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Recent Advances in EMI-Shielding Aerogels: Mechanisms, Materials, and Scalable Fabrication Methods

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ABSTRACT

Electromagnetic interference (EMI) has become a growing concern with the rapid expansion of compact, high-frequency electronic devices, especially in wearable and portable technologies. This trend has driven the need for lightweight, multi-functional, and efficient shielding materials. Among the various candidates, conductive aerogels have attracted significant attention because of their low density, porous structure, and tunable architectures, which help overcome the limitations of conventional metal- and polymer-based shields. Recent advances in aerogel design have enabled the incorporation of diverse conductive components, including carbon nanostructures, MXenes, metals, and hybrid systems, leading to improved EMI shielding performance. This review systematically examines the relationship between the structural design and compositional engineering of conductive aerogels and their shielding effectiveness. It also highlights recent efforts to enhance specific shielding efficiency, mechanical robustness, and multi-functionality through comparative analysis of current studies. In addition, this review discusses the potential of conductive aerogels for flexible electronics and environmentally friendly applications, with emphasis on scalability, sustainable fabrication, long-term durability, and structure-property optimization. Overall, this review provides a timely perspective on conductive aerogels as next-generation EMI shielding materials.

KEYWORDS

EMI shielding; EW waves; conductive aerogel; absorption loss; gradient layer; 3D printing; directional freeze-drying

關鍵字

電磁屏蔽; 導電氣凝膠; 吸收損耗; 梯度層; 3D 列印; 定向凍乾

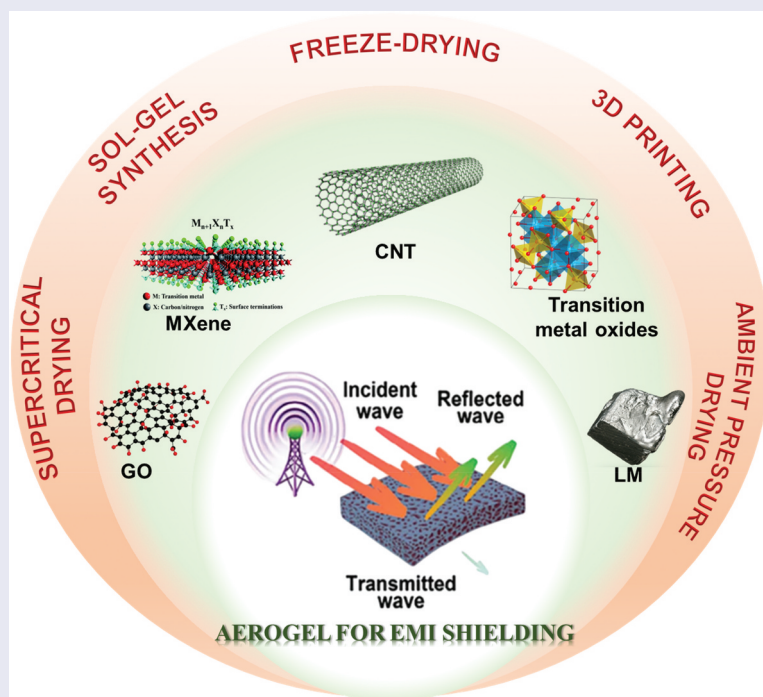
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摘要

隨著緊湊型與高頻電子裝置的廣泛應用，尤其是當代穿戴式與攜帶式技術的普及，電磁干擾 (EMI) 已成為日益嚴重的問題。這些問題促使人們必須開發出多功能、實用且輕量的屏蔽材料。為解決這些問題，研究人員已探索了多種材料。其中，導電氣凝膠因其低密度、開放孔隙結構及可調控的架構而備受矚目，這些特性使其能夠克服傳統金屬與聚合物複合材料的限制。近期研究進展凸顯了氣凝膠生長技術的突破，以及能構築精密導電系統的絕緣基質開發，這些系統運用了碳奈米結構、MXenes、金屬、混合結構及電磁干擾屏蔽方案。本綜述系統性地探討了氣凝膠的結構設計與成分工程，及其電磁干擾屏蔽性能之間的關聯性。此外，本綜述特別強調導電氣凝膠在柔性電子學與環境保護領域的應用潛力，涵蓋其可擴展性、長期穩定性、永續製程、綠色大規模製造、機械疲勞抗性，以及結構-性能優化等面向。本綜述針對與快速演進的新一代電子技術相容的電磁干擾 (EMI) 屏蔽材料之發展，提供了及時且具前瞻性的觀點。

Introduction

Aerogels are promising materials for electromagnetic interference (EMI) shielding due to their unique three-dimensional (3D) interlaced structures, low density, and high internal porosity. Unlike conventional solid substrates, aerogels have a significantly large surface area that can readily achieve multifold scattering and absorption of electromagnetic (EW) waves, making them highly suitable for mitigating unwanted EMI in sensitive electronic circuits and other complex communication systems. Recent developments in the field of aerogels have led to abandoning classical silica-based frameworks and introducing hybrid and conductive structures using carbon nanomaterials, MXenes, conductive polymers, and metallic components. Such aerogels are based on their inherent porosity, in addition to their electronic conductivity (Cheng et al. 2023; Chhetri and Kuila 2024; L. Wang et al. 2020; C. Zhang et al. 2025).

In recent years, rapid advances have been made in the design of conductive aerogels tailored for EMI shielding. Structural tuning via controlled synthesis allowed the creation of interconnected conducting pathways within the aerogel matrix. For example, sol – gel polymerization enables the formation of robust gel networks that can be infused with conductive fillers such as graphene, carbon nanotubes (CNTs), or metal nanowires. Directional freeze-drying orchestrates the assembly of these fillers into aligned macro-structures, significantly enhancing the anisotropy and efficiency of wave attenuation. Chemical reduction methods are used to transform insulating frameworks such as graphene oxide (GO) gels into conductive forms by restoring their conjugated structures within the porous network. Additionally, self-assembly

processes exploit various molecular interactions to yield hierarchical, multifunctional architectures, sometimes in conjunction with additive manufacturing, for precise structural control at the macro and micro-scales (Cheng et al. 2023; T. Li et al. 2025; J. Ma et al. 2024).

A key advantage of this synthesis flexibility is the ability to modulate not only the electrical conductivity but also the mechanical strength, flexibility, and interfacial interactions in the resulting aerogel composites. For instance, the introduction of hybrid conductive fillers can synergistically couple reflection, absorption, and multiple internal reflection mechanisms, thereby enhancing EMI shielding over a broad frequency range. Optimizing the filler load and adopting strategies, such as directional structuring or core – shell design, are actively pursued to maintain high performance with minimal material usage, thereby preserving the inherent lightweight character of the aerogels. Compared to dense metal-based barriers, conductive aerogels offer EMI shielding with significant benefits in terms of weight savings, adaptability, and multifunctionality (Cheng et al. 2023; Chhetri and Kuila 2024; Elsehsah, Noorden, and Saman 2024; J. Ma et al. 2024). In addition, in this context, advanced nanoscale surface-energy characterization provides a useful means of understanding and optimizing filler–matrix interfacial interactions; for example, Atomic Force Microscopy (AFM) PeakForce Quantitative Nanomechanical Mapping (PeakForce QNM) analysis of nano/micro scale samples has shown that differences in surface energy are closely related to particle dispersibility and the mechanical performance of powder-based composites (Ha et al. 2025; Ha et al. 2024).

The performance of conductive aerogels in shielding applications is strongly determined by their tailored structure – property relationships. Shielding effectiveness arises from the interplay of reflection at the material's conductive surface, multiple absorption and scattering within the porous frameworks, and, in some cases, magnetic loss when ferrimagnetic fillers are introduced. Researchers have measured their success in achieving high shielding effectiveness per unit thickness across key frequency bands, such as the Ku- and X-bands relevant to satellite, radar, and wireless communications. Systematic studies have shown that well-designed graphene/MXene aerogels, CNT/polymer hybrids, and hybrid carbon – metal aerogels can achieve shielding values (>40 dB) that surpass or rival commercial requirements while maintaining densities orders of magnitude lower than those of metallic foils or plates (Y. Liu et al. 2023).

