al. 2022). AGs are materials prepared by a special drying process that preserves the structure of pores and solid networks in wet gels (X. Yang et al. 2022). Kistler solved the problem of drying

gels by replacing the liquid with gases using supercritical drying conditions, discovering that the solid network structure of gel was independent of the liquid, making it one of the earliest materials to base its existence on porosity.

Epoxy Foam/Aerogel composite materials (EP-AGs) have gained attention due to their unique combination of properties, such as low density, high porosity, low thermal conductivity, and mechanical strength, which can revolutionize industries such as aerospace, construction, and energy (Gupta and Ricci 2008; Jose Varghese et al. 2021). EP-AGs are a recent material that has attracted attention due to their strong mechanical resistance and lightness. They are widely used in automobiles, aviation, and other industries due to their thermal and chemical stability (Monie et al. 2021). EP-AG is a hard polyfoam created by mixing curing and foaming chemicals with an aerogel/epoxy resin (EPN) mixture. They can be created by mechanically whipping air into a mixture of EPN, hardener, surfactant, and silica aerogel particles. These stable liquid froths can then be further hardened to create solid EP-AGs. The EP-AGs are lightweight, cheap, strong, and easy to shape. They are a workable alternative for various applications due to their ability to address the fragility of silica aerogels ("Why isn't the aerogel industry booming?" 2019). Table 1 shows the types and functional applications of aerogels.

The practical application of EP-AGs is limited by several critical gaps in applicational and processing complexity. EP-AGs have high porosity, low thermal conductivity, mechanical strength, chemical stability, and fire resistance, making them ideal for thermal insulation, structural, and protective applications (Meador et al. 2010; Vahabi et al. 2024) (Table 2). Optimizing the synthesis and processing techniques of EP-AGs is essential for achieving desirable properties and performance, and more critically deepening our understanding of the fundamental principles controlling the synthesis and processing for tailoring the EP-AGs for specific applications. The versatility and potential of EP-AGs

Table 1: Typical types and functional applications of aerogels.

	Types					
	Carbon	Metal	Oxide	Non-oxide ceramic	Biomass	Polymer
Aerogels	AC	Au	SiO ₂	BN	Silk fibroin	RF
	CNT	Pt	Al ₂ O ₃	Si ₃ N ₄	Cellulose	Polyimide
	GO	Ag	ZrO ₂	SiC	Chitosan	Aramid
	Graphene	Cu	TiO ₂	MXene	Alginate	PBO
	Applications					
	Electronic	Biomedical	Optical	Energy storage	Insulation	Chemical
Linear actuator Gas sensor	Strain sensor	Tissue engineering	Solar harvesting	Battery	Thermal	Catalyst
	Drug delivery	Anti-reflective	Supercapacitor	Acoustic	Support Adsorbent	

make them attractive for research and development but needed to bridge critical gaps, which is the major discussion of the present work. This review discusses the role of governmental initiatives, funding agencies, and industry partnerships in supporting research and development efforts, and explores various characterization techniques to assess the performance of EP-AGs. The review also explores the challenges associated with the practical application of EP-AGs, such as scaling up from laboratory-scale synthesis to large-scale production. Standardization and certification are needed to ensure the quality, reliability, and safety of EP-AG

products in various industries were also mentioned. Table 2 details about various applications of EP-AGs.

2 EPN curing properties: an overview

EPNs (ER) are thermosetting materials possessing an oxirane or epoxy ring in their molecular chain, and their properties depend on the type of epoxy and curing agent used, as well as the curing process and additives with varied surface and bulk properties and functionalities (Jouyandeh et al. 2020; Vahabi et al. 2018). Depending on the functionality of the curing agent, such as hydroxyl groups and nitrogen of an amide structure, epoxy ring-opening reactions, or so-called crosslinking leads to the formation of three-dimensional networks (Akbari et al. 2019; Jouyandeh et al. 2019). Controlling crosslinking or curing reactions in ER and its derivatives such as ER nanocomposites is the key to achieving acceptable properties (Jouyandeh et al. 2016; Karami et al. 2019).

Some of the salient features of ER over the other thermosets are:

- The manufacture of thermosetting resins requires minimal pressure.
- Cured ER have excellent tensile strength, moisture, chemical, and corrosion resistance, as well as thermal, adhesive, and electrical properties (Wouterson et al. 2007).
- Cured product had lower residual stress and shrinkage than vinyl polymerization.
- Ability to be processed under a variety of conditions
- Ability to accept a wide range of fillers and pigments (Maharsia et al. 2006).
- Curing agents can be used to control the degree of crosslinking by using a wide range of temperatures.
- No volatile products of the curing reaction can cause unwanted bubbles or void formation.

ER is affected by the type of epoxy and curing agent used, with phenolic glycidyl ethers, aromatic glycidyl amines and cyclo aliphatic being the main classes (Auvergne et al. 2014). Curing agents such as alkali, amine-type, catalytic, and anhydrides can react with the oxirane groups in epoxy monomers, leading to the polyaddition reaction when the epoxy ring is affected by active hydrogen during the curing phase (Cavezza et al. 2020). The nitrile and hydroxyl groups of curing agents react to form amide linkages, enabling crosslinking and the creation of long-chain segments with epoxy and amine functionalities. The curing process

Table 2: Various applications of EP-AGs in a short view.

Property	Feature	Application	References
Thermal conductivity	– Best insulating solid	– Architectural and appliance insulation	(Yang et al. 2020; Zhao et al. 2015)
	– Transparent	– Heat and cold storage	
	– Withstand high temperature	– Automobiles	
	– Lightweight	– Space vehicles	
Density/porosity	– Lightest synthetic solid	– Solar devices	(Gupta and Ricci 2008; Li et al. 2018)
		– Catalysis	
	– High surface area	– Sensors	
		– Fuel storage	
	– Multiple compositions	– Ion exchange	
		– Filters for gaseous pollutants	
Optical	– Transparent	– Targets for inertial confinement fusion (ICF)	(Wang et al. 2015)
		– X-ray lasers	
	– Low refractive index	– Lightweight optics	
	– Multiple composition	– Cherenkov detectors	
Acoustic	– Low speed of sound	– Light guides	(K. Wu et al. 2021)
		– Soundproof rooms	
Mechanical	– Elastic	– Acoustic impedance matching in ultrasonic distance sensors	(P. Yang et al. 2022)
		– Energy absorber	
	– Lightweight	– Hypervelocity particle trap	
Electrical	– Lowest dielectric constant	– Dielectrics for integrated circuits (ICs)	(Li et al. 2016)
	– High dielectric strength	– Spacers for vacuum electrodes	
	– High surface area	– Vacuum display spacer	
		– Capacitors	

produces an epoxy solid structure and an infinite 3D network of cross-linked polymer chains with good mechanical properties, heat and chemical resistance, and high adhesiveness (T. Liu et al. 2022).

The cell structure must be stabilized during curing by the curing process and hardener, which raises the viscosity of the epoxy and delays gas loss (Bethke et al. 2019). The use of chemical and physical blowing agents such as hydrocarbon solvents, azodicarbonamide, and chlorofluorocarbons is prohibited due to environmental concerns due to potential foaming failures such as coalescence and cell collapse (Du et al. 2021). Expanding micro hollow spheres and microspheres are used to make syntactic foams and manage cell size. The sphere-packing process is essential for the dispersion of hollow spheres, but increases viscosity of the resin/glass microsphere blend, leading to poorer dispersion quality and inhomogeneous foams (Ambika Devi et al. 2007a; Huang and Li 2015). Phenolic microspheres (PhmSs) contain hazardous formaldehyde and sulfur gas, so new methods must be used to manufacture epoxy foam (Cui et al. 2022; Gul et al. 2016; Heise and Martin 2002).

The low molecular weight of epoxy and hardener in the resin stage makes it difficult to use gas-blowing agents (GBAs) for foaming. Generally, thermoplastics with a high molecular weight are the only materials that can be foamed using GBAs, such as CO₂ and N₂ (Naguib et al. 2005). CO₂ and N₂ are impregnated in molten thermoplastics using extrusion-foaming or absorbed into solid thermoplastic polymers using a high-pressure autoclave at an appropriate temperature. The viscosity of semi-crystalline thermoplastics can be increased by adding a chain extender to raise their molecular weight and enable foaming. Shear and temperature can be used to alter the viscosity of polymer chains to increase their viscoelastic behaviour (Corre et al. 2011; Dando et al. 2018).

Pre-cured epoxy (preE) can be foamed with a GBA if it has a sufficient viscosity or modulus range. PreE has a modulus range of 2–3 GPa and comes in two flavours: large oligomers before the gel point and a single network with few free reactive end groups after. Its behaviour is viscous and has a large damping factor before the gel point, but displays elastic and plastic properties after the gel point (Bethke et al. 2021a; Parameswaranpillai et al. 2013). Epoxy foam has been created using CO₂ through absorption and desorption from the polyamine hardener's amine group. This requires a solid epoxy to be made in advance and ready to use. The molecular weight between crosslinks (Mc) is the characteristic value to produce the solid-state behavior of a pre-cured epoxy (Erdmann et al. 2017; Salgueiro et al. 2006). However, Ito et al. (2014) found that Mc values cannot make CO₂ bubble nucleation in a batch physical foaming procedure by using 2-ethyl-4-methylimidazole as a hardener and three samples of

bisphenol-A diglycidyl ether epoxy (DGEBA) with different molecular weights (Ito et al. 2014). Only the DGEBA at 900 g/mol could foam, while the other samples could not be cracked. However, the viscoelastic data showed that a foaming temperature of 90 °C was significantly lower than the Tg of epoxy, which was 135 °C (Mol wt = 470 g/mol) and 170 °C (Mole wt = 370 g/mol) and was relatively close to the Tg of the DGEBA, which was 108 °C (Mole wt = 900 g/mol). This begs the question of whether foaming could proceed if the temperature was close to the glass transition temperature (Tg) of epoxy with 470 g/mol and 370 g/mol. According to another study, the ideal pre-curing degree range for DGEBA and m-xylylenediamine (MXDA) foaming was between 37.7 and 46.3 % (Lyu et al. 2017). The CO₂ absorption and release, foaming, and post-curing operations were all carried out in a closed vessel, making it unclear when preE entered the solid stage and if foaming took place during the depressurizing procedure.

Syntactic foams are used to make tooling for composite materials, providing dimensional stability and low CTE. They are easy to machine and have high dimensional stability, making them suitable for thermoforming die and tooling. Thermoforming is a widely used process for large volume production of plastic parts (Gupta et al. 2014). An example of the Illustration of the formation of AGs and a laboratory-scale syntactic foam fabrication method is shown in Supplementary Figure S1.

2.1 Understanding thermomechanical behavior of crosslinked epoxy polymers through molecular modeling

Various methods of simulated crosslinking have been investigated by many researchers in their study of cross-linked epoxy resin production. Using a crosslinking process, Yarovsky and Evans were able to crosslink CYMEL 1158, an epoxy resin with a low molecular weight that was phosphate-modified and water-soluble (Yarovsky and Evans 2002). A static crosslinking technique was used, in which the crosslinking processes occurred all at once. Xu et al. used molecular dynamics to crosslink epoxy resins, and their model was applied to investigate water transport in these crosslinked networks (Wu and Xu 2006). With each iteration, a single crosslink was formed in the epoxy resin (DGEBA) using an iterative Molecular Dynamics (MD)/Molecular Minimization (MM) process. There have been several computer investigations on epoxies crosslinking (Fu et al. 2019; Masoumi et al. 2015; Masoumi and Valipour 2016; Sirk et al. 2013; Yang and Qu 2012). So far, every single study has relied on model systems with a tiny number of atoms, fewer than

2200. Varshney et al. (Varshney et al. 2008) employed Heine's dynamic crosslinking technique and Xu's MD/MM idea (X. Wu et al. 2021a) to crosslink EPON 862 with DETDA, whereas Heine et al. (Heine et al. 2004) used a dynamic crosslinking approach to model huge PDMS networks. The systems Varshney et al. (Varshney et al. 2008) modeled had EPON 862 and DETDA molecules in the ratios of 128:64 and 256:128 (EPON862:DETD), respectively. Even though these studies have considerably advanced molecular modeling of crosslinked epoxies, relatively large molecular models (>20,000 atoms) are still lacking for predicting how to crosslink density affects various thermomechanical properties of EPON 862-DETD polymers.

2.1.1 Crosslink density effects on epoxy polymers: molecular modeling study

A study utilized molecular mechanics and molecular dynamics simulations, verified molecular models of the EPON 862-DETD epoxy system with varying crosslink densities are constructed inside a unified atom force field (Bandyopadhyay et al. 2011). Following this, the elastic characteristics, glass transition temperatures, and thermal expansion coefficients of each crosslinked system are predicted using molecular dynamics simulations. At crosslink densities above and below the glass transition temperature, the elastic characteristics and glass transition temperature rise with increasing levels of crosslink density. However, the thermal expansion coefficient falls with increasing levels of crosslink density.

The EPON 862-DETD epoxy polymer has been the subject of a unified atom force field molecular modeling investigation into varying cross-linking degrees. Various crosslink densities were used to forecast the epoxy system's T_g , thermal expansion coefficients, and elastic characteristics. The computational technique was validated since the projected thermomechanical parameters were mainly in agreement with those published in the literature. The findings show that the coefficient of thermal expansion falls at and below T_g , whereas the T_g and elastic stiffness tend to rise with increasing crosslink density. When the crosslink density is more than 63 %, the changes in thermal expansion coefficients and elastic characteristics tend to be less. Given the magnitude of the models discussed in this study, it may be impractical to publish single values of T_g based on the density versus temperature curves used to calculate the T_g of the simulated epoxy. Determining T_g using regression analyses above and below the nonlinear region of the curves becomes rather subjective due to the nonlinearity in these curves. The correct way to report the T_g is as the temperature range where a structural change occurs in the polymer's physical structure. The study's findings also suggest that

similar to other epoxy systems, this one may have a crosslink density threshold beyond which thermomechanical characteristics don't change much. Increasing the crosslink density to 76 % may only marginally alter the thermomechanical characteristics since the structure is already heavily immobilized at 63 % crosslinking. The experimental quantification of epoxies' crosslink density is challenging, however. Using Infrared (IR) or dielectric spectroscopy, the degree of cure may be tracked during the polymerization procedure. Methods like these track the reaction's development by monitoring changes in spectrum properties such as the epoxide group vibration intensity (IR) (Heine et al. 2004; Plazek and Frund Jr. 1990) or the frequency of maximal permittivity or loss (dielectric) (Fitz and Mijovic 1999; Levita et al. 1996). These techniques can be used to examine the cure reaction and provide a relative assessment of the magnitude of the reaction, but they can't tell you how many crosslinks an epoxy sample has after it has cured (Huang, H et al. 2022; Huang, X et al. 2022; Bandyopadhyay et al. 2011). Making firm claims about the validity of the findings in this research is challenging without these data. Supplementary Figure S2 details about the crosslink density effects on epoxy polymers through a molecular modeling study. Supplementary Figure S3A details about the spatial Density distributions of 54 %, 63 % and 76 % crosslinked structures along the length of simulation box, Supplementary Figure S3B explains about the density versus temperature curves for 54 %, 63 % and 76 % crosslinked system. Supplementary Figure S3C shows the volume shrinkages concerning the volume at 300 °C for 54 %, 63 % and 76 % crosslinked structures.