Moreover, ongoing research is dedicated to addressing remaining challenges, such as scalable, green synthesis; the integration of multifunctionalities, including thermal management and environmental stability; and the development of recyclable or adaptive EMI shielding aerogels. The combined approach of linking synthesis techniques directly to microstructural outcomes and, consequently, to properties such as conductivity, thermal stability, and flexibility underpins the ongoing evolution of this vibrant field. With these advancements, conductive aerogels are positioned at the forefront of next-generation EMI shielding solutions for increasingly demanding technological landscapes, spanning wearable electronics, electrified transportation, and aerospace systems. This review focuses on the state-of-the-art conductive aerogel technologies for EMI shielding. It provides a holistic review of various synthesis methods and combines them with a critical examination of the resulting microstructures and their effects on the shielding processes. The compounded view not only highlights existing progress but also establishes future research directions that are likely to open new avenues for performance, scale, and application relevance in the synthesis and application of conductive aerogels as high-level EMI shielding materials (Cheng et al. 2023; Chhetri and Kuila 2024; Elsehsah, Noorden, and Saman 2024; Y. Liu et al. 2023; J. Ma et al. 2024).

Mechanisms of EMI attenuation in conductive aerogels

EMI shielding involves a complex interplay among reflection, absorption, and multiple internal reflections, and each process is fundamentally dependent on both the intrinsic properties and the architecture of the shielding material (Hareesh, Joseph, and George 2025; Iqbal et al. 2021; Choi, Qaiser, and Hwang 2024; Suryaprabha et al. 2026).

Reflection (SE_R) is typically the first line of defense in EMI shielding. When an EM wave encounters the interface between air (free space) and a shielding material, particularly one with high electrical conductivity such as metals, MXenes, or advanced carbon networks, a strong impedance mismatch occurs. This mismatch, characterized by the difference between the intrinsic impedance of free space ($\approx 377\Omega$) and the impedance of the shield, reflects a significant fraction of the incident energy back toward the source. Surface electrons respond to oscillating electromagnetic fields by generating opposing currents that create

a secondary electromagnetic field in the reverse direction. Quantitatively, the shielding effectiveness due to reflection is expressed as:

$$SE_R(dB) = -10\log_{10}\left(\frac{\sigma_T}{16\omega\epsilon_0\mu_r}\right) \quad (1)$$

where σ_T is the total conductivity, ω is the angular frequency, f denotes the frequency, ϵ_0 denotes the permittivity of free space, and μ_r indicates the relative permeability with respect to free space (Hareesh, Joseph, and George 2025). As conductivity (σ_T) or permeability (μ_r) of the shield increases, its impedance becomes much smaller than maximizing reflection. The reflection term primarily depends on the logarithmic ratio of these two impedances and is independent of the shield thickness for typical material dimensions. Although reflection blocks initial entry, it can generate secondary emissions if not balanced by absorption mechanisms (Aswathi et al. 2018; Iqbal et al. 2021; J. Liu et al. 2023).

Absorption (SE_A) addresses the EM wave component that enters the shield. As a wave traverses a material, its energy is depleted and dissipated as heat through different loss mechanisms: Ohmic (conduction) losses in conductive phases, dielectric polarization losses in polarizable phases, and magnetic resonance losses in magnetic fillers (Song et al. 2025; C. Zhang et al. 2025).

a) Ohmic (Joule) Loss: The alternating EM fields cause microcurrents in the conductive backbone and dissipate energy as heat rapidly, linearly with the continuity, density of percolation networks, and the incident wave causes charge carriers (electrons) to be excited in the pore-spanning conductive network in the form of graphene, MXene, or CNT networks. The flow of these excited carriers generates microscopic electric currents and resists the entire material. Consequently, the kinetic energy of such carriers is converted into thermal energy through resistive (ohmic) heating, and the EM wave is dissipated as it passes through the shield (Song et al. 2025).

b) Dielectric Loss: In EMI absorption, the conversion of the electric field component of an EM wave, rather than its reflection or transmission, is known as dielectric loss. This is principally due to several mechanisms, including conduction loss (free or hopping charge carrier movement), interfacial polarization (space-charge accumulation at heterogeneous interfaces), dipolar or molecular polarization (polar group orientation under an AC field), and defect-based or electronic/ionic polarization at higher frequencies. The effects of these mechanisms are that the polarization of the material and the applied field are in phase with a time delay that manifests as an imaginary component of the complex permittivity and a loss tangent. An increased dielectric loss (with equal impedance) results in increased absorption within the absorber instead of the reflection of incident EM energy, which results in absorption-dominated EMI shielding (Song et al. 2025).

c) Magnetic Loss: This is caused by the addition of magnetic fillers (ferrites, iron oxides, and cobalt nanoparticles), which give rise to additional dissipation via magnetic resonance, spin relaxation, and eddy current loss. Such losses are high at high frequencies, and the occurrence of several magnetic domains and surfaces increases the energy conversion between electromagnetic waves and heat. One of the reasons is that the existence of many magnetic domains and nonuniform interfaces aids in transforming a larger fraction of the electromagnetic energy into thermal energy (Song et al. 2025). Moreover, the overall EMI shielding performance and conversion efficiency can be significantly enhanced by closely regulating the density of the interface and the distribution of the phase inside the aerogel matrix.

The mathematical description of absorption shielding effectiveness is:

$$SE_A(dB) = -20\frac{t}{\delta}\log_{10}e = -8.68\left(\frac{t}{\delta}\right) = -8.68t\left(\frac{\sigma_T\omega\mu_r}{2}\right)^{1/2} \quad (2)$$

In this equation, t represents the shield thickness, while f denotes frequency. The formula demonstrates that SE_A is directly related to the square root of the product of the shield material's permeability (μ_r) and conductivity (σ_T) (Hareesh, Joseph, and George 2025; Iqbal, Sambyal, and Koo 2020; J. Liu et al. 2023; Song et al. 2025).

Multiple internal reflection (SE_M) arises when EM waves, after entering the shield, encounter multiple interfaces within the material, such as pores, layers, or particles. Each interface scatters and partially reflects the wave anew, increasing the effective travel path and the probability of eventual absorption. This effect is

critical for aerogels, foams, and layered composites with large interfacial areas. Theoretically, multiple internal reflections can be described as:

$$SE_M(dB) = 20\log_{10}\left(1 - e^{-2t/\delta}\right) = 20\log_{10}|1 - 10^{-SE_A/10}| \quad (3)$$

This effect becomes especially notable in lightweight or thin shields. However, it diminishes in importance when the absorption loss exceeds 10dB, as the internal energy is quickly absorbed and no longer available for repeated scattering (Hareesh, Joseph, and George 2025; Iqbal et al. 2021; Iqbal, Sambyal, and Koo 2020).

Overall Total Shielding Effectiveness (SE_T) combines these three mechanisms:

$$SE_T = SE_R + SE_A + SE_M \quad (4)$$

$$SE_T = 10\log_{10}\left(\frac{P_{incident}}{P_{transmitted}}\right) \quad (5)$$

where $P_{incident}$ is the incoming electromagnetic power and $P_{transmitted}$ is the amount that passes through the shield.

The Specific Shielding Effectiveness (SSE) and its normalization by thickness (SSE/t) are critical metrics for comparing and evaluating the EMI shielding performance, especially for ultralight aerogels, by factoring out the density and thickness to allow meaningful comparisons across different material systems.

SSE (dB · cm³/g) is calculated as:

$$SSE = \frac{SE}{\rho} \quad (6)$$

where SE is the total shielding effectiveness in decibels (dB) and ρ is the material density (g/cm³). This metric emphasizes the efficiency of EMI shielding per unit weight and is particularly important for lightweight materials, such as aerogels.

SSE/t (dB · cm²/g) further normalizes SSE by the thickness of the shield:

$$\frac{SSE}{t} = \frac{SE}{\rho \cdot t} \quad (7)$$

The SSE/t value enables a direct comparison of the surface-area-specific shielding efficacy, which is crucial for practical, thin-film, or space-constrained applications (Song et al. 2025).

A concise overview of the key compositions and EMI shielding efficiencies of state-of-the-art aerogels is presented in Table 1.

Significant contributions have demonstrated that by engineering composite and nanostructured materials such as conductive aerogels, graphene/MXene foams, CNT-polymer hybrids, or hierarchically porous architectures, researchers can finely tune the contributions from reflection and absorption. Meanwhile, the design of highly porous interconnected structures extends the effective path length for wave migration, promoting multiple scattering and boosting the total EMI shielding, even at low densities. Practical devices require not only high total shielding effectiveness across relevant frequency bands (often aiming for $SE_T > 20$ dB (99.99% attenuation)), but also lightweight, mechanically robust, and multifunctional materials suitable for next-generation wearable applications. In this context, a mechanistic understanding of EMI

Table 1. Representative benchmark data of EMI-Shielding aerogels (2022–2025).

Material/ System	Structure	Density (mg/ cm ³)	SE (dB)	SSE (dB·cm ³ /g)	SSE/t (dB·cm ² /g)	Ref
Nanocellulose-MXene aerogel	Hierarchical, porous	4.1	40	9,756	189,400	Zeng et al. (2020)
Laminated CNT aerogel film	Layered, aligned	4.6	38.2	8,304	200,648	C. Fu, Sheng, and Zhang (2022)
Silver nanowire aerogel	3D conductive, ultralight	4.87	109.3	22,444	353,183	Peng et al. (2023)
MXene/PBO asymmetric aerogel	Asymmetric lamellar	7.7	61.8	8,026	39,742	A. Liu et al. (2025)

shielding anchored in the interplay of reflection, absorption, and internal scattering remains central to the rational design and synthesis of advanced shielding materials (Hareesh, Joseph, and George 2025; Iqbal, Sambyal, and Koo 2020; Shi et al. 2025). Figure 1(a) shows how EMI shielding works by blocking unwanted electromagnetic waves through reflection, absorption, and repeated internal reflections inside the material. The shielding performance mainly depends on the material's ability to conduct electricity and absorb energy. Figure 1(b) explains what happens when an EM wave hits a surface part of it is reflected, part is absorbed, and the rest part may pass through overall, the figures show how shielding materials reduce electromagnetic interference in a practical way.

Synthesis and fabrication of conductive aerogels

Sol-gel synthesis

Sol-gel synthesis is a wet-chemical process in which a molecular starting material (usually a metal alkoxide or salt) is hydrolyzed and condensed in solution to create a colloidal suspension that slowly assembles into a continuous gel structure with a 3D geometry. This network can then remove the liquid and heat-treat the solid to form metal oxides or hybrids with controlled composition, nanostructure, and porosity. A typical example of the intricate decision-making involved in the sol-gel method was reported by Pisarek et al. who investigated the structural stability of aerogels made with vinyltrimethoxysilane (VTMS). Their work explained the choice of precursor composition, the use of dual-crosslinking (via both siloxane and carbon chains), and the careful control of the aging process, thereby directly controlling key attributes such as gel structure, optical transparency, drying shrinkage, and bulk density. By changing the alcohol used in the sol (methanol and n-butanol) and adjusting the aging temperature, the authors demonstrated fine control over mass loss, volumetric contraction, and pore size, which are crucial applications in thermal insulation and lightweight cushioning (Pisarek et al. 2025).

Similarly, El-Cheikh et al. synthesized nanoporous ZnO/SiO₂ aerogels via an epoxide-assisted sol-gel route, enabling the co-gelation of zinc and silica at ambient temperature to produce hybrid aerogels with controllable pore structures, crystallinity, and thermal stability. By systematically varying the zinc precursors and chloride ion concentrations, the team engineered materials ranging from fluffy, thermally stable aerogels to robust, ceramic-like xerogels. This versatility highlights the power of sol – gel chemistry for engineering mixed-metal oxide frameworks with controlled pore structures, crystallinities, and thermal behaviors (El-Cheikh et al. 2025). Together, these studies underscore how even subtle adjustments in the sol-gel chemistry and post-gelation processing profoundly influence the aerogel composition, microstructure, and overall performance, reinforcing the importance of the sol-gel route in advanced aerogel design.

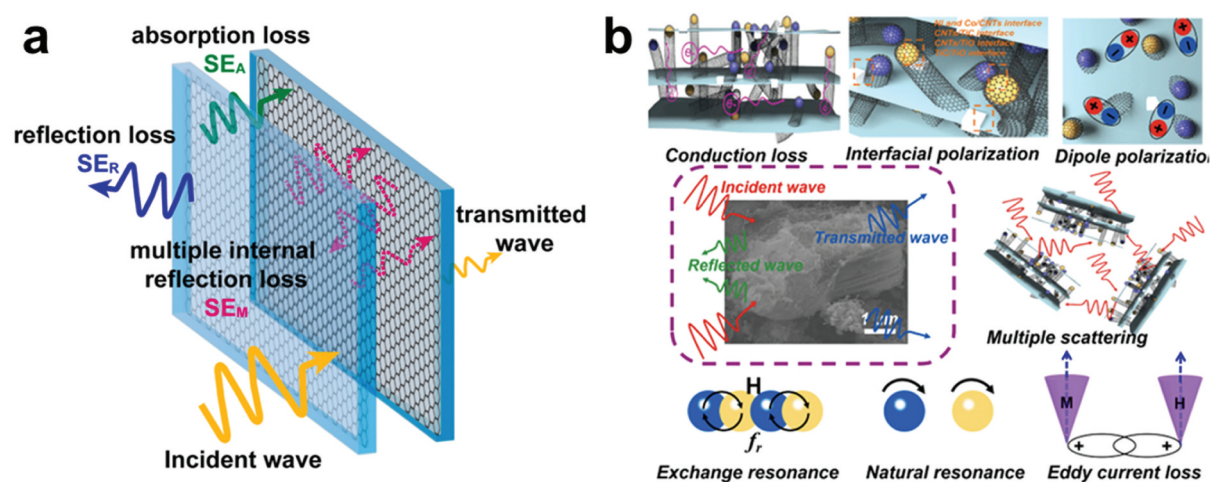


Figure 1. a) Diagram of EMI shielding mechanism (Cheng et al. 2023), b) schematic illustration of em wave mechanism (Kim and Byun 2024).

Vacuum freeze-drying method

Vacuum freeze-drying (lyophilization) is used to remove the solvent from a wet gel by freezing the pore liquid, then subliming the ice under low pressure, so that there is no liquid-vapor interface. Because capillary stresses are avoided to a large degree, the original pore structure is preserved with low-density, highly porous solids (commonly called cryogels or aerogels), which shrink and crack much less than in simple evaporative drying; however, traditional freeze-dried aerogels often suffer from brittleness, shrinkage, and structural collapse.

To address these limitations, Ma et al. refined vacuum freeze-drying technology, enabling the fabrication of crack-free superhydrophobic monolithic silica aerogels. In their method, the sol-gel reaction first forms crosslinked silica networks, followed by controlled freezing, which regulates ice crystal growth and determines the final pore structure. Vacuum freeze-drying removes solvents by sublimation, thereby eliminating the capillary stress that typically damages the gel structure. The resulting aerogels exhibited uniform porosity, improved mechanical integrity, and excellent moisture resistance, overcoming the microcracking issues common in conventional freeze-drying approaches (Y. Ma et al. 2025). Zhu et al. simplified this method by developing an energy-efficient freeze-drying process for polymer-based aerogels. For this process, researchers dissolved syndiotactic polystyrene (sPS) in a suitable solvent, aged it to initiate network formation, and freeze-dried it, avoiding the extensive solvent exchange steps required in earlier sPS aerogel processes. This rapid freezing and sublimation protocol produces low-density, highly porous aerogels with tailorable mechanical properties, while markedly reducing time and energy consumption. Collectively, these advances highlight freeze drying as an increasingly practical method for producing high-performance silica and polymer aerogels for thermal insulation, separation, and lightweight packaging applications (T. Zhang et al. 2025).

Qiao et al. presented a biomimetic approach to fabricate polyimide (PI)/CNT aerogels inspired by the macromorphology of the bovine omasum, a natural filtration apparatus with stratified, folded networks. Researchers have employed directional freeze drying combined with morphogenetic processing to recreate these complicated hierarchical folds, resulting in aerogels with core-radiating macroscopic channels, omasum-type microscopic folds, and nanoscale CNT bridges. This multiscale architecture enables exceptionally long dissipation pathways of EM waves, delivers remarkably high EMI shielding up to 71 dB alongside mechanical robustness, with a negative Poisson's ratio and 90% height retention after 500 compressive cycles, this multiscale structure enables exceptionally long dissipation pathways of electromagnetic waves. This work shows how careful adoption of biological motifs, along with more sophisticated approaches using advanced chemistry and processing strategies, can be used to create aerogels optimized for the specifications of specific materials needed for aerospace and wearable devices, balancing durability, thermal stability, and multifunctional shielding (Kim and Byun 2024).