3 Manufacturing process

Gel creation, solvent exchange, and drying are the three processes used to manufacture aerogels, which involve chemical reactions, crosslinking, and sol-gel transformation (Dervin and Pillai 2017; Lebedev et al. 2021). Post-processing (hydrophilization, coating, etc.) is necessary during the gel-forming process to protect the microstructure and form from compaction and other alterations. This is done by moulding the final aerogel shape and moulding the subsequent aerogel's microstructure.

The gel formation process is based on well-known reactions of organic and/or inorganic components (Zuo et al. 2015). The key problem in the synthesis of EP-AGs is the preservation of the microstructure of the reaction. Large-scale aerogels now use solvents specifically designed for drying, eliminating the need for a solvent exchange. There is no industrially applicable state of the art for solvent exchange,

as water and CO₂ are only weakly miscible at low pressures and temperatures (Lebedev et al. 2021). Three methods of drying are possible: ambient temperature, supercritical pressure, or freeze-drying. Therefore, future development must focus on scaling up the solvent exchange process or using solvents that do not require solvent exchange.

The sol-gel approach has many advantages, such as increased chemical homogeneity, high surface area for gels or powders, high purity, quick and easy preparation of fibers, powders, coatings and spheres, low temperatures, moulding of gels into desired shapes, and shrinkage during drying and sintering (Baumann et al. 2011). Even though, the method has drawbacks such as long processing times, cracks from during drying, and expensive alkoxide precursors are required for high purity aerogels (Lyu et al. 2017; Kwon et al. 2021). A schematic diagram of the ER foaming process under CO₂, specimen manufacturing process (epoxy foam interface of EP-AG sandwich composites, EP foams cured at different temperatures and interfacial fracture of cured ER-AGs) are detailed in Supplementary Figure S4.

The ultra-low density and hydrophobic nature of aerogels pose challenges in their mixing with epoxy resins. Aerogel particles require careful encapsulation within polymeric resin to prevent infiltration. Stir-mixing is the primary method for crafting particulate composites, including aerogel composites. However, alternative techniques like pressure or vacuum-assisted infiltration risk resin infiltration into aerogel particles' nanosized pores, increasing the composite's density and posing a drawback (Gupta and Ricci 2008). Surface modification for epoxy resin compatibility is challenging due to open-cell porosity and high viscosity, which hinders effective infiltration and may enhance resin pore infiltration. Besides, attempts to modify aerogel surfaces may result in poor wetting behavior. Elevated viscosities cause inadequate wetting due to out-weighing adhesive forces between particles and matrix (Chen et al. 2021). Solvent addition reduces resin viscosity, improving mixing and wetting characteristics in aerogel-resin systems. However, this method introduces additional challenges during solvent removal, requiring careful consideration. Manufacturers suggest keeping the epoxy resin below a certain temperature threshold (50 °C) to prevent unintended self-polymerization. After solvent removal, the hardener was introduced for curing, causing a composite with significant porosity and poor quality (Payanda Konuk et al. 2023). This poor quality was likely due to residual acetone from the curing process, possibly due to solvent penetration into the aerogel's nanoporous structure. Despite multiple adjustments to heating time and curing schedule, no satisfactory results were achieved. The solution processing method demonstrated the potential for improved mixing by decreasing the viscosity of the matrix resin.

In a recent study, researchers aimed to develop fabrication methods for aerogel/epoxy composites, focusing on encapsulating aerogel particles within the epoxy resin without infiltration (Gupta and Ricci 2008). The study produced composites with 20–30 % aerogel volume, with lower density compared to resin, which has a density of 1,160 kg/m³. However, resin penetration was observed in the porous aerogel structure. The measured densities for three composite compositions were 980, 1,070, and 1,130 kg/m³. Compression tests were conducted on these composites to analyze their deformation and fracture behavior. The results revealed a compressive failure strain of over 25 % for the composites. Interestingly, higher-density composites exhibited a higher compressive modulus but a lower yield strength. This reduction in yield strength was attributed to early crack initiation observed in these specimens. Supplementary Figure S5 shows the processing and compressive properties of aerogel/epoxy composites (Gupta and Ricci 2008).

The study demonstrates the successful fabrication of ultra-light composites, but nanoscale pores within aerogel particles limit the weight reduction. However, the composites' behavior under compressive loading resembles other porous composites like syntactic foams, suggesting the potential for highly damage-tolerant ultra-light composites using aerogel particles.

4 Advanced applications of EP-AGs: challenges and overcoming strategies

EP-AGs have a wide range of applications across various industries due to their unique properties (Ge et al. 2009; Guzel Kaya et al. 2018; Pierre and Pajonk 2002). Some of the major applications include but are not limited to thermal insulation, acoustic insulation, lightweight structural components, energy storage, the oil and gas industry, environmental remediation, aerospace and defence, and electronics and sensors (Cao et al. 2022; Hassani and Dackermann 2023; Hebalkar et al. 2020).

EP-AGs are highly effective thermal insulators due to their low thermal conductivity (Vahtreus et al. 2017). They are used in applications where thermal insulation is crucial, such as in buildings, refrigeration systems, cryogenic storage, and insulation for pipelines and tanks (Siengchin 2023a). Their lightweight nature makes them advantageous for reducing energy consumption and improving thermal efficiency.

The porous structure of EP-AGs also lends them excellent acoustic insulation properties. They reduce noise

transmission in the automotive, aerospace, and construction industries (Back et al. 2018; Kucharek et al. 2020). EP-AGs improve noise control and comfort by minimising sound vibrations and absorbing acoustic energy. EP-AGs possess a high strength-to-weight ratio, making them suitable for lightweight structural components in various industries (Anirudh et al. 2022). They can be used in aerospace applications, such as aircraft interiors, where weight reduction is critical (Siengchin 2023a). EP-AGs also find applications in automotive components, marine structures, and sports equipment where lightweight materials are desired (Salimian et al. 2018).

EP-AGs have shown promise in energy storage applications, particularly in supercapacitors and batteries (Giménez Pérez et al. 2022). Their high surface area and porosity allow for efficient ion diffusion and storage, leading to enhanced energy storage capacity. This makes them suitable for use in portable electronics, electric vehicles, renewable energy systems, and grid storage. EP-AGs find applications in the oil and gas industry, particularly in subsea insulation systems and pipeline coatings (Kumar et al. 2021). Their excellent thermal insulation properties help maintain the temperature of transported fluids, reducing heat loss and energy requirements. They also provide corrosion protection and contribute to the integrity of offshore structures.

EP-AGs have been explored for environmental remediation applications, such as oil spill cleanup and water purification (Esmaili et al. 2018). Their high oil absorption capacity, buoyancy, and hydrophobicity make them effective in oil spill recovery efforts. Also, their porous structure allows for the adsorption of contaminants and pollutants from water, contributing to water treatment and remediation processes (Huang et al. 2022). EP-AGs are utilized in the aerospace and defence sectors for applications such as thermal protection systems, radars, and stealth coatings (Siengchin 2023b). Their exceptional thermal insulation, low dielectric constant, and radar-absorbing properties make them valuable in these high-performance applications.

EP-AGs have potential applications in electronics and sensors (Wei et al. 2017). Their high porosity and surface area make them suitable for gas sensors, humidity sensors, and chemical sensors (Wei et al. 2020). They can also be used as substrates for electronic devices, providing insulation and mechanical support. The unique combination of their properties, including low thermal conductivity, low density, sound absorption, and energy storage capabilities, make them highly versatile materials with potential across a wide range of industries. Supplementary Figure S6 shows the various industrial applications of epoxies.

Upscaling and cost-efficiency are significant challenges in the widespread adoption of EPAGs for all applications.

Traditional manufacturing methods, such as supercritical drying, are time-consuming and expensive, limiting large-scale production and commercial viability. It is important to explore alternative synthesis methods that are more scalable and cost-effective. Techniques such as ambient drying, freeze-drying, or microwave-assisted synthesis offer faster and more economical routes for producing EP-AGs. Optimization of raw material selection, process parameters, and post-treatment steps can ease the manufacturing process.

4.1 Thermal insulation

EP-AGs are promising materials for thermal insulation due to their low thermal conductivity and lightweight characteristics (Zhang et al. 2021). However, they face several challenges, such as limited flexibility and conformability, fragility, moisture absorption, upscaling and fire safety. Strategies to address these challenges include incorporating additives, improving mechanical robustness, enhancing hydrophobicity, exploring scalable and cost-effective synthesis methods, and incorporating flame retardant materials. EP-AGs have limited flexibility and conformability, making them difficult to fit into irregularly shaped surfaces or complex geometries, limiting their application in areas where seamless insulation is required (Shutov 1986). Additives and modifiers can improve the material's flexibility without compromising its thermal insulation properties, while alternative manufacturing methods such as spray-coating or layer-by-layer deposition can facilitate the application of EP-AGs on curved or irregular surfaces (Pack et al. 2020). EP-AGs are not durable or long-lasting in practical applications due to their fragility and susceptibility to impact damage. External causes like vibration, impact, or handling can cause particle breakage or structural damage, reducing the efficacy of thermal insulation. Reinforcing techniques such as fibres, nanoparticles or polymers (Muringayil Joseph et al. 2020; Rashid et al. 2024) can improve the mechanical properties and resistance to mechanical stress of the material (Arshad et al. 2021). Hybrid or composite materials that combine EP-AGs with other flexible or robust materials can also enhance the insulation system's strength and durability. EP-AGs are highly porous materials and tend to absorb moisture, compromising their thermal insulation performance over time. Moisture ingress can lead to issues such as mold growth, reduced mechanical properties, or degradation of the insulation material. Improving the hydrophobicity of EP-AGs can be the best solution to address moisture absorption (Ren et al. 2015). Surface modification techniques, such as coating the aerogels with hydrophobic materials or using chemical treatments to modify their

surface properties, also can significantly reduce moisture absorption (Sakhadeo and Patro 2022). Encapsulation techniques, such as using impermeable coatings or films, can provide an additional barrier against moisture ingress, ensuring long-term insulation performance.

Fire safety is a critical consideration in thermal insulation applications. EP-AGs, like other organic materials, are combustible and can contribute to the spread of fire if not adequately protected. To address fire safety concerns, it is necessary to investigate flame retardant additives or coatings that can be incorporated into the EP-AG matrix which can help improve the material's fire resistance and reduce its contribution to flame spread and smoke generation. Hybrid materials or composite structures that combine EP-AGs with inherently flame-retardant materials can provide enhanced fire protection for thermal insulation applications. By overcoming these challenges, EP-AGs can become more practical and effective solutions for thermal insulation, contributing to improved energy efficiency and sustainability (Ambika Devi et al. 2007b).

4.2 Acoustic insulation

The use of EP-AGs in acoustic insulation applications faces several challenges, including limited sound transmission loss, frequency dependency, mechanical stability, moisture sensitivity, cost and scalability due to their lightweight, porous structure and sound absorption properties. Such challenges need to be addressed to optimize their performance and practical use, in which one among them is the limited sound transmission loss capability. Although EP-AGs exhibit good sound absorption properties, they may not provide sufficient sound insulation performance, especially at higher frequencies or in the presence of heavy sound sources (Shi et al. 2022). One strategy is to optimize the composition and structure of EP-AGs to enhance their sound-blocking capabilities. This can be achieved by incorporating additional materials with higher density or sound-damping properties into the foam/aerogel matrix. Another approach is to develop hybrid structures by combining EP-AGs with other sound-insulating materials, such as barrier membranes or composite panels, to improve overall acoustic performance. EP-AGs typically exhibit frequency-dependent sound absorption behaviour, meaning their effectiveness varies across different frequency ranges (Adhika et al. 2020; Xu et al. 2017). Moreover, their sound absorption performance may be limited to a narrow bandwidth, reducing their effectiveness in wide frequency ranges. To address the frequency dependency and narrow bandwidth challenges, researchers are exploring the use of multi-layered or gradient

structures. By designing and optimizing the layering or grading of EP-AGs with different properties, a broader frequency range of sound absorption can be achieved. Besides, tuning the composition and pore size distribution of the foam/aerogel materials can help improve their broadband sound absorption capabilities. EP-AGs can be fragile and prone to mechanical damage, which may affect their long-term stability and durability in acoustic insulation applications (Embrey et al. 2017). External factors such as vibration, impact, or humidity can cause structural deformation or breakage, compromising the material's acoustic performance over time. To enhance the mechanical stability and durability of EP-AGs, studies are exploring reinforcement techniques. Incorporating reinforcing agents, such as fibres or polymers, into the foam/aerogel matrix can improve its mechanical properties and resistance to external stressors. Also, surface coatings or encapsulation methods can provide extra protection and prevent moisture ingress, ensuring long-term stability and acoustic performance.

EP-AGs can exhibit high moisture sensitivity and hygroscopic behaviour, which can lead to a reduction in their acoustic insulation properties (H. Liu et al. 2021). Moisture absorption can affect the material porosity and structure, altering its sound absorption characteristics. To address the moisture sensitivity and hygroscopicity challenges, studies can be focused on improving the hydrophobicity and moisture resistance of EP-AGs. Surface modification techniques, such as coating the materials with hydrophobic substances or incorporating moisture-resistant additives, can lessen moisture absorption and preserve the material's acoustic performance. Encapsulation methods, such as barrier coatings or films, can provide an additional layer of protection against moisture ingress. To overcome all these challenges, strategies such as optimizing the material composition and structure, incorporating additional sound-insulating materials, utilizing reinforcement techniques, improving hydrophobicity, and exploring cost-effective manufacturing methods can enhance the acoustic performance and practical use of EP-AGs in various industries.

4.3 Lightweight structural components

EP-AGs have garnered significant attention as potential materials for lightweight structural components due to their unique combination of low density, high porosity, and mechanical strength (Sun et al. 2022). Even though EP-AGs in lightweight structural components offer numerous advantages, several challenges need to be overcome to fully realize their potential which include limited mechanical strength, structural integrity and stability, fire resistance, durability

and environmental stability, and cost and upscaling that hinder their widespread use in this application. One of the primary challenges in using EP-AGs for lightweight structural components is their limited mechanical strength. Despite their low density, these materials may not possess sufficient strength to withstand the mechanical loads and stresses encountered in structural applications (Anirudh et al. 2022). To address this challenge, various reinforcement techniques have to be optimised. One strategy is to incorporate reinforcing materials, such as fibres or nanoparticles, into the EP-AGs matrix (X. Wu et al. 2021a). These reinforcements can enhance the mechanical properties and provide additional structural integrity. Another approach is to explore hybrid structures by combining EP-AGs with other lightweight materials, such as carbon fibres or polymer composites, to achieve a balance between strength and weight. EP-AGs are susceptible to structural deformation, compression, or collapse under prolonged loading or external forces (Chung et al. 2007; Odegard and Bandyopadhyay 2011). This poses a significant challenge in maintaining the structural integrity and stability of lightweight components made from these materials. To overcome this challenge, researchers are focusing on optimizing the foam/aerogel structure and architecture. By controlling the pore size, distribution, and connectivity within the material, it is possible to enhance its load-bearing capacity and structural stability. Besides, surface modifications or coatings can be applied to improve the interfacial bonding between the foam/aerogel and the surrounding matrix, enhancing the overall structural integrity (Maharsia et al. 2006). Fire resistance is a critical requirement for structural components in many applications (Mathews et al. 2022; Xia et al. 2022). However, EP-AGs are inherently flammable, limiting their use in situations where fire safety is a concern. To address the fire resistance challenge, researchers are exploring various approaches. One strategy involves incorporating fire retardant additives or coatings into the EP-AGs matrix to improve its fire resistance properties. Also, exploring alternative precursor materials or developing hybrid structures that incorporate inherently fire-resistant materials can enhance the overall fire performance of the lightweight components.