Supercritical drying

Supercritical drying replaces the pore liquid with a fluid (usually CO₂ or alcohol). Then it increases the temperature and pressure beyond the fluid's critical point, where the distinction between liquid and gas no longer exists. The fluid in the supercritical state is then removed to eliminate capillary forces and produce crack-free, ultralight aerogels with extremely high porosity and surface area at the expense of more complicated high-pressure equipment. This introductory work focuses on producing silica aerogels through the synthesis of a combination of sol-gel techniques with supercritical drying as shown in Figure 2(a). In this process, silica gel is first prepared through a sol-gel reaction using precursors such as TEOS, which polymerize into a three-dimensional (3D) network. The gel was further reinforced by a subsequent aging process, followed by supercritical drying of the sample- solvent exchange between water and ethanol, and substitution of ethanol with liquid CO₂. The system is subsequently taken above the critical point of CO₂ (31.1°C, 73.9 bar), enabling solvent removal without inducing capillary pressures that would otherwise collapse the porous architecture of the gel. The obtained aerogels were highly transparent and exhibited a very open mesoporous structure with a uniform density. As shown by Blaszczyński et al. fine control over aging duration and solvent-exchange steps is essential for preserving the nanoscale pore structure and

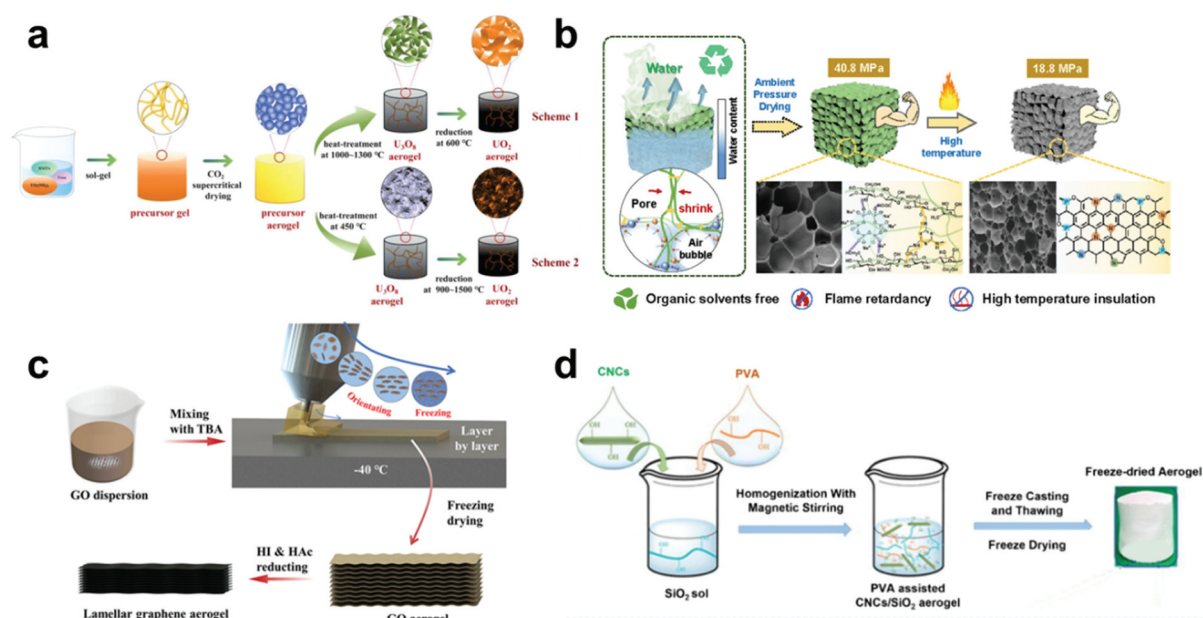


Figure 2. a) preparation of UO_2 aerogel by sol-gel method combined with supercritical drying (W. Wang et al. 2025), b) schematic illustration of ambient pressure drying (Zhan et al. 2024), c) scheme of 3D printing LGA process (H. Guo et al. 2022), d) schematic illustration of freeze drying (Y. Li et al. 2025).

ensuring that supercritical drying consistently yields low-density, high-surface-area silica aerogels with properties central to thermal insulation and engineering applications (Błaszczynski, Ślosarczyk, and Morawski 2013).

Basak et al. extended this concept by using supercritical drying as a green, sustainable method for preparing bio-aerogels derived from polysaccharides and proteins. Supercritical CO_2 drying is superior to traditional air and freeze drying because it minimizes pore collapse and preserves high porosity and surface area, both of which are significant factors for bioactive loading and water/oil absorption. The authors explained that the process starts with the formation of a hydrogel (through sol-gel chemistry) followed by solvent exchange, in which water is replaced by ethanol, and finally dried under supercritical CO_2 . The resulting bioaerogels exhibited high structural integrity and low thermal conductivity, making them suitable for food packaging and biomedical applications. This study also highlights the importance of biopolymer concentration in determining aerogel mechanical strength and emphasizes the need to optimize solvent-exchange kinetics for scalable production. Their environmental assessment concluded that supercritical drying saves energy and causes less structural damage than other drying methods for such materials (Basak and Singhal 2023).

Ambient pressure drying

Ambient pressure drying (APD) is a drying process in which a wet gel is dried directly at normal atmospheric pressure, rather than by supercritical drying or freeze-drying as shown in Figure 2(b). In APD, the sol-gel is initially surface-modified (or the solvent is modified) to minimize capillary stress, and then the solvent is evaporated at controlled temperature and pressure, allowing the porous skeleton to survive without collapsing and enabling cheaper, scalable aerogel production. Zhu et al. described an innovative technology for preparing silica aerogels using industrial solid waste as the primary source of silica. The synthesis begins with a sol-gel process, in which the sludge is reacted with NaOH and heated to extract silica, followed by ion exchange to remove impurities and pH adjustment to enable gelation. The resulting wet gel was aged in water to strengthen its network. Before drying, water was replaced with ethanol and, subsequently, hexane, both low-surface-tension solvents that reduce capillary forces and prevent pore collapse during evaporation. A critical improvement is the use of a silylation step (with trimethylchlorosilane (TMCS) or hexamethyldisilazane (HMDS)), which replaces hydrophilic –OH groups in the silica gel with hydrophobic – CH_3 groups. This modification

not only preserves the porous network during atmospheric drying but also prevents corrosion of the equipment. By systematically optimizing the ratios of silylation agents and thermal treatment conditions, aerogels with high porosity and thermal insulation were obtained. This study demonstrated that ambient-pressure drying can be used to produce high-quality hydrophobic silica aerogels from low-cost, sustainable raw materials, enabling scalable production (L. Zhu et al. 2018).

To address the shrinkage and structural degradation of cellulose-based aerogels, Tang et al. (2025) developed a physicochemical crosslinking strategy. This approach was initiated by the construction of a nanocellulose hydrogel, followed by careful modification and solvent exchange. Instead of alcohol solvents, which can be ineffective for some starting materials, their process leverages a tailored crosslinker and exchange protocol that maintains network integrity and, crucially, preserves pore structure during drying. By carefully controlling solvent replacement (water to low-surface-tension organics), pH and ionic strength, the method achieved shrinkage rate of about 10% without compromising porosity (higher than 95%), or bulk density (less than 50 mg cm^{-3}). The reported process is rapid, nondestructive, and scalable to large volumes, making it suitable for producing aerogels for thermal insulation, absorbents, and lightweight green composites. This work highlights the flexibility and growing significance of ambient-pressure drying in the production of sustainable biopolymer-based aerogels (Tang et al. 2025).