The long-term durability and environmental stability of EP-AGs are crucial considerations for their practical use in lightweight structural components (Jayalath et al. 2023). Exposure to environmental factors such as moisture, UV radiation, and temperature variations can lead to degradation and loss of mechanical properties over time. To enhance the durability and environmental stability of EP-AGs, studies have to be focused on improving their resistance to moisture, UV radiation, and temperature extremes. This can be

achieved through the use of surface coatings, protective layers, or chemical modifications that enhance the material's resistance to environmental degradation. Furthermore, thorough testing and accelerated ageing studies can help assess the long-term performance and stability of lightweight components made from EP-AGs. The cost-efficiency and upscaling pose challenges to the widespread use of EP-AGs in lightweight structural components (Smorygo et al. 2019). Advanced manufacturing methods, such as additive manufacturing or 3D printing, offer the potential for cost-effective and customizable production of lightweight components. Ongoing research and development efforts and promising strategies are being explored to address these challenges. By incorporating reinforcement techniques, optimizing the material structure, enhancing fire resistance, improving durability, and exploring advanced manufacturing methods, the use of EP-AGs in lightweight structural components can be significantly advanced.

4.3.1 Structural components for next-generation industrial machinery

The use of advanced materials in the manufacturing industry has become increasingly important to meet the demands of next-generation industrial machinery (Monie et al. 2021). EP-AG materials have gained attention due to their unique properties, which require scaling up production processes, optimizing processing techniques, standardizing testing methods, and promoting interdisciplinary collaborations. Accurate assessment of mechanical and thermal properties is essential for ensuring the reliability and safety of structural components. Industry-wide standards and guidelines can promote consistent quality, reliability, and performance of EP-AG materials in industrial applications. Government support, funding agencies, and industry partnerships are needed to promote research and development efforts. To address these challenges, scaling up production processes, optimizing processing techniques, standardizing testing methods, and promoting interdisciplinary collaborations are essential steps.

4.4 Energy storage applications

EP-AGs have gained attention as potential materials for energy storage applications due to their unique properties such as high porosity, low density, and excellent thermal stability (Pan et al. 2023). However, they face five major challenges: limited electrical conductivity, mechanical durability, ion diffusion and transport, thermal stability, and cost-

effectiveness. EP-AGs are used for energy storage, but their limited electrical conductivity limits their performance in applications that require efficient charge transfer, such as batteries and supercapacitors (Li et al. 2019). Adding conductive additives such as carbon nanotubes or graphene can improve the EP-AG structure. Surface functionalization techniques can also be used to enhance the interfacial contact between the EP-AGs and the active electrode materials, improving charge transfer efficiency. EP-AGs are fragile and prone to mechanical deformation, which also makes them difficult to use in energy storage applications. To improve their mechanical durability, reinforcement strategies, such as incorporating nanofibers (Li et al. 2019) into the EP-AGs which can enhance their mechanical properties and resistance to deformation are efficient (Dimchev et al. 2010; Zhou et al. 2022). Besides, combining EP-AGs with other mechanically robust materials can improve both mechanical and energy storage performance. Efficient ion diffusion and transport are essential for energy storage devices (Zhang et al. 2022). To achieve this, optimizing the pore structure of EP-AGs is necessary by controlling the pore size, distribution, and connectivity to enhance ion diffusion pathways and facilitate faster ion transport. Also, surface modification techniques can improve surface wettability and promote ion adsorption/desorption processes, improving energy storage performance. This will enable energy storage devices to perform better.

Thermal stability is essential for energy storage materials, particularly in high-temperature applications. EP-AGs may suffer thermal degradation or phase transitions, compromising their performance and longevity. The most important idea is to incorporate thermal stabilizers or flame-retardant additives into the EP-AGs matrix to improve its resistance to thermal degradation (Mohd Sabee et al. 2022). Composite structures with thermally stable materials or hybrid systems can also improve thermal stability. EP-AGs can revolutionize energy storage technologies by incorporating conductive additives, reinforcing the foam/aerogel matrix, optimizing pore structure, and exploring advanced manufacturing techniques which enable more efficient and sustainable energy storage systems.

4.5 Oil and gas industry

EP-AGs have potential for various applications in the oil and gas industry due to their unique properties, such as high porosity, low density, excellent thermal insulation, and chemical resistance (Cavasin et al. 2018; John and Reghunadhan Nair 2014). EP-AGs must meet temperature and pressure resistance, chemical compatibility, mechanical

durability, hydrocarbon fluid compatibility, scale-up, and manufacturing challenges to effectively utilize them in this demanding industry. The oil and gas industry operates under extreme temperature and pressure conditions, which can cause structural degradation, loss of insulation properties, and reduced mechanical strength (Mazzon et al. 2020). To overcome these challenges, approaches like incorporating high-temperature resistant additives into the EP-AGs matrix are highly promising. Optimizing the structure and exploring composite materials can improve the material's thermal stability and mechanical strength. The surface modification techniques and coatings ensure the chemical compatibility of EP-AGs to maintain their integrity and performance over time in oil and gas industry environments. Functionalizing the foam/aerogel surface or applying protective coatings can increase its resistance to chemical attack and degradation, and compatibility studies are essential to identify the optimal formulations and materials for specific applications (Lang et al. 2015; Mekonnen et al. 2021). The oil and gas industry requires materials to withstand mechanical stresses, vibration, and impact. EP-AGs are lightweight and highly porous but may lack sufficient mechanical durability for certain applications. To improve mechanical durability, reinforcement strategies can be used to incorporate structural fibres into the foam/aerogel matrix. Composite structures by combining EP-AGs with other mechanically robust materials can provide a synergistic effect and enhance both mechanical and functional properties.

EP-AGs must be compatible with hydrocarbon fluids in the oil and gas industry to avoid dimensional changes, loss of insulation properties, and reduced performance (El Gazzani et al. 2016). Surface modification techniques and coatings can reduce the absorption of hydrocarbon fluids and prevent their penetration into the foam/aerogel structure, while EP-AG materials with low affinity for hydrocarbons can minimize negative effects on performance. Scalability and cost-effectiveness are important considerations in the oil and gas industry. Interdisciplinary research efforts, including materials science, chemistry, and, engineering, are needed to address these challenges and unlock the full potential of EP-AGs in the oil and gas industry.

4.6 Environmental remediation

EP-AGs have gained attention as potential materials for environmental remediation due to their unique properties, such as high porosity, large surface area, and chemical stability (Quinayá and D'almeida 2017; Wei et al. 2020). They have shown promise in water and soil treatment, pollutant adsorption, and containment of hazardous substances. EP-

AGs offer great promise in environmental remediation, but several challenges need to be addressed to effectively utilize them which include contaminant selectivity, long-term stability, regeneration, and environmental impact and ecotoxicity (John and Reghunadhan Nair 2014). EP-AGs are challenging to use for environmental remediation due to their ability to selectively adsorb and retain specific contaminants, making it difficult to achieve high selectivity and capacity simultaneously. Functionalization techniques to enhance the surface chemistry of EP-AGs can introduce functional groups that enhance the material's affinity for target contaminants while minimizing interactions with unwanted substances. Also, composite structures or hybrid materials can be developed to improve the adsorption capacity and selectivity of EP-AGs and other selective adsorbents (Karaer Özmen et al. 2020). Environmental remediation processes require EP-AGs to maintain their effectiveness but may face challenges such as degradation, leaching of contaminants, and loss of mechanical strength and durability (Zhao et al. 2023). Encapsulating the foam/aerogel matrix with protective coatings or membranes can provide a barrier and improve its chemical and mechanical stability while understanding degradation mechanisms and optimizing formulation and processing parameters can lead to long-term performance (Ambika Devi et al. 2007a). EP-AGs require large-scale implementation, but and cost-efficiency are challenges. Advancements in manufacturing technologies can help reduce production costs by exploring more cost-effective precursor materials, improving synthesis efficiency, and optimizing material usage.

The ability to regenerate and reuse EP-AGs is essential for sustainable environmental remediation practices. Thermal treatment, solvent extraction, or advanced oxidation processes can be used to remove adsorbed contaminants from the foam/aerogel matrix (Coste et al. 2020). Surface regeneration techniques such as desorption-enhancing coatings and functionalization can help restore the material's adsorption capacity while exploring strategies for the recovery and reuse of desorbed contaminants can further enhance the sustainability of remediation. EP-AGs have potential for environmental remediation, but it is important to evaluate their potential impact and ecotoxicity to ensure safety and sustainability. Research should focus on assessing the fate, transport, and persistence of EP-AGs in the environment to address environmental impact and ecotoxicity concerns (Coste et al. 2020). Eco-design principles should be incorporated into material development to ensure sustainable use. Strategies such as surface functionalization, protective coatings, optimized synthesis methods, regeneration techniques, and comprehensive environmental assessments can help harness the full

potential of EP-AGs in environmental remediation applications.

4.7 Aerospace and defence

EP-AGs are a promising material for aerospace and defence applications due to their lightweight structure, high strength-to-weight ratio, thermal insulation, and mechanical properties (Nair et al. 2001). However, there are challenges to address such as structural integrity, thermal and fire resistance, manufacturing complexity, EMI shielding, and environmental compatibility (Kumar et al. 2016). Among the various challenges, one is to enhance the structural integrity and durability of EP-AGs in aerospace and defence applications. Reinforcing the foam/aerogel matrix with additives and optimizing formulation and processing parameters can improve mechanical strength and resistance to deformation. Advanced testing methods, such as mechanical, thermal, and accelerated ageing tests, can be used to evaluate the material's performance (Bunn and Mottram 1993). Aerospace and defence applications require materials with excellent thermal insulation and fire resistance properties. EP-AGs have inherent thermal insulation capabilities, but their flammability can be a challenge (Jin et al. 2023). Incorporating fire-retardant additives into the foam/aerogel matrix can improve their fire resistance properties. Multilayered or hybrid structures combining EP-AGs with other fire-resistant materials can improve thermal and fire performance, and advanced coating techniques and surface treatments can provide additional protection against high temperatures and flame propagation. The manufacturing complexity and scale-up of EP-AGs can pose challenges to their use in aerospace and defence applications. Advanced manufacturing techniques, such as 3D printing, are needed to simplify the production process and address these challenges. Optimizing formulation and processing parameters can help streamline the manufacturing process and ensure consistent material quality. Collaborations between academia, industry, and government agencies can facilitate the transfer of knowledge, resources, and expertise.

EP-AGs have limited EMI shielding capabilities due to their low electrical conductivity, making them ineffective for aerospace and defence applications (Chandra et al. 2019; S. Liu et al. 2021). Incorporating conductive fillers into the foam/aerogel matrix can improve electrical conductivity and EMI shielding effectiveness. Hybrid structures combining EP-AGs with conductive coatings or metallic layers can also enhance EMI shielding performance (Panahi-Sarmad et al. 2022). Optimizing the material's microstructure and porosity can

help maximize EMI attenuation (Gupta and Tai 2019). Xun Fan and his team developed a method for creating lightweight carbon-aerogel-based foams with an anisotropic carbon structure and excellent electromagnetic interference (EMI) performance (Fan et al. 2022). They used a step-by-step process called “gelation-press drying-impregnation & micro-foaming” to produce microcellular m-EP/rGO-SCF composites. The aerogel morphology transitioned from an isotropic honeycomb to an anisotropic corrugated structure, and density reduction was achieved using scCO₂ foaming. The resulting nanocomposite had low density, high electrical conductivity, enhanced compressibility, and exceptional EMI performance, highlighting its potential in various applications. Supplementary Figure S7 details the anisotropic microcellular epoxy/rGO-SCF aerogel foam with excellent compressibility and superior electromagnetic interference shielding performance.

Eco-friendly synthesis routes and renewable feedstocks for EP-AGs are needed to address environmental compatibility and sustainability challenges in aerospace and defence applications. This includes considering factors such as recyclability, biodegradability, and non-toxic components. Recycling and recovery methods can contribute to their circular economy, while life cycle assessments can provide insights into sustainability. Adopting strategies such as reinforcement techniques, fire-retardant additives, advanced manufacturing processes, conductive fillers, and sustainable approaches can help overcome the challenges of EP-AG integration in next-generation aerospace and defence systems (Monie et al. 2021).

4.8 Electronics and sensors

EP-AGs have gained attention for their potential applications in electronics and sensors due to their unique properties (Rand 1978). However, several challenges need to be addressed, such as electrical conductivity, moisture sensitivity, compatibility with integration processes, thermal management, and mechanical strength (Wouterson et al. 2007). Incorporating conductive fillers such as carbon nanotubes, graphene, or metallic nanoparticles into the foam/aerogel matrix can improve their electrical conductivity. Surface modification techniques can also create conductive pathways within the structure. Moisture sensitivity is a major challenge for EP-AGs in electronics and sensor applications, leading to decreased electrical performance and long-term degradation (Yang et al. 2021). Surface coatings or encapsulation techniques can provide a protective barrier against moisture ingress. Incorporating moisture-resistant additives and optimizing the curing process and post-processing treatments can improve the foam/aerogel matrix's moisture stability.

Compatibility with Integration Processes is one of the important parameters in electronics and sensor applications (Wei et al. 2017). EP-AGs must be compatible with common fabrication techniques such as printing, microfabrication, or chip packaging to enable seamless integration into electronic devices and sensor systems. Tailoring the material's rheological properties and developing novel bonding methods or adhesives for foam/aerogel integration can ensure reliable and robust assembly.

Studies are exploring strategies to improve the thermal conductivity of EP-AGs to address the thermal management challenge in electronic devices. EP-AGs possess excellent thermal insulation properties but can be challenging in applications that require efficient heat dissipation. Incorporating thermally conductive fillers and developing hybrid structures combining foam/aerogels with thermally conductive materials can improve thermal performance (P. Liu et al. 2022). Optimizing the foam/aerogel microstructure and pore size can facilitate heat transport through the material.

EP-AGs are essential for long-term performance in electronics and sensor applications, but their low-density nature can reduce mechanical strength and susceptibility to mechanical deformation or damage. To enhance mechanical strength and reliability, researchers are exploring reinforcement techniques (Li and John 2008). Reinforcing fibers or nanoparticles can improve the foam/aerogel matrix's mechanical properties while optimizing the curing process and post-treatment methods can improve its structural integrity and resistance to deformation. Incorporating conductive fillers, moisture-resistant additives, optimized fabrication processes, enhanced thermal conductivity, and reinforcement techniques can help overcome these challenges (Li and John 2008).

4.9 Adsorbents

EP-AGs face challenges in stability and durability due to their susceptibility to extreme temperatures, high humidity, and other harsh environmental conditions. This can lead to degradation or loss of structural integrity, affecting their adsorption capabilities (Khan et al. 2024). A comprehensive approach involving technological innovations and methodological improvements is needed to tackle these challenges. Efficient synthesis techniques are crucial for consistent quality and performance across larger batches. Material design advancements, including stabilizing additives or polymer matrix modifications, can improve environmental stability and durability.

Understanding the adsorption mechanisms of EP-AGs is crucial for optimizing material formulations and improving

efficiency, as research on interactions between adsorbates and porous structure could enhance performance (Garg et al. 2023). Computational modeling and simulation are essential for predicting material behavior and developing next-generation adsorbents (Malloum et al. 2023). They allow researchers to simulate conditions and optimize properties before production. However, bridging the gap between theoretical potential and practical application requires collaboration among researchers, manufacturers, and end-users. Aligning research objectives with practical needs and addressing economic constraints and performance challenges is crucial for developing robust solutions.

5 The current state of the industry and key market segmentation

Aerogels are ultra-lightweight materials with up to 99.98 vol% porosity that can be used to create lightweight composite materials. However, they are difficult to mix with EPNs due to their low density and hydrophobic character. Aerogel composites are used to enclose aerogel particles in EPN without penetrating them. They are subjected to compression testing and their fracture behavior and deformation are interesting. Only a few of these types are now marketed (X. Wu et al. 2021a). Aerogels are used in the construction industry for thermal insulation, but further applications are being explored in the fields of absorber, supercapacitor, and carrier and filler material (Maharsia et al. 2006).

Cases resulting in extremely low-weights:

- Laptop computers, smartphones, and other portable electronics cases must be lightweight and shock-resistant to ensure ease of use.
- Epoxy foam can be moulded into pieces less than 1 mm thick, curve, and have local thickness variations due to its ultra-thin and free-form moulding characteristics.
- An integrated moulded structure made of foam cores to create electronic boxes that are lighter and more shock-absorbent than standard versions.
- Structural components for next-generation automobiles
- The car industry is replacing metals to conserve energy.
- Epoxy foam absorbs stress and speeds up production, while also providing qualities to vehicle structural components that metals cannot.

The use of thermoset foams is becoming increasingly important in business industries, such as automotive, electrical, marine, aviation, and spacecraft. Examples of thermoset foams include polyurethane, phenolic, and epoxy. They

provide great solvent resistance, thermal stability, flame resistance, and drip-free burning. Polyurethane is widely used in construction, transportation, and furniture, but isocyanate exposure during processing can irritate, tightness in the chest, and breathing problems. Phenolic foams are less popular due to their fragility and the negative consequences of residual formaldehyde. EP-AGs can be created in one stage, combining foaming and curing from viscous resins to solid foams. Switching the epoxy-hardener ratio can offer a range of moduli, from viscoelastic to stiff. The resin direct foaming procedure involves both foaming and curing, with early cured, gel, and fully cured being the three stages. The epoxy-hardener combination's blowing agent and rheological characteristics have a major impact on the foaming process.

Aerogels are being used in numerous end-use industries, such as aerospace and construction, to manufacture wetsuits and spacesuits, as well as superlight concrete and wall insulators. This is leading to strong growth in the market. Aerogel is a key component in fire suits, spacecraft, vehicles, electronics, oil and gas industries due to its thermal insulation and other advantages. Leading vendors are increasing their budget for R&D activities to introduce polymer-based aerogels with enhanced strength and flexibility, which are expected to expand their consumer base and market share, leading to market growth (Benderly et al. 2004). Silica aerogel dominates the global aerogel market, with blanket accounting for most of the market share, with North America leading the way.

The global aerogel market is experiencing steady growth due to increasing demand across sectors like oil & gas, construction, automotive, and aerospace. These materials are favored for their thermal insulation, lightweight properties, and high surface area. The trend is expected to continue due to ongoing research, manufacturing advancements, and environmental awareness. Green building standards and energy efficiency regulations are also expected to further boost global demand for aerogels. The aerogel industry is primarily concentrated in North America, Europe, Asia Pacific, Latin America, and the Middle East & Africa. North America and Europe have historically been dominant due to their strong manufacturers, technology advancements, and infrastructure ("Aerogel Market - Share, Size & Industry Analysis" n.d.). However, the Asia Pacific region is experiencing significant growth due to the growing construction and automotive sectors, while the Middle East & Africa region is expected to see substantial growth. The global aerogel market faces processing challenges due to the intricate manufacturing process, high production costs, and limited scalability. The fragility of aerogels during handling and transportation also poses challenges. However, ongoing research focusing on cost-effective production techniques

and improving aerogel mechanical characteristics is expected to alleviate these issues. Silica aerogels are widely used due to their thermal insulation and versatility. Carbon aerogels are used in energy storage and electronics due to their high surface area and electrical conductivity. Polymer aerogels, like epoxy foam, are lightweight and flexible, making them ideal for insulation and cushioning.

Leading aerogel sector enterprises like Aspen Aerogels, Cabot Corporation, Aerogel Technologies, BASF SE, and Guangdong Alison Hi-Tech Co., Ltd (“Aerogel Companies - Top Company List” n.d.) are actively involved in research, development, product innovation, strategic alliances, and mergers and acquisitions to strengthen their market position and gain a competitive edge. The aerogel industry involves synthesis, drying, modification, and application. The synthesis starts with precursor preparation, followed by gelation and aging. Drying removes solvent, often using supercritical techniques. Modification focuses on surface functionalization or doping to enhance properties. Applications include thermal insulation, acoustic insulation, energy storage, electronics, and healthcare. Aerogel materials are versatile and useful across various industries.

The aerogel industry involves a complex value chain, starting with sourcing raw materials like silica precursors, carbon precursors, and polymers. The process includes preparation, gelation, and drying, often managed by specialized manufacturers. The processed aerogels are then distributed to end-users through distributors and retailers, used in various sectors like construction, automotive, aerospace, electronics, and healthcare. The aerogel market is driven by increasing demand for energy-efficient materials, strict building regulations, environmental sustainability awareness, and technological advancements. Aerogels offer thermal insulation, lightweight properties, and environmental performance, attracting adoption across industries. However, challenges like high production costs, intricate processing requirements, and limited scalability hinder market growth.

The global aerogel market is dominated by established players like Aspen Aerogels, Cabot Corporation, and Aerogel Technologies, who use their extensive product portfolios, technological prowess, and extensive distribution networks to dominate the industry. They invest heavily in research and development to introduce innovative products and gain a competitive advantage. Key players also use strategic partnerships to expand their market footprint and enhance their product offerings. The global aerogel market is highly competitive, with key players vying for supremacy based on product quality, pricing strategies, innovation, and customer service. This intense rivalry drives frequent product launches, technological breakthroughs, and strategic

collaborations. The threat of new entrants and substitute materials further challenges incumbent players, prompting them to innovate and differentiate their offerings. The aerogel market is characterized by dynamism, growth opportunities, and evolving consumer demands and technological advancements.

6 Challenges in EP-AGs business

EP-AGs have been found in the 1930s, but have not yet achieved commercial success. Significant growth has occurred since the turn of the century, but the sector has paused before further expansion. Construction and building, such as hydrophobicity, lightweight installation, potential fire retardancy, and superior thermal insulation properties highlights the possibilities EP-AGs (Yang et al. 2023). IDTechEx forecasts that the market-size for aerogel manufactures will return to growth and reach \$530 million by 2029 (X. Wu et al. 2021b). EP-AGs for advanced materials and other developing technologies are a research area that includes a technical analysis of the sector, including company profiles, market estimates, production solutions, material benchmarking, and more (X. Wu et al. 2021b; Zhang et al. 2021). Silica aerogels and their application as composite blankets dominate the business. The EP-AGs sector is predicted to increase due to a comeback of usage, expansion into new areas, and new market entrants or technological advancements (Di Maio and Kiran 2018). The industry is facing many challenges and what is being done to address them is discussed below.

- (1) **Production method:** Epoxy/aerogel composites can be made by mechanically whipping air into EPN, mixing curing and foaming chemicals with EPN, or using chemical foaming agents. Each method has its challenges in terms of cost and engineering. Cabot Corporation’s creation of a production facility propelled competitive ambient pressure drying for aerogel particles to the commercial front, highlighting the need for supercritical drying advancements. Technology advancements such as continuous processes and recycled feedstocks are being used to improve the supercritical process and reduce costs. Alternative techniques such as ambient pressure drying, freeze-drying, and 3D printing are also being researched.
- (2) **Material feedstocks:** Material feedstocks are often overlooked, but they can have a significant impact on prices. For example, a major aerogel producer attributed 40–50 % of their product sales to material expenses.

- (3) Technical advancements: The use of less expensive materials, such as waste or natural resources, is being explored to save expenses and improve environmental sustainability.
- (4) Material durability: The biggest drawback is their fragility. To give structural integrity, additional components must be added during gelation or after processing. Besides, post-processing techniques have been created to enable the porous structure to resist a variety of environmental conditions.
- (5) Technical progress: Silica aerogels are being used to create hybrid parts with varying structural performance. Polymer aerogels, such as polyimides, polyureas, polyurethanes, and polyamides, are being developed with good mechanical performance in monolithic panels or thin films.
- (6) Market drivers and economics: The aerogel industry has had many false starts, with BASF's Basogel ceasing production in 1996. These setbacks have been related to identifying market needs and competitive pricing. Aerogels are thermally insulating materials with a higher cost than other materials. However, there are applications where a cost/benefit analysis indicates that the superior insulating properties of aerogels are worth their higher cost. Aerogel powders, such as Quartzene, which can be used as additives for EP-AGs and other materials, are commercially available.
- (7) Technical progress: Capacity expansions, end-user awareness, market requirements, and technical advancements are helping to diversify the market.

Europe is an important target market due to legal restrictions, land price premiums, and ageing structures. BASF and Aspen Aerogel have collaborated to develop Slentex, a non-combustible building material with a thermal conductivity of 19 mW/mK at 10 °C.

6.1 Recycling of epoxy-based aerogels

Recycling EP-AGs, known for their mechanical strength, thermal insulation, and chemical resistance, is a crucial and growing task in sustainable materials management, particularly in industries like aerospace, automotive, and construction (Gharde and Kandasubramanian 2019; Klose et al. 2023). EP-AGs, due to their durability and cross-linked polymer structure, are difficult to recycle conventionally. As environmental concerns and waste management regulations increase, the need for effective recycling solutions for EP-AGs becomes more urgent.

Chemical recycling is a method being explored for recycling EP-AGs. This involves breaking down the cross-linked network of the epoxy polymer into its original monomers or other useful chemicals, typically using acids, bases, or solvents to depolymerize the epoxy resin (Chanda 2021). Solvolysis is a method where solvents like glycol, alcohols, or water are used to break down chemical bonds in epoxy networks, resulting in a mixture of small molecules like BPA and epichlorohydrin (Yang et al. 2012). This can be purified and reused as raw materials for new epoxy resins, contributing to the circular economy by diverting waste from landfills and recovering valuable chemicals.

Mechanical recycling is a method of recycling EP-AGs, where the foam is broken down into smaller pieces or ground into powder. These recycled particles can be used as fillers or reinforcement in new polymeric materials, including fresh epoxy formulations (Lucignano et al. 2011). This method is less complex and environmentally friendly. Mechanical recycling has limitations due to the potential degradation of mechanical properties in the recycled product due to particle size and distribution. However, when combined with advanced processing techniques, it remains a viable option for improving the dispersion and integration of recycled particles into new polymer matrices.

Thermal recycling processes like pyrolysis or thermal depolymerization are gaining attention for their ability to convert waste EP-AGs into smaller hydrocarbons, gases, and char (Laredo et al. 2023). This process occurs without oxygen and is particularly effective in converting EP-AGs into oil-like substances that can be used as chemical feedstocks or fuel. Thermal recycling uses char as a carbon-rich material for various applications, including composite material filler and energy source (Amalina et al. 2022). It handles heavily contaminated waste streams, making it easier to process than chemical or mechanical methods. However, it requires significant energy input and may release harmful byproducts, which must be managed carefully.

Reprocessable epoxy systems are a new method for recycling EP-AGs, offering a more efficient recycling process than traditional thermosetting resins. These systems incorporate dynamic covalent bonds that can be broken and reformed under specific conditions, enabling reshaping, repair, or complete reprocessing into new forms (Jin et al. 2019). Reprocessable epoxies, despite being in their early stages of development and not yet widely adopted in industrial applications, offer a promising future for epoxy foam recycling by simplifying recycling and reducing the environmental impact of EP-AGs, potentially addressing sustainability challenges in epoxy-based products. Supplementary Figure S8 details the recycling of EP-AGs.

Recycling EP-AGs presents significant challenges due to their durability and resistance to degradation. The cross-linked structure and diverse formulations used in different applications also complicate recycling efforts (Fortman et al. 2018). Standardized recycling processes are difficult to develop due to the variability in waste epoxy foam composition. The economic viability of recycling methods is crucial, as chemical and thermal processes can be expensive compared to virgin materials. To make recycling more attractive, further research is needed to enhance efficiency and cost-effectiveness, as well as develop new technologies to overcome challenges in recycling cross-linked polymers. The recycling of EP-AGs is a crucial aspect of sustainable materials management, as demand for durable, high-performance materials increases. To ease the environmental impact, innovative epoxy technologies in chemical, mechanical, thermal, and reprocessible sectors can be developed. This can reduce waste, recover valuable resources, and contribute to a circular economy in the polymer industry, ultimately reducing waste and promoting a more sustainable approach.

6.1.1 Recycling technologies for epoxy aerogels: industrial perspectives and challenges

The need for eco-friendly industrial waste management solutions necessitates advanced recycling methods for epoxy aerogels. These complex, crosslinked polymer networks make it challenging to retrieve high-quality materials. Advanced methods like microwave-assisted procedures, catalytic depolymerization, and supercritical fluid recycling can provide a focused and effective breakdown of these polymers (Tian et al. 2019). The recovery of crucial monomers or oligomers through closed-loop recycling is a key aspect of a circular economy, aiming to minimize energy consumption and harsh chemicals (Zhao et al. 2024). These technologies are becoming increasingly necessary for companies to meet environmental standards and reduce waste, as sustainability remains a top priority. This approach not only reduces environmental impact but also promotes a more sustainable future.

Advanced methods for recycling epoxy-based aerogels include catalytic depolymerization, photocatalytic recycling, electrochemical recycling, microwave-assisted recycling, biocatalytic recycling, advanced solvent systems, ultrasonic-assisted recycling and plasma-assisted recycling, each with unique mechanisms and advantages (Dağlar et al. n.d.; Dattilo et al. 2022; Kang et al. 2022; Liu et al. 2020; Menon et al. 2024). Supercritical fluid recycling utilizes supercritical CO₂'s unique properties to disintegrate polymer chains at low temperatures, while catalytic depolymerization uses catalysts to reduce activation energy. Electrochemical and

microwave-assisted recycling utilize microwaves' localized heating for depolymerization. Electrolysis drives redox processes, breaking down the polymer network. Environmentally friendly biocatalytic recycling uses enzymes for selective depolymerization, while innovative solvent systems dissolve and break down specific polymer matrix components. Plasma-assisted recycling uses chemical reactions to depolymerize materials at low temperatures, while ultrasonic-assisted recycling uses high-frequency sound waves to disrupt polymer networks. Photocatalytic recycling uses light-triggered catalysts to drive chemical processes within a polymer matrix, providing an interesting method for recovering materials.