3D printing method

3D printing has emerged as a powerful tool for precisely shaping colloidal aerogels, as highlighted by Gu et al. involves the creation of a shear-thinning MXene-polymer ink, in which $\text{Ti}_3\text{C}_2\text{T}_x$ (with Fe_3O_4 and Ag nanowires in a CaCl_2 -crosslinked CMC matrix) comprises the primary conductive element, and where extrusion of this ink along programmed toolpaths is done by using 3D direct ink writing to create honeycomb-like lattice aerogels in which printing path, layer stacking, and a 35% fill density selectively control filament separation, pore structure, and anisotropy. Upon printing the wet constructs, the cross-linking and drying of the wet products are done to maintain the architecture and form ultralight porous aerogels with continuous conductive networks, such that when the MXene content is titrated to 40 wt percent and the 3D-engineered lattice is compressed to 60% strain the contact between the conductive pathways is increased and that the architecture provides an optimum EMI shielding effectiveness of approximately 80 dB tunable in situ through the strain exerted on the constructs (Y. Zhang et al. 2025).

As shown by Yan et al. 3D printing with Fused Deposition Modeling (FDM), in combination with post-dipping gradient coating of the CNT, produces a low-reflection EMI scaffold. This design and fabrication initially employed a triply periodic minimal surface (TPMS) type lattice with 70% porosity produced by FDM 3D printing, resulting in a lightweight and mechanically robust high-energy-absorption polymer scaffold. A monolithic layered dipping process was then applied to the printed TPMS, in which the same 3D scaffold was dipped to produce a controlled gradient distribution of CNTs across the thickness, while maintaining structural integrity. The outcome is a gradient-conductive 3D-printed scaffold (as shown in Figure 2(c)) with an increasing CNT content in the direction of propagation of the EM wave, a very low reflection power coefficient (~ 0.13), and an EMI SE $\approx 35.9 \text{ dB}$, which is a direct combination of architected TPMS 3D printing and gradient CNT deposition (Chongyang et al. 2025). Figure 2 highlights the different processing routes influence the final aerogel structure and properties.

Types of various aerogel composites for EMI shielding

Carbon nanomaterial-based aerogel

Carbon-based materials are an important category of EMI shielding media owing to their high electrical conductivity, low mass density, and strong electromagnetic attenuation properties, which are difficult to replicate with traditional metals or simple polymers. They can be systematically tuned in terms of their conductivity, whether to insulative sp^2 graphitic layers, highly conductive 1D CNTs, or 2D sheets of graphene, which allows them to match the impedance of free space and allow incident waves to couple into and dissipate within them instead of being fully reflected. Consequently, absorption prevails during the shielding process, resulting in less secondary radiation. Furthermore, carbon foams, aerogels, and

composite architectures have a large specific surface area and interfacial contact, which favor multiple scattering events and interfacial polarization losses; therefore, attenuation can be enhanced at relatively low filler loadings. The inherent properties of lightweight carbonaceous materials, such as corrosion resistance, chemical stability, and ease of manufacturing in the form of flexible, thin, or complex shapes, make them unavoidable for the construction of portable electronics, wearable products, and aerospace applications, where traditional metal shielding leads to problems of excessive mass or mechanical rigidity.

CNT-Based aerogels

CNTs are unique owing to their one-dimensional conductive networks, high aspect ratios, and large specific surface areas (Pyo et al. 2022). Their tubular and nanoscale structures facilitated the formation of continuous, percolated electron-transport networks at relatively low loadings and contributed significantly to conduction loss and incident electromagnetic wave reflection. The abundance of interfaces and structural defects on the CNT walls further contributes to interfacial polarization and polarization rest between grid structures, leading to multi-scattering and high dielectric losses as electromagnetic waves pass through the CNT grid. The frequency-dependent alternating-current conductivity of CNTs and the relatively small skin depth at gigahertz frequencies are properties that are preferable for absorbing the electromagnetic energy of skin depth rather than reflection, as is the case with thin sections. Together with their low densities and mechanical strengths, these electrical and interfacial characteristics make CNT networks much more effective than lightweight absorption-based EMI shielding films, foams, and aerogels.

Zhao et al. were the first to demonstrate a laminated structural engineering method that generated freestanding CNT-based aerogel films with densified porous structures and preferential orientation as shown in Figure 3(a). The films have a phenomenal specific surface area of $341.9 \text{ m}^2/\text{g}$, a staggering ultra-high electrical conductivity of 8540 S/m and a record breaking absolute (SSE/t) in excess of $200,647.9 \text{ dB-cm}^2/\text{g}$ with, at the same time, continuous conductive pathways, adjustable wettability, and impressive Joule heating performance – an elegant path to lightweight, high-performance EMI shielding and wearable

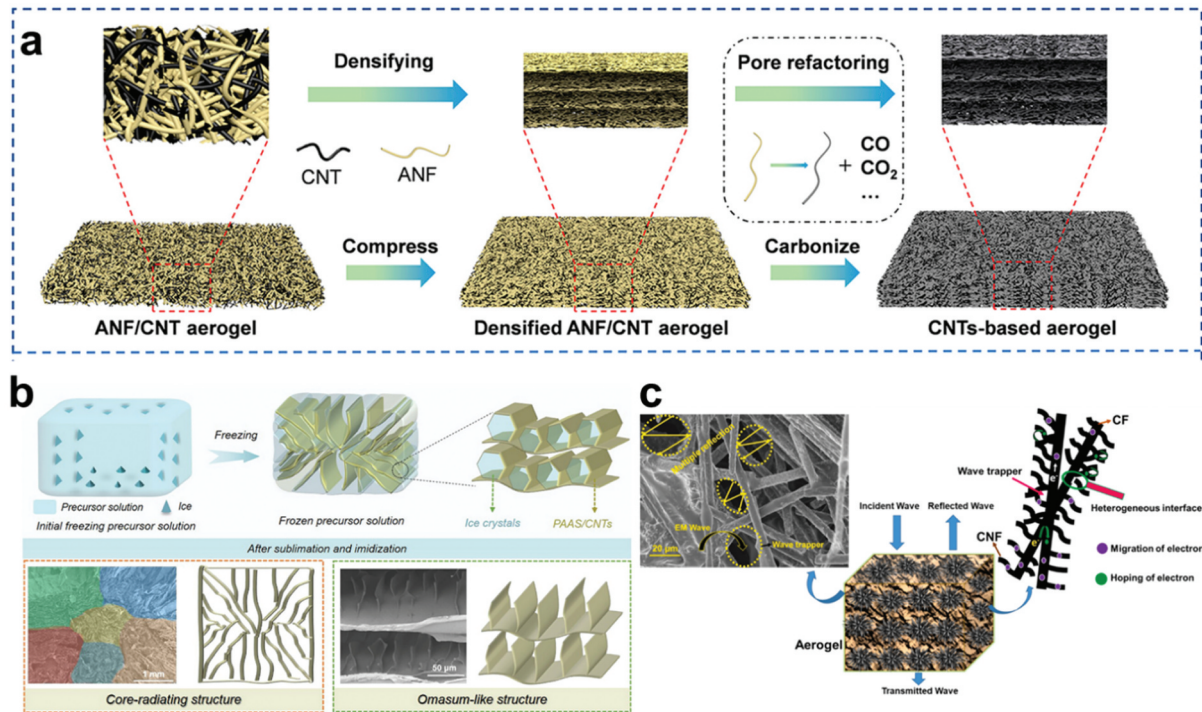


Figure 3. a) ANF/CNT aerogel film can be formed with a three-dimensional fiber network. By directional compressing, the lamination structure can be generated. Following carbonization, CNT-based aerogel film with a dense fiber layer and laminated structure can be obtained as well as pore refactoring in between the layers (C. Fu, Sheng, and Zhang 2022), b) design principle and fabrication process of aerogels with a core-radiating structure and omasum-like morphology (Qiao et al. 2025), c) shielding mechanism in CNF@CU/PEDOT:PSS/PU aerogel (Bose et al. 2023).

heating (C. Fu, Sheng, and Zhang 2022). Building on this concept, Chen et al. developed a hierarchical carbon nanostructure comprising sea-urchin-shaped carbon nanofibers (CNFs) by microwave heating self-assembled carbon urchins incorporated into a PEDOT:PSS ionomer matrix, followed by freeze-drying to form an ultra-light aerogel. The CNF@CU (Carbon Urchin) aerogel provides -50.8 dB EMI shielding (99.999% blocking) at the X-band in synergy with conductive, interface, and dipole polarization losses, in addition to flame retardancy and an efficient block to Bluetooth signals, with just 1.7 wt% additive as shown in Figure 3(c) (Bose et al. 2023). In 2024, Scalable CNT yarn laminate composites reported by Liang et al. were shown to be superior to conventional carbon-fiber reinforced polymers (CFRPs), with more than twice the specific tensile modulus, similar specific tensile strength, and a significantly higher in-plane thermal conductivity (75.78 W/mK) and longitudinal electrical conductivity (5359 S/cm). Their EMI shielding exceeded 100 dB in the X-band, nearly twice that of CFRP, demonstrating the potential of CNT laminates to perform mechanically, thermally, electrically, and electromagnetically simultaneously (Evers et al. 2024).