Recycling technologies show promise but face challenges like finding efficient systems, creating long-lasting catalysts or solvents, and perfecting reaction conditions for diverse epoxy aerogels (Cui et al. 2025; Parale et al. 2024). Current research is focused on improving efficiency, selectivity, and environmental friendliness. Future advanced systems may be created by integrating these technologies with existing processes or one another. The table provides a comprehensive overview of various techniques for recycling epoxy-based aerogels, detailing their mechanics, industrial benefits, problems, and potential future uses, based on the provided section. Here is a summarized table based on the provided section on various advanced technologies for recycling epoxy-based aerogels. This table captures the essence of each technology, focusing on key points related to their mechanisms, industrial advantages, challenges, and future directions (Table 3).

6.2 Upcycling of waste epoxy thermosets

The research on upcycling waste epoxy foams is crucial due to their non-biodegradable nature and environmental concerns. Despite their superior mechanical and thermal properties, these foams often pose challenges at the end of their life cycle. Upcycling offers a promising solution to mitigate these environmental impacts by converting waste epoxy foams into high-value products (Wang et al. 2023; Zhao et al. 2023). Chemical recycling is a crucial strategy for upcycling waste EP-AGs (Türel and Tomović 2023). This involves breaking down the foam into its components, which can be reused to create new polymeric materials through solvolysis, a method using solvents like alcohols, acids, or bases. Depolymerized products like polyols or BPA can be purified and reused as raw materials in the production of new polymeric products, reducing waste and recovering valuable chemicals, contributing to a circular economy model in polymer manufacturing (F. Highmoore et al. 2024).

Table 3: Summary of advanced technologies for recycling epoxy-based aerogels, focusing on their mechanisms, industrial advantages, challenges, and future directions, while also highlighting their industrial advantages and challenges (Cui et al. 2025; Dağlar et al.; Dattilo et al. 2022; Kang et al. 2022; Liu et al. 2020; Menon et al. 2024; Parale et al. 2024).

Technology	Introduction	Mechanism	Industrial applications & advantages	Challenges & future directions
Catalytic depolymerization	Destroys epoxy networks selectively using catalysts	Reduces activation energy by targeting certain bonds using homogeneous or heterogeneous catalysts	Optimal for recovering high-purity monomers and oligomers; energy-efficient; selective; compatible with current recycling infrastructure	Method is in its early stages. There are obstacles to scalability and catalyst stability, and it requires selected and cost-effective catalysts
Supercritical fluid recycling	Using CO ₂ and other supercritical fluids, it breaks down epoxy aerogels	It is common to use co-solvents or catalysts to speed up the break-down process since supercritical CO ₂ expands and enters the polymer	Does not produce any harmful byproducts, may be used with a variety of epoxy kinds, and operates at low temperatures	The continuing quest for more cost-effective solutions, the high capital and operating expenses, and the need for specialist equipment
Microwave-assisted recycling	Degrades the polymer matrix by heating it with microwave radiation	Heat is produced by dielectric loss in microwaves, which leads to bond scission; additives and catalysts that absorb microwaves promote this process	Optimal for continuous processing, quick and selective heating, shorter processing durations, less over-degradation	Possible uneven heating, difficulties with specialist equipment, and the need for optimization of various materials
Electrochemical recycling	Used electrochemical processes to degrade epoxy aerogels	Initiates redox processes using electrolysis, which in turn cleaves polymer chains on the surfaces of electrodes	Scalability, minimal side effects, operation at room temperature, and precise control of depolymerization	Investigation into renewable energy integration, improvement of cell design and electrolyte composition, and the use of long-lasting electrode materials are all necessary
Biocatalytic recycling	Degrades the polymer network using enzymes or whole-cell biocatalysts	In moderate environments, enzymes and biocatalysts accelerate the breaking of bonds	Low energy usage, great selectivity for selective depolymerization, and operation in moderate environments	Research on strong enzymes and biocatalysts derived from entire cells is necessary due to slow reaction rates and the possibility of enzyme deactivation
Advanced solvent systems	Improves chemical recycling by using innovative solvent systems	Depolymerizes particular bonds using polar solvents, ionic liquids, etc.	Works with a variety of epoxy formulas, runs cool, and is compatible with eco-friendly procedures	Research on task-specific solvents, the cost and availability of specialist solvents, and the environmental effects of solvent disposal
Ultrasonic-assisted recycling	Boosts depolymerization with the use of high-frequency sound waves	To break polymer chains, ultrasound produces cavitation, which is a localized increase in pressure and temperature	Improves solvent/catalyst penetration, shortens depolymerization time, and boosts chemical recycling efficiency	Deterioration of equipment, need for exact control, investigation into the most effective ultrasonic settings, and combination with other technologies
Plasma-assisted recycling	Uses plasma with high energy to degrade polymer networks	Reactive species produced by plasma cause bond scission at atmospheric pressure and temperature	Quick and effective depolymerization; selective degradation; compatible with environmentally friendly chemistry	Research on scalable, cost-effective plasma systems; the complexity and expense of plasma equipment; the need for exact control
Photocatalytic recycling	Catalyzes the degradation of polymers using light-activated molecules	Light activates a photocatalyst, such as TiO ₂ , which causes redox processes to occur in the polymer	Low impact on the environment, works at room temperature, and can exhibit high selectivity	Constraints include using only photocatalytic materials, continuing to investigate efficient photocatalysts, and ensuring process scalability

The upcycling of waste EP-AGs involves incorporating recycled foam into composite materials (Lucignano et al. 2011; Podara et al. 2024). This involves mechanically shredded or ground waste foam into fine particles, which are mixed with fresh resin or polymers to create reinforced composites. These composites are versatile and suitable for

construction, automotive components, and aerospace lightweight panels. The use of recycled foam particles in composites can enhance properties like impact resistance and thermal insulation, while also reducing material costs by replacing virgin polymer with recycled content.

Thermal reprocessing is a method for upcycling waste EP-AGs, especially those that cannot be chemically recycled due to additives or fillers. This involves controlled pyrolysis or thermal degradation, where the foam is heated in an inert atmosphere to break down the polymer matrix into smaller molecules (Bifulco et al. 2024; Ma et al. 2017). Thermal reprocessing of byproducts of epoxy resin can be used as fuels, chemical feedstocks, or fillers in various industrial processes, reducing the environmental footprint of waste disposal by recovering energy and useful materials.

Researchers are exploring the upcycling of waste EP-AGs into functional materials with added value (Gusel'nikova et al. 2023). Waste EP-AGs can be transformed into porous carbon structures with high surface area and tunable properties, making them suitable for energy storage, catalysis, and water purification (Smorygo et al. 2018; Szeluga et al. 2018). This approach diverts waste from landfills and creates high-performance materials that contribute to sustainability in other sectors, thereby reducing the need for landfills.

A study reported that high-efficiency and energy-saving conversion of epoxy thermosets into “three-high” (high value, high quality and high performance) products is highly desired from the viewpoints of both environmental protection and resource utilization (Zhao et al. 2023). Here, the study demonstrates a new strategy for mild degradation of epoxy thermosets and *in situ* preparation of polyurethane foam from degradation solutions. The degradation solution contains the unreacted solvent polyethylene glycol and polyol degradation products after alcoholysis, both of which can react with isocyanate to produce polyurethane. The use of an insoluble catalyst makes it possible to achieve *in-situ* foaming of the degradation solution, which realizes the direct and full utilization of degradation products. Owing to the rigid epoxy skeleton of the degradation products, the obtained rigid polyurethane foam exhibited high mechanical properties (~170 kPa), good thermal insulation performance (33–35 mW m⁻¹ K⁻¹), low water absorption (3–5 %), regular pore structure and good thermal stability, thus can be a good candidate for building insulation materials. Supplementary Figure S9 details the graphical representation showing the upcycling of waste epoxy thermosets to robust polyurethane foams via an *in situ* degradation-foaming process.

The upcycling of waste EP-AGs presents significant challenges due to the variability in their composition, particularly in different applications and with varying additives and fillers. The economic feasibility of waste foam

recycling processes is crucial, as the costs of collecting, processing, and upcycling must compete with virgin material production. Advances in sorting and processing technologies and efficient upcycling methods are necessary to overcome these challenges. Upcycling waste EP-AGs offers a promising solution to environmental challenges by transforming them into new products or valuable materials. This not only reduces the environmental impact of EP-AGs but also contributes to a more sustainable and circular economy in the polymer industry.

6.3 Epoxy foams/aerogels in medicine: opportunities and challenges

EP-AGs and aerogels have significant potential in medical applications, especially in biocompatible implants, wound care, and controlled drug delivery systems (Stastny et al. 2018; White et al. 1986; Yang et al. 2014). They can mimic bone's mechanical properties, making them ideal for orthopedic implants (Bagares et al. 2022). Their porosity can improve osseointegration, promoting bone cell and blood vessel infiltration for long-term stability (Petersen 2014). Epoxy based nanocomposites can be impregnated with bioactive agents, serving as structural supports and localized drug delivery systems (Borah et al. 2023). They offer breathability and moisture management, making them effective for dressings in chronic wounds or burns (Z. Tang et al. 2024). The surface can be functionalized with antimicrobial agents, protecting against infections and maintaining a stable temperature, aiding pain reduction and tissue regeneration. Application of epoxy resin to a solid-foam pelvic model: creating a dry-erase pelvis has also been reported (Weaver et al. 2014).

Epoxies generally offer controlled drug delivery due to their porous structure, enabling significant drug loading and release, making them useful in managing chronic diseases (Harismah et al. 2022; Maltas et al. 2013). These materials can be engineered to respond to specific stimuli for targeted and sustained delivery. They are being used in diagnostic and therapeutic devices due to their lightweight and high surface area, improving biosensor sensitivity (Arora et al. 2009; Galán-Vidal et al. 1997) and wearable device comfort (Godzierz et al. 2024; Stennermann et al. 2022). It is crucial for the development and commercialization of epoxy-based medical devices while maintaining performance.

6.3.1 Health effects

Epoxy if not being fully dried when sanded can pose serious health risks to human beings (Gul et al. 2016). Epichlorohydrin is a reactive chemical that can irritate the airways or

trigger allergic reactions. Modern EPNs contain less epichlorohydrin, but when exposed to DDS, laboratory animals develop cancer (Luo et al. 2003). DDS is a curing chemical used in many EPN systems which processes adverse health impacts (Gao et al. 2022). Experimental animals get genetic alterations due to certain glycidyl ethers used in EPNs. To prevent respiratory discomfort from breathing in extremely concentrated epoxy fumes for an extended period, wear a respirator mask (Fiore and Valenza 2013). Exposure to these gases can cause inflammation and irritation of the nose, throat, and lungs, and can lead to hypersensitivity and asthma.

6.4 Biobased epoxy foams: advances, applications, and challenges

Biobased EP-AGs are a sustainable alternative to petroleum-based epoxies, produced from renewable sources like vegetable oils and lignin (Ebrahimnezhad-Khaljiri and Ghadi 2024; Khundamri et al. 2019). These eco-friendly foams offer high-performance applications without compromising mechanical and thermal properties, making them a significant advancement in sustainable material development. Biobased EP-AGs are being developed to reduce environmental impact by reducing carbon footprints and reliance on fossil fuels. This shift is driven by regulatory pressures and societal demands for greener technologies. Biobased EP-AGs also offer improved biodegradability, potentially reducing long-term waste buildup in landfills, a significant drawback of traditional EP-AGs.

The development of efficient and scalable techniques for synthesizing bio-resins, typically derived from plant-based oils like castor, soybean, or linseed oil, has revolutionized the production of biobased EP-AGs, which can cross-link into foam structures (Gupta et al. 2011; Negrell et al. 2017a). Studies have improved the reactivity and functionality of bio-resins, enabling them to match or surpass traditional epoxies performance standards. Advances in catalysts and curing agents have improved the mechanical strength, thermal stability, and flame retardancy of biobased EP-AGs, broadening their applicability across industries. Incorporating fillers like cellulose nanofibers, starch, or biochar has further enhanced these foams' mechanical properties. Supplementary Figure S10 details the preparation, intrinsic flame retardancy, high rigidity and hydrophobicity, glass transition temperature, processability and flame retardancy of epoxy resin.

Biobased EP-AGs offer significant environmental and health benefits compared to traditional EP-AGs, which are produced from petrochemicals and contribute to the unsustainability and release of volatile organic compounds (Agbo

et al. 2023; Altuna et al. 2015; Baroncini et al. 2016). Biobased epoxies have cleaner production processes, resulting in lower VOC emissions and a reduced overall environmental footprint (Negrell et al. 2017b). Since biobased materials are becoming increasingly popular due to their biocompatibility and lower toxicity, making them ideal for sensitive applications like medical devices and consumer products, this shift is driven by environmental sustainability and the growing demand for safer, healthier products that meet stringent regulatory standards across various industries.

Biobased EP-AGs are gaining popularity in various industries like automotive, construction, packaging, and aerospace due to their lightweight yet strong properties. These foams are used in structural components, thermal insulation, and noise-damping applications due to their mechanical and thermal properties (Esmaeili et al. 2018; Ramon et al. 2018). Biobased EP-AGs are being used in construction and packaging as insulation materials due to their thermal resistance and fire retardancy, and as a sustainable alternative to conventional foams, particularly in protective packaging for biodegradability and waste reduction (Supplementary Figure S11).

Biobased EP-AGs have made significant progress, but challenges persist, particularly in achieving consistent mechanical performance during large-scale production due to variability in bio-based feedstocks, unlike petrochemical-based epoxies, which typically exhibit uniformity due to chemical consistency in raw materials. Biobased foams have improved their thermal and mechanical properties, but they often fall short of traditional EP-AGs' performance levels, particularly in demanding environments requiring high thermal resistance or significant load-bearing capacity. Biobased EP-AGs face production challenges due to limited feedstock availability and chemical processing, necessitating economies of scale advancements and efficient production research for economic competitiveness.

The durability and biodegradability of biobased EP-AGs are still under investigation due to challenges in achieving biodegradability without sacrificing performance. Many biobased materials rely on synthetic curing agents and additives, making it difficult to fully realize their environmental advantages. Natural fillers and fibers in biobased EP-AGs can enhance mechanical reinforcement but may cause moisture sensitivity, potentially compromising durability in high-humidity or wet conditions. Future developments should focus on optimizing performance and environmental sustainability through innovative materials chemistry and advanced production techniques. Biobased EP-AGs offer a safer, healthier alternative to petroleum-based epoxies, but challenges like cost, and material performance need to be addressed for widespread adoption.

6.5 Carbon emissions of epoxy and epoxy foams

The remarkable mechanical qualities, chemical resistance, and adaptability of epoxy resins and foams make them extensively used in several sectors (Gencel et al. 2024; Mazzon et al. 2015). These materials find employment in coatings, structural composites, insulation, and more. Nevertheless, there are substantial environmental consequences linked to their manufacture, use, and disposal, especially in regards to carbon emissions. To comprehend these effects, one must investigate epoxy resins and foams throughout their whole life cycle, beginning with the extraction of raw materials and ending with recycling or disposal.

6.5.1 Production of epoxy resins and epoxy foams: carbon footprint analysis

Bisphenol A (BPA) and epichlorohydrin are the primary basic ingredients extracted and processed to make epoxy resins. The manufacturing of bisphenol A (BPA) is a major contributor to global warming since it relies on energy-intensive procedures that start with feedstocks obtained from petroleum. Another essential component, epichlorohydrin, is usually synthesized by chlorinating propylene, which is a method that uses fossil fuels and produces a lot of carbon dioxide (CO₂). Due to the energy needed for these chemical reactions and the emissions from related transportation and industrial activities, the manufacture of epoxy resins leaves a significant carbon footprint.

The carbon emissions from these materials are amplified when you use EP-AGs, which are created by mixing a foaming agent with epoxy resin. Foaming agents, like blowing agents, are made using chemicals like hydrocarbons, which have their carbon footprints and, if not controlled, may produce powerful greenhouse gasses. A significant amount of energy is often required during the expansion process to generate the foam structure, which in turn increases the total carbon emissions (Kwon et al. 2021).

Life cycle assessments (LCAs) take into account the total energy demand (CED) and emissions of greenhouse gases during the whole product life cycle, allowing for the quantification of epoxy resins' and foams' carbon footprints (Frischknecht et al. 2015). Depending on the procedures and energy sources used, producing 1 kg of epoxy resin might release about 5–7 kg of CO₂-equivalent (CO₂e) emissions, according to studies (informe_tec_carbotainer200_2019.pdf n.d.). Considering the extra stages and materials needed for foam manufacture, the carbon footprint of EP-AGs may be significantly greater. The energy-intensive chemical

processes required to create the epoxy resin, together with the extraction and processing of raw materials, are the main culprits responsible for these emissions (Kočí and Picková 2019).

6.5.2 Use and end-of-life management: impacts on carbon emissions

Epoxy resins and foams may contribute to carbon emissions during their usage as well, but the consequences are often lesser than during manufacture. In the case of epoxy resins used as adhesives or coatings, for example, the main source of emissions is the energy required for curing, which is often heat. Some of the emissions from making EP-AGs, a popular insulating material, may be offset by the energy savings they bring when employed (Schelte et al. 2023). But how well the foam insulates and how it's applied determines how much of an advantage this is.

When considering the environmental impact of epoxy resins and foams, there are many obstacles to be overcome in terms of end-of-life management (Liu et al. 2018). Their carbon impact is exacerbated by the production of CO₂ and other greenhouse gases during traditional disposal techniques like incineration or landfilling. Not only may incineration emit CO₂, but it can also release other toxic pollutants like dioxins and furans if not managed correctly. Although landfilling uses less energy than other options, it still leaves behind the carbon footprint of making and using epoxy materials and, when the material breaks down, may produce methane, a powerful greenhouse gas.

Although there is some theoretical possibility of recycling epoxy resins and foams, the process is still in its infancy and faces several economic and technological obstacles. Because they do not remelt, thermosetting polymers like epoxies are not amenable to traditional mechanical recycling techniques (Morici and Dintcheva 2022). Potential energy-intensive and carbon-emitting chemical recycling technologies for recovering useful components from epoxy waste include catalytic depolymerization and supercritical fluid recycling. In addition, most epoxy waste is being disposed of using conventional techniques since the infrastructure for large-scale recycling of epoxy materials is not completely built.

6.5.3 Future of epoxy foams/aerogel industry from a carbon emission standpoint

Improvements in lowering the carbon footprint of EP-AGs and aerogels will determine the industry's future. Manufacturers are under increasing pressure to create and use environmentally friendly substitutes for traditional epoxy

resins and foams as sustainability and carbon neutrality become more important to global governments and businesses (Chen et al. 2024). Legislative actions, consumer demand for eco-friendly goods, and technical advancements that lessen the ecological footprint of epoxy-based materials are expected to propel this change.

Creating bio-based epoxies from sustainable sources like lignin, vegetable oils, or other biomass might be a way to lessen the environmental impact of EP-AGs and aerogels (Vrabič-Brodnjak 2023). Since these bio-based resins are not dependent on fossil fuels, they may greatly reduce the carbon emissions caused by the extraction of raw materials. To add insult to injury, bio-based epoxies are often less hazardous and biodegradable than their petroleum-based equivalents, making them even more eco-friendly (Admin 2024). However, bio-based epoxies are still in their infancy as a product, and there are still obstacles to overcome before manufacturing can be scaled up and the materials can match the performance standards of conventional epoxies.

Enhancing the recyclability of aerogels and EP-AGs is the subject of more study (Ravindran et al. 2024). More effective catalytic depolymerization methods and sophisticated solvent systems are two examples of how chemical recycling is making strides toward a future where less carbon dioxide is released into the atmosphere from discarded epoxy materials. Technologies like this have the potential to minimize the total carbon footprint by recovering and reusing important monomers and oligomers from epoxy waste, thereby closing the loop in the life cycle of epoxy materials.

One further way to cut down on carbon emissions is to make epoxy resins and foams using carbon capture and utilization (CCU) technology (Dziejarski et al. 2023; Pires da Mata Costa et al. 2021). CO₂ emissions from industrial activities may be collected and used as a raw material for chemical and material synthesis by CCU. For instance, one way to decrease the carbon footprint of epoxy manufacture is to utilize CO₂ to make epichlorohydrin, an essential ingredient in epoxy resins (“Epoxy resin - an overview | ScienceDirect Topics,” n.d.; Memon et al. 2022). This would mean less dependence on fossil fuels. Decarbonizing the epoxy sector and contributing to global efforts to reduce climate change might be made possible by CCU technologies, which are currently in the early phases of research.

The answer to the issue of whether aerogels and EP-AGs are “green enough” in terms of carbon emissions hinges on developments in these and other fields. Due to their energy-intensive manufacturing methods and the difficulties connected with end-of-life disposal, epoxy materials now have a somewhat high carbon footprint. The carbon footprint of epoxies is now high, but it might be drastically reduced in the

future thanks to further R&D into environmentally friendly alternatives and more sustainable manufacturing and recycling methods.

To sum up, the industry is heading towards a more sustainable future, even if EP-AGs and aerogels aren’t completely “green” in terms of carbon emissions just yet. Possible solutions to lessen these materials’ negative effects on the environment include bio-based epoxies, improved recycling methods, and the incorporation of carbon capture and utilization. Nevertheless, there are still a lot of obstacles to overcome, especially when it comes to making these technologies more economically feasible and meeting the performance standards set by conventional epoxies. The sector producing EP-AGs and aerogels will have to be creative and flexible if it wants to lessen its impact on the environment and help ensure a sustainable future in the face of the ongoing worldwide movement towards sustainability.

6.6 Life cycle assessment of epoxy foams

The life cycle assessment (LCA) of EP-AGs is a comprehensive process that assesses the environmental impacts of their entire life span, from extraction to disposal, which is crucial for understanding their true environmental footprint, especially as they are increasingly marketed as sustainability-conscious (Moshood et al. 2022; Parameswaranpillai and Vijayan 2014). The LCA process involves stages like raw material acquisition, manufacturing, usage, and disposal, each impacting the environment differently, necessitating detailed analysis for potential improvements.

6.6.1 Raw material acquisition and manufacturing

The initial stage of the LCA for EP-AGs focuses on raw material acquisition and manufacturing, primarily composed of epoxy resins from petrochemical feedstocks and fillers or additives, which can be energy-intensive and lead to significant greenhouse gas emissions (Turhan Kara et al. 2024). Studies highlight the significant energy consumption and environmental degradation associated with the production of epoxy resins, often derived from non-renewable sources. The chemical processes used to convert feedstocks into usable epoxy resins, such as bisphenol-A (BPA), have been linked to toxic emissions and contamination (Hahladakis et al. 2023). Plant-based or recycled materials can reduce reliance on fossil fuels in foam, but their environmental benefits are limited if they constitute a small percentage of the total formulation, according to Patel et al., highlighting the importance of considering the proportion and type of additives.

Epoxy foam manufacturing involves complex processes that contribute to environmental impact. The foaming process, involving blowing agents and catalysts, can release pollutants and energy while curing and processing the foams further exacerbating the environmental footprint. It is important to consider energy use and emissions during the manufacturing stage of EP-AGs. They argue that while some manufacturers have reduced energy consumption and emissions, the energy-intensive nature of foam production and the use of harmful blowing agents or catalysts can exacerbate these negative impacts. Therefore, a comprehensive examination of the entire manufacturing process is necessary.

6.6.2 Usage and end-of-life disposal

EP-AGs are used in construction, automotive, and packaging industries, with primary environmental concerns being the release of VOCs and potential health impacts. Although fully cured EP-AGs are considered inert, the curing process and uncured components can pose risks, despite their generally inert nature (Smoleń et al. 2022). Research indicates that exposure to epoxy foam fumes during curing can cause respiratory issues and dermatitis, requiring ventilation and personal protective equipment (Luchtel et al. 1989). Although the environmental impact during usage is less significant, it still requires consideration for occupational health and safety.

EP-AGs face significant challenges in end-of-life disposal due to their chemical composition, making recycling and composting difficult (Klose et al. 2023; Liu et al. 2020). Studies show limited recycling and long-term persistence in landfills, contributing to environmental issues like leachate contamination and habitat disruption. Therefore, end-of-life disposal is a critical aspect of the LCA for EP-AGs. Studies highlight the potential for enhancing the end-of-life impact of EP-AGs by advancing recycling technologies and developing more environmentally friendly formulations, as incineration can release toxic gases and particulate matter (Petrakli et al. 2020).

The development of solutions for EP-AGs is in its early stages, and a comprehensive LCA is needed to address disposal challenges and explore sustainability opportunities through improved waste management practices and innovative recycling technologies. The life cycle assessment of EP-AGs reveals a complex interplay of factors, from raw material acquisition to manufacturing, presenting unique challenges and opportunities for reducing environmental harm. Understanding these aspects is crucial for developing sustainable epoxy foam products and improving their environmental performance throughout their lifecycle.

7 Aerogel technology knowledge gaps/needs

Aerogels of diverse origins have been researched in academics and further developed in EU efforts over the past few decades, demonstrating that current aerogel manufacturing is limited to inorganic aerogels (Budtova et al. 2020). Organic aerogels of diverse origins have also been developed. Biopolymers can be used to create aerogels with unique capabilities that can be applied in a variety of industries, such as adsorption, biocatalysis, cosmetics, and drug delivery (Abdul Khalil et al. 2023; Bakhori et al. 2023; Ulker and Erkey 2014; Yahya et al. 2020). They have qualities such as mechanical elasticity, functional groups, biodegradability, and biocompatibility. Polymeric and biopolymeric aerogels offer numerous benefits for applications in the life sciences, but their availability can be limited due to challenges related to their mechanical properties, synthesis methods, and the need for specific functionalization to achieve desired biodegradability and biocompatibility (Yahya et al. 2020). Slentite (a polyurethane aerogel) is manufactured on a pilot scale in Lemförde, Germany (SLENTITE® (basf.com)) and offers mechanical elasticity, diverse functional groups, biodegradability, and biocompatibility. Aerogels must be manufactured at a larger scale and the raw materials must be carefully analyzed to produce competitive commodities. These data point towards future developments (Dervin and Pillai 2017; Di Maio and Kiran 2018). The most important idea is to identify gaps and requirements in basic and process-related areas:

- The use of recycled polymers as raw materials for aerogels is recommended due to their availability, environmental impact, and eventual recycling.
- Structure-properties connections between polymer characteristics and matrix qualities are essential for creating hybrid aerogels.
- Solvent exchange is used to improve the production of organic aerogels.
- Establishing and expanding a production method for organic and hybrid aerogels with controlled porosity and size distribution.
- Future process optimization and scaling up require multiscale modelling of all process steps, including drying, solvent exchange, swelling and shrinking of the gel matrix, and gel formation for hybrid systems.
- Organic aerogels are currently produced in small amounts, but switching to continuous operations would be beneficial, but the answer is unclear due to depressurization phases.
- Standardizing aerogel characterization procedures (pore size distribution, density, thermal conductivity, and mechanical properties) may improve the ability to

compare data from different sources. Suggestions for these actions developed in collaboration with relevant institutions may be useful.

Table 4 summarizes the in-depth analysis of proposed solutions and detailed strategies to overcome gaps in the practical use of epoxy foam/aerogels.

Table 4: In-depth analysis of proposed solutions and detailed strategies to overcome gaps in the practical use of epoxy foam/aerogels.

Strategies	Solutions
1 Mechanical fragility and reinforcement techniques	
Nanofiller integration	The mechanical characteristics of epoxy may be greatly improved by adding nanoscale fillers like graphene, silica nanoparticles, or carbon nanotubes (CNTs) to the matrix. This increases the mechanical strength, elasticity, and fracture toughness of the material.
Hybrid materials	A more durable composite with improved structural integrity and load-bearing capability may be created by mixing epoxy with various additional polymers, fibers, or metals to create hybrid foams.
Controlled curing processes	Increasing the material's strength while keeping its lightweight properties is possible by optimizing the curing process to fine-tune the microstructure of the foam, namely cell size and distribution.
3D printing and structural optimization	Improved mechanical qualities customized to particular applications may be achieved via the use of sophisticated 3D printing methods to produce complex, optimized foam structures.
2 Environmental stability and resistance	
Surface coatings and treatments	EP-AGs and aerogels may be made more environmentally stable by applying protective surface coatings such as fluoropolymer-based treatments or silane. This will make them more resistant to chemical degradation, moisture, and UV radiation.
Chemical modifications	The material's resistance to environmental elements including humidity, temperature variations, and oxidative conditions may be enhanced by adding functional groups or cross-linking agents during the polymerization process.
Hybrid organic-inorganic composites	Improved thermal stability and resistance to environmental degradation may be achieved by the creation of hybrid materials that include both organic polymers and inorganic components, such as silica.
3 Scalability and manufacturing challenges	
Scalable production techniques	Improving the uniformity of the material's qualities in large-scale applications and lowering production costs may be achieved via the development of scalable manufacturing processes, such as continuous processing or extrusion techniques.
Material homogeneity	To keep material qualities constant over large quantities, it is essential to ensure uniform dispersion of additives and fillers throughout manufacture. This may be accomplished by modern compounding and mixing procedures.
Cost-effective raw materials	One way to lower manufacturing costs without sacrificing performance is to look into and use more affordable raw materials. This might be bio-based epoxies or recycled fillers.
4 Thermal management and insulation properties	
Enhanced thermal conductivity control	For better heat dissipation management and insulation, epoxy matrices reinforced with thermally conductive fillers such as graphene or boron nitride may be used.
Optimized porosity	Depending on the needs of the application, the foam's thermal insulation qualities may be fine-tuned by regulating its porosity and pore size distribution.
Multifunctional foams	A wider range of applications might be realized via the creation of multifunctional foams that provide thermal insulation in addition to other desirable qualities like electrical conductivity and flame retardancy.
5 Flame retardancy and fire resistance	
Incorporating flame retardants	The mechanical qualities of epoxy foam may be preserved while increasing its fire resistance with the use of flame retardant additives, such as phosphorus-based compounds or halogen-free retardants.
Synergistic additive systems	One way to make foams that are resistant to ignition and also build protective char layers during combustion is to use a mixture of flame retardants that have synergistic effects, such as intumescent systems.
Thermal barrier coatings	To make the foam even more fire-resistant, thermal barrier coatings may be applied to its surface. This makes it acceptable for uses that need very high fire safety requirements.
6 Aging and durability	
Accelerated aging studies	The creation of longer-lasting materials may be guided by studying the long-term performance of EP-AGs and aerogels under different environmental conditions via accelerated aging research.
Stabilizing additives	You may make the material last longer in tough settings by adding antioxidants or UV stabilizers, which stop it from degrading over time.
Resilient material formulations	To make epoxy last longer, scientists need to find ways to make it more resistant to things like mechanical stress, temperature cycling, and water absorption.