Most recently, Martinez et al. employed a morphogenetic freeze-drying technique to produce polyimide/CNT aerogels with triaxial hierarchical structures, such as core-radiating macroscopic structures, omasum-like microscopic folds, and CNT bridges of nanoscopic size, to lengthen EM Wave dissipation chains as shown in Figure 3(b). These aerogels had a high EMI shielding effectiveness of 71 dB, a specific efficiency of 6470 dB·cm²·g⁻¹, and maintained 90% of their height across 500 compressive cycles, demonstrating exceptional adaptability, mechanical stability, and resistance to thermal cycling. Taken together, these developments focus on the physics and chemistry of the converging approach of tailored micro- and nanoarchitectures, synergistic compositions, and scalable fabrication methods to produce CNT aerogels that break conventional trade-offs and open new opportunities for ultralight, multifunctional structural and protective systems (Qiao et al. 2025).

Graphene-based aerogels

Graphene is also known to have an extremely high intrinsic electrical conductivity, a large specific surface area, and a 2D conjugated structure that, when combined, provides efficient interaction with electromagnetic waves (Xiang et al. 2022). Planar sheets of atoms readily form continuous conductive networks in films, foams, and aerogels, providing low-resistance conductive channels for induced currents and high reflection at the air-shield interface. Simultaneously, the high density of defect sites, surface functional groups (in the case of graphene oxide or reduced graphene oxide), and the high surface-to-bulk interface (high defect density) allow interfacial polarization and dipole relaxation, facilitating dielectric loss and absorption during wave propagation through graphene. The interconnected pores and tortuous routes formed when constructed as 3D porous structures, such as graphene aerogels, foams, or laminated structures, allow numerous internal reflections and propagation distances. Therefore, incident waves are scattered and attenuated many times before leaving the structure, resulting in absorption-dominated shielding, even in denser materials with low density.

In literature, GO was included to enhance the aerogel structure (Figure 4a), maintain the low density (0.074 – 0.185 g/cm³), and inhibit contraction. Such aerogels exhibit highly anisotropic insulation properties, a low radial thermal conductivity (0.038 W/mK), and, when they contain high concentrations of GO, remarkable electrical conductivity (0.77 S/cm) and EMI shielding capabilities of up to 54.6 dB. The entire procedure is simple and environmentally friendly, yielding aerogels that are superior in insulation and EMI shielding (Jiang et al. 2022). Building on this concept, Gao et al. fabricated ultra-stable face-to-face stacked graphene aerogels that are well suited for real-world EMI shielding under severe conditions. The ultralight graphene aerogel (GA) (3.7 mg cm⁻³) exhibited an enormous shielding efficiency of 64.1 dB with 1 mm thickness, and a remarkable specific EMI SE of $173,243$ dB·cm²·g⁻¹ as shown in Figure 4b. The robust stacked building maintains the shielding performance at high levels even when the shielding is subjected to mechanical deformation, extreme temperature, exposure to flames, and under a water environment, and addresses the low-density/large-volume dilemma by means of the use of the vacuum bagging without compromising the performance of the shielding (E. Zhu et al. 2023).

In 2022, Liu et al. developed an eco-friendly, high-performance way of making lightweight, anisotropic carbon/graphene composite aerogels by freezing a polyamic acid ammonium salt/graphene oxide (PAS/GO) suspension unidirectionally and then lyophilizing, thermal imidizing, and oxidizing it. The resultant aerogels have a tubular, oriented pore structure, which reduces the volume shrinkage and produces low

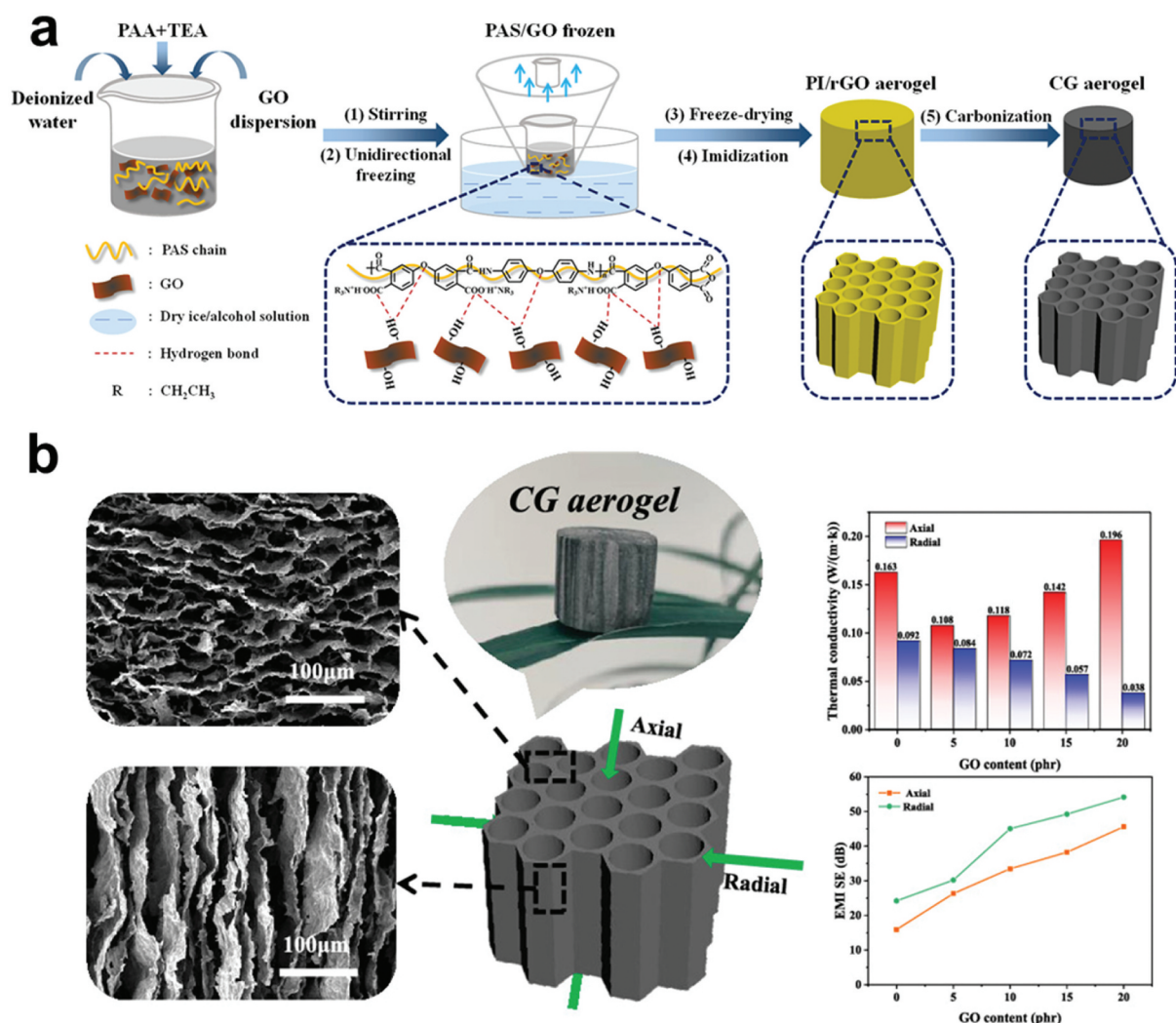


Figure 4. a) schematic illustration for the preparation of graphene aerogel, b) EMI shielding performance of GO aerogel (Jiang et al. 2022).

densities ($0.0740.185 \text{ g/cm}^3$). Addition of graphene oxide improves structural integrity of the structure and gives anisotropic thermal insulation, and the radial thermal conductivity is low at $0.038 \text{ Wm}^{-1}\text{K}^{-1}$. The composites with the content of GO rose to 20 phr exhibit excellent electrical conductivity (0.77 S cm^{-1}) and a high electromagnetic interference shielding (54.6 dB), which is indicative of a sustainable approach to the production of high-performance carbon aerogels as shown in Figure 3 (Jiang et al. 2022).