Table 4: (continued)

Strategies	Solutions
7 Acoustic insulation and damping	
Optimized acoustic properties	For noise reduction applications, it is possible to design foams with appropriate porosity and cell structure to maximize their acoustic absorption and damping qualities.
Viscoelastic damping materials	Epoxy foam may be made more effective as an acoustic insulator by adding viscoelastic elements to it, which increase its capacity to absorb and disperse vibrational energy.
Lightweight acoustic panels	An excellent method of soundproofing vehicles, airplanes, and buildings is to create lightweight panels out of EP-AGs that have exceptional acoustic qualities.
8 Chemical resistance and barrier properties	
Chemical-resistant additives	To improve their performance in chemically demanding situations, EP-AGs may be enhanced with additives that increase their chemical resistance, such as organosilicon compounds or fluoropolymers.
Barrier layer integration	The core material may be protected and used in severe settings for longer by applying or integrating barrier layers that resist gas, liquid, or chemical permeability.
Cross-linking density control	A more robust polymer network, and enhanced resistance to chemical assaults, may be achieved by varying the amount of cross-linking within the epoxy matrix.
9 Processing and handling flexibility	
Processable formulations	To increase manufacturability and enable more complicated geometries, it is necessary to develop epoxy foam compositions with lower viscosity, better flowability, and simpler processing.
Customizable curing profiles	To enhance processing flexibility and save production times, it is possible to provide curing profiles that may be customized according to application demands, such as quick or slow curing.
Improved machinability	Optimising the hardness and toughness of EP-AGs may increase their machinability, making them simpler to cut, shape, and polish, and thus increasing their use.
10 Sustainability and environmental impact	
Bio-based epoxy resins	To lessen the ecological footprint of foam manufacturing without sacrificing performance, researchers and developers should focus on bio-based epoxy resins made from sustainable sources.
Recycling and reusability	Chemical recycling technologies and other recycling procedures for EP-AGs and aerogels may help make their usage more sustainable and less wasteful.
Eco-friendly additives	To improve the material's environmental profile, eco-friendly additives like biodegradable fillers or non-toxic flame retardants may be used.
11 Integration with other materials	
Composite material systems	It is possible to design materials with synergistic qualities that are application-specific by constructing composite material systems that integrate EP-AGs with metals, ceramics, and other polymers.
Layered and graded structures	EP-AGs may be used to create constructions with varying layers or functional grades, allowing for the customization of features like impact resistance and thermal insulation at specific locations.
Adhesion and bonding enhancements	Composite constructions that improve the mechanical performance and durability may be made more effective by increasing the adhesion and bonding of EP-AGs with other materials.
12 Cost reduction and economic viability	
Optimizing raw material use	The total cost of the foam may be reduced without compromising performance by optimizing the use of less costly raw ingredients, such as high-cost nanofillers.
Lean manufacturing techniques	Epoxy foam production may be made more cost-effective by using lean manufacturing principles, which include reducing waste and boosting process efficiency.
High-volume production strategies	EP-AGs may be more economically viable for commercial uses if high-volume manufacturing procedures can be developed that maintain quality while decreasing per-unit costs.
13 Adapting to diverse applications	
Application-specific formulations	Either thermal insulation, structural support, or acoustic dampening are just a few examples of the many uses that epoxy foam compositions may be fine-tuned to fulfill.
Customizable material properties	Adjustable formulations allow for the customization of material characteristics, including density, stiffness, and thermal conductivity, to match the demands of varied applications.
Modular design approaches	Facilitating the adoption of EP-AGs into new applications may be achieved via the development of modular design techniques that allow for their simple integration into existing systems.
14 Enhanced electrical conductivity	
Conductive fillers	EP-AGs may be enhanced for use in electronic and electromagnetic shielding by adding conductive fillers like graphene, carbon black, or silver nanoparticles, which increase their electrical conductivity.
Hybrid conductive networks	The optimal compromise between weight, mechanical strength, and conductivity may be achieved by integrating several kinds of fillers into the foam to form hybrid conductive networks.

Table 4: (continued)

Strategies	Solutions
15 Multifunctionality and smart materials	
Self-healing properties	One way to improve the material's longevity and resilience in high-stakes uses is to create self-healing EP-AGs by including vascular networks or microcapsules that carry healing agents.
Sensing capabilities	Applications in aerospace, automotive, and civil engineering might benefit from smart materials that monitor structural health, temperature, or strain by integrating sensors or responsive features into the foam.
16 Optimization for lightweight structures	
Density reduction techniques	If you want to make EP-AGs even more lightweight without sacrificing structural integrity, you may use techniques like gas infusion or foaming agents.
Microcellular foams	Aerospace and transportation industries stand to benefit greatly from the development of microcellular EP-AGs with homogenous, ultra-small pores, which may improve mechanical qualities while drastically reducing weight.
17 Tailored thermal expansion coefficients	
Coefficient of thermal expansion (CTE) matching	To avoid delamination and enhance thermal stability in high-temperature applications, it is recommended to adjust the CTE of EP-AGs to match that of other materials in a composite construction.
Inorganic fillers	EP-AGs may have their thermal expansion properties fine-tuned for particular technical uses by including inorganic fillers with negative or low CTEs.
18 Impact resistance and energy absorption	
Energy-absorbing additives	Enhancing the impact resistance and energy absorption capacities of EP-AGs may be achieved by including materials such as rubber particles or hollow glass microspheres. This makes the foams more suitable for protective applications.
Optimized foam structures	Improved impact energy absorption is possible with foam structures designed with certain geometries, including honeycombs or gradient density layers; these materials find use in protective gear and automobiles.
19 Nanotechnology integration	
Nanoporous structures	A variety of filtration and insulating uses may benefit from the novel characteristics that can be achieved via the development of nanoporous epoxy aerogels, such as very low thermal conductivity and a large surface area.
Nano-scale control	To create materials with better performance qualities, nanotechnology may be used to precisely regulate the microstructure and properties of foam.
20 Long-term reliability in extreme conditions	
Cryogenic stability	Expanding the usage of epoxy formulations in aircraft, space exploration, and cryogenics requires research into how these materials operate at cryogenic temperatures.
High-temperature resistance	Improving EP-AGs' thermal durability to prevent degradation at high temperatures might lead to new uses in high-performance settings, such as engine parts or turbines.
21 Biocompatibility for medical applications	
Non-toxic formulations	The potential for foams to be used in medical devices, implants, and tissue engineering scaffolds may be realized with the development of non-toxic, biocompatible epoxy formulations.
Antimicrobial properties	EP-AGs may be made more acceptable for use in healthcare and sanitation by adding antimicrobial chemicals or coatings that inhibit the growth of biofilms and infections.
22 Adhesion to diverse substrates	
Surface functionalization	To increase the bonding strength in composite constructions, EP-AGs may have their surfaces modified to make them stick better to metals, ceramics, or polymers.
Adhesive interface layers	EP-AGs and other materials in multi-material systems may attach strongly with the help of adhesive interface layers or primers.
23 Optimization for additive manufacturing	
3D printable formulations	The development of 3D-printable epoxy foam compositions opens the door to the precise fabrication of intricate, one-of-a-kind structures with specialized uses in mind.
Layer-by-layer control	Modern additive printing processes enable precise control of foam properties on a layer-by-layer basis, opening the door to gradient materials with variable densities or mechanical characteristics.
24 Water and moisture resistance	
Hydrophobic surface treatments	To improve performance in situations with a lot of moisture, you may make the foam more resistant to water absorption by applying hydrophobic surface treatments or adding hydrophobic chemicals to it.
Closed-cell structures	Marine and offshore applications are ideal for EP-AGs designed with closed-cell structures, which prevent water penetration and promote buoyancy.

Table 4: (continued)

Strategies	Solutions
25 Improved chemical interactions for functionalization	
Reactive functional groups	Enabling post-curing functionalization, which involves adding reactive functional groups to the epoxy matrix, allows for the attachment of extra molecules with specialized capabilities, including drug transport in biomedical applications.
Tailored polymer blends	By combining epoxy with other polymers, one may create a customized polymer blend that can alter the chemical interactions inside the foam, leading to improved solubility, adhesion, and chemical resistance, among other qualities.

Expanding the practical application of EP-AGs and aerogels via focused research and development may overcome present difficulties and open new potential in numerous sectors. The research and development efforts needed to solve the practical usage issues of EP-AGs and aerogels are further expanded by the additional aspects mentioned above. This will make these materials more flexible and adaptable for a wide variety of applications.

8 Definition of the present problem, future prospects and trends

EP-AG composites are becoming increasingly popular due to their outstanding qualities, but they face several problems that must be addressed before they can be used in broader applications. These include a lack of understanding of interactions, models to predict performance and a property database. Foaming an epoxy requires mixing a gas phase with the epoxy phase and allowing it to cure together, which must be done when the epoxy is at its best curing state to prevent cell coalescence and promote growth (Lyu et al. 2017). However, industrial-scale testing is often hampered by a lack of material quantities. Epoxy/aerogel materials are still developing, and several issues must be addressed to exploit their features fully. However, their limitations, such as costly preparation techniques and raw materials, have led researchers to seek substitute materials. Rapid economic growth has led to increased waste production, but few studies have been conducted to explore the potential of recycling waste to create aerogels (Ziegler et al. 2017).

These issues need to be addressed before EP-AGs can be used in broader applications (Maleki et al. 2016). This research aims to understand the effects of EP-AGs on the thermal and mechanical characteristics of epoxy and vinyl ester polymers by integrating different weight contents and sizes of EP-AG particles into these polymers (Bethke et al. 2021a). The thermal conductivity of generated composites decreased significantly, while the addition of porous particles harmed the mechanical properties. Micromechanical testing of the interface between aerogel and fiber reinforcement was conducted to better understand their bonding potential.

Micro bond experiments were enabled by depositing an aerogel droplet around the fiber, and the findings showed

poor adhesion between the aerogel and the chosen fiber type. It is important to model EP-AGs and aerogel composites to understand the interactions between aerogels and reinforcing materials. A nanoscale study utilizing molecular dynamics enabled the thermal and mechanical characteristics of low-density EP-AGs to be estimated. The values of aerogel-fiber interfacial characteristics were derived using modelling, and the thermal and mechanical characteristics of epoxy composites can be modelled using the microscale model. By adding nanoscale features, a close match between experimental and predicted heat conductivity and compressive modulus can be studied (Maharsia et al. 2006).

EP-AGs-based adsorbents have emerged as efficient and ecologically benign materials for extracting heavy metal ions from aquatic environments (Ihsanullah et al. 2022). However, their implementation in practical water filtration is hindered by multiple hurdles.

EP-AG adsorbents should be made using simple synthesis processes and more simple solutions that use less energy and harmful chemicals (Wu et al. 2022). It is important to assess the potential of synthetic EP-AGs-based adsorbents in commercial water treatment, as most research has been done on a lab scale. Post-treatment studies are needed to create an effective, ecological, and long-lasting approach to the removal of hazardous metal ions from water (Ribeiro et al. 2018). Specific attention is needed to eliminate flaws such as complicated drying, mechanically brittle structure, and processing expense of aerogel-based adsorbents (Li and Jones 2007).

Cost estimates are uncommon in the literature, so cost analysis should be thoroughly investigated. The potential hazardous and environmental consequences of EP-AGs-based adsorbents should be investigated. To fully understand the interactions between pollutant molecules and the adsorbents, a more in-depth understanding of the adsorption process is needed. Machine learning and computational

technologies should be used to forecast the performance of aerogel-based adsorbents in water purification. The viability of using EP-AG -based materials in the creation of membranes for desalination and water treatment should be studied. Their unique combination of properties may be used for a variety of purposes, some of which have already found a market.

Aerogels are open colloidal or polymeric networks made up of loosely packed particles or fibres expanded by gas. They have a low density and a significant surface area and are often created by removing all swellable substances from an initial gel. Aerogel chemistry is highly adaptable, as its surface area and pore size can be customized and functional groups added to provide the desired properties (Quadrini and Squeo 2008; Squeo and Quadrini 2010).

The authors believe that many more forms of aerogels will be found in the coming years, particularly since hybrid aerogels allow for the modification of characteristics and the addition of new capabilities depending on the desired application (X. Wu et al. 2021b). If aerogels' attributes are improved, future uses that were previously impractical would be possible. The main goal of this study is to list and briefly describe the most promising research directions to achieve this objective (Quadrini and Squeo 2008).

The EP-AGs sector is expected to grow rapidly in the future, so material features and manufacturing processes must be developed to reduce costs and allow for applications beyond academic research. Collaboration between academic groups and industry partners should be encouraged to create new EP-AG types, with intended product attributes and constraints established from the start. EP-AGs can cause severe artefacts when used without evaluating their applicability, so additional attention must be paid to nitrogen sorption studies, particularly Hg-porosimetry. Small angle scattering, gas permeation measurements, and thermal conductivity analysis are useful techniques for determining pore sizes while avoiding compressional forces. Small angle scattering, beam-bending, and NMR are also useful approaches for characterizing gels, but the application must be taken into account. It is advisable to investigate features near to the application rather than just basic parameters such as pore size.

EP-AGs offer effective thermal insulation, supercapacitors, and carriers for active agents. Future studies should focus on practical applications and determining the characteristics of aerogels to advance electrochemistry, environmental applications, and life science. Aerogel composites are becoming increasingly popular due to their exceptional properties, but face challenges such as a lack of understanding, models to predict performance and property databases. This work aims to address these issues and provide

a better understanding. Aerogel particles in polymers decreased thermal conductivity, compressive properties, and thermomechanical properties, while porous particles deteriorated composite mechanical response. Micromechanical testing revealed poor adhesion between aerogel and fiber reinforcement, and a microscale model was used to model the thermal and mechanical properties of epoxy composites, resulting in a close match between experimental and modelled conductivity and a compressive modulus.

9 Epoxy foams: past, present, and future

EP-AGs have evolved significantly since their inception, combining lightweight characteristics with superior mechanical properties. Initially developed for aerospace and marine applications, they aimed to create materials with enhanced structural integrity, reducing weight without compromising strength, thereby enhancing structural integrity. Early epoxy foam formulations used basic chemical blowing agents like CFCs and hydrocarbons to create a cellular structure. These agents generated gas bubbles within the epoxy matrix, but often caused irregular cell sizes, resulting in inconsistent mechanical properties and limited thermal stability. Environmental concerns about CFCs, including their potential to deplete ozone, limited their applicability (Wazalwar et al. n.d.). As a result, early EP-AGs were primarily used in less demanding applications like insulation and non-structural components, where mechanical performance and thermal resistance were less stringent.