Zhang et al. introduced a flexible emulsion-based approach to produce ultralight, elastic, and highly conductive graphene aerogels by forming Pickering emulsions of GO, poly(amic acid), and octadecylamine. The resulting aerogels exhibited micron-scale close-pore structures, thermally induced nanowrinkles, and molecular-scale bridging from PAA-derived carbon, which collectively increased the structural integrity. These multiscale characteristics enable the creation of aerogels with ultralow density ($\sim 3.0 \text{ mg/cm}^3$), high electrical conductivity, excellent thermal insulation, high EMI shielding (75.0 dB), 90% strain-compressibility, and excellent fatigue resistance. In addition, their gel-like emulsion characteristics enable programmable 3D printing of ultralight graphene scaffolds, providing a general approach to advanced lightweight and superelastic graphene aerogels with promising EMI shielding applications (Y. Zhang et al. 2024).

In 2024, Feng et al. developed a superelastic graphene/polyimide fiber/CNT composite aerogel (G-PI@F20/CNT) that overcame the typical trade-off between high interfacial density and fatigue resistance in nanomaterial-based aerogels. It maintains superelasticity and endures 90% compressive strain cycling

across extreme temperatures (-196 to 160 °C) with less than 5% irreversible deformation. The porous network effectively suppresses phonon conduction, resulting in low thermal conductivity ($0.0313 \text{ W m}^{-1} \text{ K}^{-1}$). In electromagnetic wave absorption, the aerogel achieves an effective absorption bandwidth of 12.48 GHz at 4.1 mm thickness and ultra-broadband (15.24 GHz) absorption at 20.3 mm thickness, with a minimum reflection loss of -43.49 dB. These results highlight a versatile strategy for designing superelastic, thermally insulating, and high-performance EMW-shielding aerogels (Yue et al. 2025).

Han et al. proposed a heterogeneous carbon-stacking technique to fabricate an all-carbon 3D hybrid aerogel (rGO-CNT-VG) to modify epoxy resin. The covalent bonding between the components and the hierarchical structure enhanced charge transport and interfacial polarization, thereby efficiently attenuating EM waves. As a result, the composite exhibited better EMI shielding performance of 56.65 dB and thermal conductivity of $2.46 \text{ W m}^{-1} \text{ K}^{-1}$ compared to conventional rGO/epoxy composites. This work highlights the significance of microstructural control for multifunctional performance by precisely tuning carbon-based composites, with strong potential for thermal management and EMI shielding (Han et al. 2023). In 2023, Du et al. designed a 3D CNT/graphene aerogel film (CGAF) that resembled a natural leaf structure, where CNTs encased within graphene resembled veins and mesophyll. The 3D architecture enhanced the SE_T to 26.6 dB, surpassing those of both the compressed and CNT-free aerogels. Rather than predominantly reflecting electromagnetic waves, the structure promoted multiple internal reflections and absorption, thereby increasing the attenuation efficiency. The specific shielding effectiveness by mass (SEMA) is $12,091 \text{ dB}\cdot\text{cm}^2\cdot\text{g}^{-1}$. A multilayer CGAF with polydimethylsiloxane (PDMS) has an SE_T of 74.7 dB at 8.2 GHz and maintains an SE_T of 45.6 dB even after 100 bending cycles, demonstrating excellent flexibility and durability, along with high performance exceeding industrial requirements (H. Liu et al. 2022).

Gu et al. reported an ultralight, environmentally friendly, cotton nanocellulose-based porous carbon aerogel capable of simultaneously achieving infrared (IR) and radar stealth. A 3D macroporous system was designed to balance thermal radiation control (IR Stealth) and EM wave attenuation (radar absorption). The aerogel showed a low infrared emissivity of 0.56 in the $3\text{--}5 \mu\text{m}$ band and 0.52 in the $8\text{--}14 \mu\text{m}$ band, a minimum reflection loss of -19.8 dB, and a maximum effective absorption bandwidth of 4.64 GHz, spanning the X and Ku bands and partially extending into the C band. The numerical radar cross-section simulations suggested a significant reduction in radar cross-section (RCS) to $15.86 \text{ dB}\cdot\text{m}^2$, confirming its ability to reduce radar detectability. Overall, this study concluded that biomass-derived lightweight porous carbon aerogels can serve as IR-radar-compatible stealth and provide a sustainable path toward multiband camouflage materials (Gu et al. 2024).

MXene-based aerogels

Bulk MXene-based systems leverage their metallic-level conductivity, two-dimensional lamellar structure, dense surface chemistry, and analogs to form highly efficient electromagnetic attenuation channels (Zaed et al. 2024). Their extreme electrical conductivity and variable surface endings ($-\text{OH}$, $-\text{O}$, and $-\text{F}$) result in an enormous impedance disparity at the air-shield interface, promoting reflection and, at the same time, strong electricity loss and interfacial polarization in the bulk media. At low densities, when stacked into three-dimensional porous structures or hybrid aerogels (usually with graphene, polymers, or hollow spheres), MXene sheets create interlaced lamellar or cellular frameworks that increase a variety of internal reflections and cooperative dielectric/magnetic losses, providing shielding efficiencies with easy reach of over 70–80 dB and simultaneously attaining a very high SSE and SSE/t. In addition, MXenes are solution-processable and printable, compatible with flexible substrates, and enable the fabrication of ultrathin, shape-adaptable, and multifunctional EMI shields for next-generation wearable, aerospace, and high-frequency electronic applications (J. Fu et al. 2025).

Liu et al. presented a 3D printing (direct ink writing) strategy for manufacturing lightweight, stiff MXene/GO aerogels (SMGAs) with tunable electromagnetic absorption performance. Although MXenes are highly conductive and exhibit EM wave dissipation, their high reflectivity leads to an impedance mismatch, limiting their absorption efficiency. To address this, the fret-like structural design of the SMGAs enabled a maximum -61.2 dB difference in reflection loss to be achieved by varying the structural width. These aerogels exhibited a broad, tunable effective absorption band at 14.05 GHz, spanning the C, X, and Ku bands. Their hierarchical, well-aligned 3D structure had high mechanical stiffness and exceptional

compression resistance, capable of supporting 36,000 times their own weight without observable deformation. Finite element analysis confirmed that the structural hierarchy effectively dispersed the stress. Overall, this study demonstrates an efficient, scalable method for fabricating tunable, lightweight MXene-based EM wave absorbers with high mechanical strength (X. Liu et al. 2023).

Building on this concept, Wu et al. described an ambient-pressure-drying (APD) methodology for the rapid, energy-efficient, and scalable production of large-area, multifunctional MXene-based aerogels featuring polyurea and transition-metal carbides/nitrides. By leveraging self-foaming, dip-coating, and graphene-oxide-assisted crosslinking, these aerogels exhibited low density, high mechanical strength, and remarkable ultraflexibility, including stretchability and resilient conductivity. The synergy of robust, elastic cell walls and a tailored porous structure enables the superior absorption of high-frequency mechanical shock waves, outperforming standard alternatives such as plastics, ceramics, and metals. APD MXene aerogels exhibit potent broadband microwave shielding capabilities (over 40 dB at 4–40 GHz as shown in Figure 5(c)) and enhanced oxidation stability, supporting their utility in extreme environments. Moreover, their strong light absorption translates into efficient photothermal conversion, antibacterial action, water purification, and oil absorption, thereby extending their application scope to the aerospace industry, device protection, and next-generation electronics (Zheng et al. 2024).