The epoxy foam industry has seen significant advancements in chemistry and processing techniques, resulting in a fine-tuned balance between density and mechanical strength. This is achieved through optimizing blowing agents, curing processes, and filler materials. The shift from chemical to physical blowing agents, like supercritical CO₂, has improved control over cell size and distribution, resulting in more uniform foam properties (Bethke et al. 2021b).

Polymer chemistry advancements, including new curing agents and epoxy resins with enhanced cross-linking, have produced foams with improved thermal stability, flame retardancy, and environmental resistance, making them suitable for high-performance sectors like automotive, aerospace, and electronics (Beena Unni and Muringayil Joseph 2024; Sharma et al. 2024). Advanced filler materials like nanosilica, alumina, and carbon-based fillers have improved the mechanical, thermal, and electrical properties of foams. These nanomaterials enhance the structural integrity, electrical conductivity, and thermal management capabilities of

the epoxy matrix, enhancing the foam's multifunctional properties. The nanoscale control of the microstructure of EP-AGs has led to the creation of materials with superior performance, specifically designed for applications requiring high strength-to-weight ratios, electrical conductivity, or thermal insulation properties, such as lightweight structural components, electromagnetic shielding, and thermal interface materials in electronic devices (Fan et al. 2019).

Future epoxy foam development will prioritize sustainability and bio-based materials. With environmental concerns and a push for greener manufacturing, research is focusing on renewable resources and recyclable materials. Bio-based epoxies derived from natural sources like vegetable oils, lignin, and cashew nutshell liquid could significantly reduce the carbon footprint of conventional epoxy production. Bio-based resins are being integrated into EP-AGs to address environmental concerns and improve biodegradability and end-of-life recyclability. The future of EP-AGs is expected to see smart technologies like self-healing capabilities and adaptive thermal management, allowing the material to respond to environmental changes or damage autonomously. Advancements in EP-AGs are enhancing their durability and longevity, expanding their applications in wearable electronics, smart packaging, and thermal management systems. Tunable properties, like variable stiffness or shape-memory capabilities, could revolutionize their use in dynamic structures, creating next-generation materials that can adapt to changing operational conditions.

EP-AGs have evolved through continuous improvement and innovation, transitioning from simple insulating materials to high-performance multifunctional composites due to advancements in materials science and processing techniques, enabling them to transition from simple materials to sophisticated composites. Future research in EP-AGs is expected to focus on sustainability and smart functionality, aiming to create environmentally friendly and adaptable materials. This will enhance the performance and versatility of EP-AGs, ensuring their continued relevance and expansion into new applications. Advanced manufacturing techniques like 3D printing and additive manufacturing combine with epoxy foam technology to create complex, lightweight structures with tailored properties, extending the potential of EP-AGs in the future.

10 Evaluating the claims of “green” epoxy foams

The rise in the marketing of EP-AGs as “green” or environmentally friendly products has garnered significant attention

within the materials industry (Huang et al. 2019; J. Tang et al. 2024). This trend aligns with a broader societal push towards sustainability and eco-conscious manufacturing practices. EP-AGs, valued for their lightweight and insulating properties, are now being promoted with claims of reduced environmental impact through various means such as improved recyclability and sustainable raw materials. However, the true environmental impact of these products is often multifaceted and complex. Recent research indicates that thoroughly examining these claims is essential to understand their validity and implications.

10.1 The rise of “green” epoxy foams

The “green” label has become prevalent in various industries, including the foam sector, due to rising consumer demand for sustainable materials and stricter environmental regulations. EP-AGs, known for their strength and thermal insulation, are now being marketed as environmentally friendly due to this shift (Esmaeili et al. 2018). However, the application of the “green” label is not standardized and can be ambiguous, with some products incorporating minimal eco-friendly elements without addressing broader environmental impacts.

Reports highlight the variability and lack of standardization in defining “green” epoxy foam. They argue that while some foams incorporate recycled or bio-based materials, these may only represent a small fraction of the total formula, potentially reducing the foam's environmental footprint (Mazzon et al. 2015). They also suggest that marketing “green” foams can sometimes be a form of greenwashing, promoting marketing over actual environmental benefits.

10.2 Complexities in assessing environmental impact

The environmental impact of EP-AGs can be evaluated through a comprehensive lifecycle, including sourcing, production, usage, and disposal (Bhatia et al. 2018; Garcia et al. 2018). While some foams claim reduced emissions or alternative materials, other lifecycle factors like energy consumption during production and disposal challenges can overshadow these benefits, as noted by researchers. Studies emphasize the energy-intensive production of EP-AGs, which often emit significant greenhouse gases, and the challenges of end-of-life disposal, as these materials are not always recyclable and may contribute to landfill waste, urging for a lifecycle approach to accurately assess their environmental benefits.

10.2.1 Health implications of epoxy foams

EP-AGs, unlike polyurethane foams, are generally considered less health-risking due to their fewer chemical emissions. Polyurethane foams can release volatile organic compounds, causing respiratory irritation and allergic reactions (Huang et al. 2017). However, handling and application of fully cured EP-AGs can still pose health hazards, especially during the mixing and curing phases. Overall, EP-AGs are a safer alternative to polyurethane foams.

10.2.1.1 Allergic reactions and dermatitis

EP-AGs pose a health risk due to dermatitis, a condition resulting from skin contact with uncured foam components (Brookstein 2009; Eckardt and Hindin 1973). This condition can develop over time, particularly with prolonged or repeated contact, and can range from mild irritation to severe allergic reactions, depending on individual sensitivity and exposure. Reports reveal that dermatitis is a prevalent issue among individuals handling EP-AGs, especially in industrial settings. It emphasizes the need for protective equipment and good hygiene practices, such as thorough hand washing, to minimize skin contact.

10.2.1.2 Respiratory issues and precautions

Exposure to epoxy foam fumes can cause respiratory issues, including dermatitis, coughing, and shortness of breath (“How do Epoxies Negatively Affect our Health?” 2020; Sargent et al. 1976). Despite fully cured EP-AGs emitting fewer VOCs than polyurethane foams, inhaling fumes during curing can lead to irritation and coughing. To minimize exposure, the study recommends using respiratory protection like masks or respirators. Reports emphasize the importance of proper ventilation during the curing process to disperse fumes and minimize airborne contaminants. They recommend using local exhaust ventilation systems or working in well-ventilated areas to mitigate risks associated with handling EP-AGs.

10.2.2 Environmental impact of epoxy foams

EP-AGs, like other thermosetting polymers, are inert once cured, preventing harmful substances from leaching into the environment. However, their environmental safety depends on their formulation and application (Song et al. 2020).

10.2.2.1 Importance of 100 % solids formulations

The environmental impact of EP-AGs is determined by their formulation with 100 % solids, which eliminates solvents and water, thereby preventing the release of volatile organic compounds (VOCs) during or after curing (El Gazzani et al.

2016; Lo et al. 2016). Reports show the importance of VOC-free formulations in reducing the environmental footprint of EP-AGs, thereby improving air quality and preventing potential environmental damage (Lin 2023). Research suggests that 100 % solids formulations are environmentally friendly due to their lack of solvents, which can contribute to air pollution. These formulations also offer better durability and performance without volatile components, making them a best practice for minimizing the environmental impact of EP-AGs (Michel and Ferrier 2020).

10.2.2.2 Proper mixing and curing

Studies emphasize the importance of precise mixing ratios and curing times in achieving complete polymerization in foam (Pomilovskis et al. 2024). Incomplete polymerization can lead to residual uncured components, potentially emitting VOCs or pollutants. Proper curing ensures the foam's molecular structure is fully formed, reducing the risk of leaching or degradation. Report highlights the importance of curing conditions like temperature and humidity in achieving optimal polymerization (Michel and Ferrier 2020). Deviations from these conditions can lead to incomplete polymerization, residual emissions, or reduced product performance, thus ensuring the environmental safety and effectiveness of EP-AGs.

10.3 Assessing “green” claims (green foaming)

The rise in “green” EP-AGs, made from plant-based or recycled materials, calls for a thorough examination of their claims, as the actual benefits may be limited (“Green foaming” n.d.).

10.3.1 Proportion of plant-based additives

It is reported that some foams incorporate plant-based or recycled materials, they often comprise only a small percentage of the total formula, which may not significantly impact the foam's environmental profile (Mazzi et al. 2023). The benefits of these additives can vary depending on their type and source. Studies found that plant-based additives in EP-AGs have limited environmental impact (“Super Resin Inc. highlights plant-based epoxy resin, foam core” 2024). Although they reduce reliance on virgin resources, their overall contribution to foam's ecological performance is small. The authors recommend a more comprehensive approach to evaluate the ecological impact of EP-AGs, considering factors like resource use, energy consumption, and end-of-life disposal.

10.3.2 Evaluating genuine environmental benefits

Environmental benefits of plant-based or recycled additives in EP-AGs are not always clear, and their use could be primarily a marketing strategy rather than a significant improvement in environmental performance (Huang et al. 2019; Lee et al. 2023). The environmental benefits of plant-based or recycled additives in EP-AGs are often inconclusive. They suggest that factors like resource consumption, energy use, and end-of-life disposal must be considered to fully understand the impact of these additives. They call for more rigorous research and transparent reporting to better understand the environmental implications of these additives.

10.3.3 Performance improvements

Studies explored the performance of EP-AGs with plant-based or recycled additives, finding that while these additives can affect properties like density and thermal insulation, their overall performance improvements are often marginal, and their presence doesn't necessarily improve foam durability or effectiveness (Cavasin et al. 2018; Chulikavit et al. 2023; Mort et al. n.d.). Comparison with EP-AGs with and without plant-based or recycled additives, finding minor performance differences. While these additives can affect properties like density and thermal conductivity, the overall foam performance remains similar to traditional formulations. The authors suggest that the primary benefits of these additives may be marketing and consumer perception rather than tangible improvements in product performance.

The marketing of environmentally friendly EP-AGs responds to consumer demand for sustainable products. However, their environmental impact is complex and requires a detailed lifecycle assessment. While some foams may use plant-based or recycled materials, their overall contribution to sustainability may be limited. 100 % solid formulations and proper mixing and curing procedures are crucial. This exploration explores the environmental and health implications, performance characteristics, and veracity of "green" claims related to EP-AGs. It emphasizes the need for proper protective measures and a more transparent evaluation of "green" claims in the evolving industry to ensure genuine environmental benefits.

11 Conclusions

Overall, using greener and more sustainable materials and manufacturing techniques would be the main necessity for future investigations in the field of polymer science and technology (Rabiee et al. 2023; Wiśniewska et al. 2023b,

2023a). Moreover, challenging aspects of epoxy-based systems such as flammability, low mechanical strength and biodegradability (Movahedifar et al. 2019; Tikhani et al. 2020) as well as developing green or bio-epoxy (Rad et al. 2019) should be more frequently practiced. Specifically, EP-AGs are still relatively new materials, and there are still several obstacles to be overcome before they can be considered fully potent for known applications. The most promising method is to introduce aerogels into composite materials, but the lack of knowledge about how elements interact hinders this. Key questions answered in this review:

- How has the global aerogel market performed so far and how will it perform in the coming years?

Ans: The global aerogel market is experiencing significant growth due to rising demand across various industries, anticipated to continue expanding due to advancements in material technology and increasing applications in insulation and pharmaceuticals.

- What are the key regions in the industry?

Ans: The aerogel industry is expected to experience significant growth in North America, Europe, and Asia-Pacific, with emerging markets like China and India also experiencing significant growth.

- What has been the impact of processing challenges on the global aerogel market?

Ans: The widespread adoption of Aerogels is hindered by processing challenges like production scaling, high manufacturing costs, and uniform properties, which can impact supply availability and pricing.

- Which are the popular types in the industry?

Ans: Aerogels, including silica, polymeric, carbon, and alumina, are widely used in insulation, oil and gas, and biomedical fields due to their unique properties.

- What are the leading firms in the industry?

Ans: Cabot Corporation, Aspen Aerogels, Armacell International, BASF SE, and Aerogel Technologies are prominent aerogel industry firms known for their innovative solutions and substantial market share.

- What are the major processing segments in the industry?

Ans: The aerogel industry employs three main processing segments: supercritical drying, ambient pressure drying, and sol-gel processing each tailored to produce specific aerogels with specific properties and applications.

- What are the dominant applications in the industry?

Ans: The primary application of aerogel industry is thermal insulation and companies are making insulation materials for industries such as, oil and gas refineries and pipelines exploration, aerospace, automotive and electronics, with emerging uses in pharmaceuticals and electronics.

- What are the various stages in the value chain of the industry?

Ans: The aerogel industry's value chain comprises sourcing, processing, manufacturing, quality control, distribution, logistics, end-use application development, recycling, and waste management.

- What are the key driving factors and challenges?

Ans: Key driving factors for the aerogel industry include increasing demand for lightweight materials, advancements in technology, and growing applications in insulation and environmental solutions; challenges involve high production costs, processing difficulties, and limited awareness of aerogel benefits among potential users.

- What is the structure of the global aerogel market and who are the key players?

Ans: The global aerogel market is dominated by key manufacturers like Cabot Corporation, Aspen Aerogels, Armacell International, BASF SE, and Aerogel Technologies, who innovate and partner strategically.

- What is the degree of competition in the global aerogel market?

Ans: The global aerogel market faces high competition due to established companies, innovation, and growing demand for advanced materials, requiring significant investment in research and development.

This review mainly focused on the use of EP-AGs and their processing complexity in various applications. This will help aerogel materials be used more widely in future projects due to the investigation of how aerogel affects polymer matrix characteristics.

The following goals have been established to achieve the purpose of this review:

- 1) When conducting an experimental investigation into how EP-AG particles affect some of the most popular resin materials, such as epoxy and vinyl ester, in terms of their mechanical and thermal characteristics.

- 2) To use micromechanical testing techniques to examine the interfacial adhesion of aerogel fibrous composites.
- 3) Investigate the thermal, mechanical, and interactions of EP-AGs with reinforcing materials using a multiscale modelling strategy.
- 4) To make a general understanding of the various challenges which face in the production of EP-AG-based materials on large scale.

Overcoming the challenges described in the review will bring a large lot of uniqueness by focusing on the interface between the EP-AGs and reinforcing elements, even though some studies has already been devoted to evaluating the characteristics of EP-AGs composites either physically or by modelling methods. The review, as a consequence, contains a guideline for the following field of novel investigations:

- Aerogel-fiber adhesion micromechanical testing
- The characteristics of EP-AGs studied by molecular dynamics
- The interface thermal and mechanical characteristics of aerogel composites as studied by molecular dynamics.
- The extensive thermomechanical investigation of epoxy resins including aerogel particles.

The above investigations may become future applications such as:

- Biomedical implants and tissue engineering
- Water purification and desalination
- Flexible electronics and wearable devices
- Energy storage and conversion
- Aerospace and automotive lightweighting
- Renewable energy technologies.

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