Qi et al. reported multifunctional asymmetric bilayer aerogels for broadband absorption-dominated EMI shielding. The aerogels were fabricated by sequentially printing an MXene-GO (MG) layer and a conductive MXene layer, then freeze-drying to form multiscale porous structures. The top MG layer, optimized by matching the impedance and secondary absorption, was facilitated by the lowest MXene layer, and on average, the absorption coefficient reached 0.95 along the X-band and tunable absorption at a frequency range of 8.24–30 GHz. Simulations confirmed the effectiveness of the bilayer configuration in promoting EM-wave attenuation as shown in

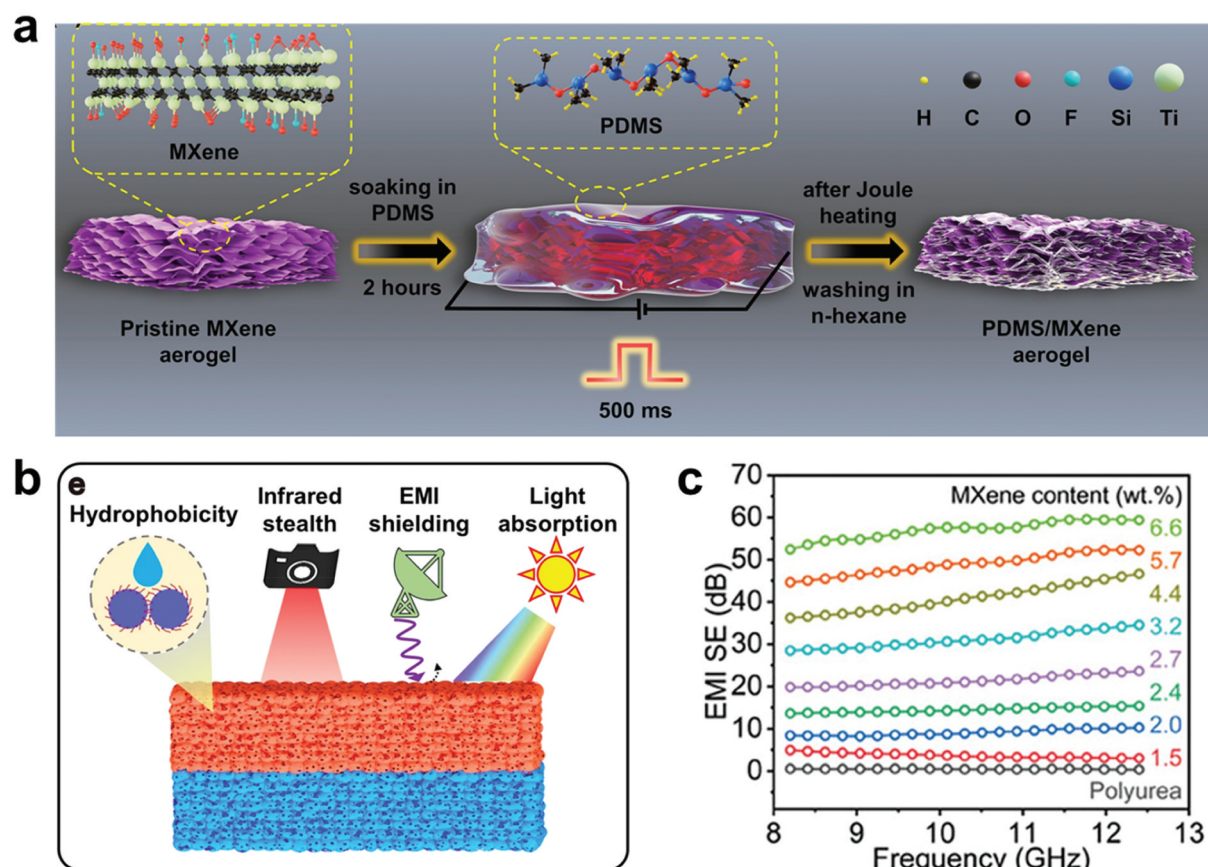


Figure 5. a) schematic illustration of the synthesis of JPM aerogel (Deb et al. 2024), b) schematic illustrating multifunctionalities of the bilayer aerogels (Qi et al. 2025), c) EMI shielding performance of APD MXene-based aerogels (Zheng et al. 2024).

Figure 5(b). Additional multifunctionalities such as hydrophobicity, thermal insulation, Joule heating, solar-thermal/electric heating, infrared stealth, and good oil cleanup highlight their wide application potential (Qi et al. 2025).

Finally, Subramanian et al. demonstrated a Joule-heating-driven, PDMS crosslinking approach to reinforce MXene aerogels as shown in Figure 5(a). In this method, ultrafast voltage pulses reduce PDMS curing to a thin layer on the quasi-oriented 3D MXene skeleton, enabling sub-second tuning of the PDMS content while maintaining a low density and internal porosity. The resultant MXene-PDMS aerogel (JPM) was light, mechanically robust, hydrophobic, and very simple, with enhanced multifunctionality compared to conventional PDMS-filled MXene aerogels. It exhibited extremely high absolute EMI shielding efficiency per unit density and thickness ($SSE/t \approx 17,752 \text{ dB} \cdot \text{cm}^2 \cdot \text{g}^{-1}$), supported efficient electrothermal deicing at just 4 V by rapidly reaching $>200^\circ\text{C}$, and functioned as an extremely sensitive strain sensor with the ability to measure human motions and even extremely weak vibrations such as pulse signals (Deb et al. 2024).

Metal-based aerogels

Metal-based aerogels are composed of metal nanoparticles or nanowires, such as silver or copper. Metals are naturally excellent conductors; these aerogels can block or absorb EM waves effectively and often exhibit high shielding, even at very low thicknesses and densities (Kefeni and Mamba 2020). Wang et al. fabricated a biomass-based, low-cost EM wave absorber by coating cellulose-based carbon aerogels with magnetic FeCo-alloy nanoparticles as shown in Figure 6(a). First, Fe^{2+} and Co^{2+} ions were absorbed by the cellulose hydrogel, which was subjected to hydrothermal treatment and freeze drying to produce CoFe_2O_4 aerogels, followed by calcination to produce FeCo-decorated cellulose carbon aerogels (FeCo@CCA). The hydrothermal process enhances the homogenous distribution of FeCo nanoparticles throughout the porous carbon network, and these features jointly improve the impedance matching and introduce strong dielectric and magnetic losses. The hierarchical porosity of the aerogel also facilitates additional reflection and scattering of incident EM waves, thereby enhancing attenuation. Optimizing metal ion concentration significantly improves the EM wave absorption; at 100-mmol/L (FeCo@CCA-100) material achieved reflection loss (RL) of 49.5 dB at a frequency of 9.84 GHz with a thickness of 4.05 mm and an effective absorption bandwidth of 10.88 GHz spanning the entire X and Ku bands and a portion of the C band. Overall, this research demonstrates a sustainable design method for achieving high-efficiency EM absorbers using cellulose-based carbon aerogels with adaptable broadband EMW absorption (Y. Guo et al. 2022).

Recently, Shen et al. extended this concept by employing natural wood as a 3D template to synthesize lightweight magnetic metal-loaded wood-carbon aerogel composites loaded with FeCo, Fe, and Co nanoparticles (FeCo@WCA, Fe@WCA, and Co@WCA) to combine EM shielding and microwave absorption. Here, metal-organic complexes were *in situ* loaded onto the aerogel skeleton through a solvothermal method. The hierarchical porous structure of the wood facilitated multiple reflections and scattering of EM waves, while metal nanoparticles contributed to very strong magnetic losses and improved impedance matching. All composites delivered EMI shielding performance exceeding 60 dB and a minimum RL of approximately -50 dB, indicating an efficient absorption-dominated behavior as shown in Figure 6(b). Additionally, these composites demonstrated high electrothermal conversion, rapid temperature reactions, and thermal stability, offering a sustainable pathway toward high-performance wood-based carbon aerogels for EM shielding and absorption tasks (Shen et al. 2025).

Further advancements have been demonstrated in strong SiC@carbon nanowire aerogels, as reported by Liu et al., who found that 3D printing combined with graphene-like carbon deposition was suitable for aerospace-grade EMI shielding. The resulting aerogels exhibited compressive strength of 1.581 MPa, Young's modulus of 46.230 MPa (approximately 50–60 times higher than usual), and a high EMI shielding capability of 38.39 dB and high specific EMI performance of $666.53 \text{ dB} \cdot \text{cm}^3 \cdot \text{g}^{-1}$. These significant attributes were attributed to the synergistic relationship between the hierarchical design and the SiC@carbon nanowire network, establishing a pathway toward lightweight yet mechanically strong EMI protection materials for next-generation aerospace and automotive systems (P. Guo et al. 2024).

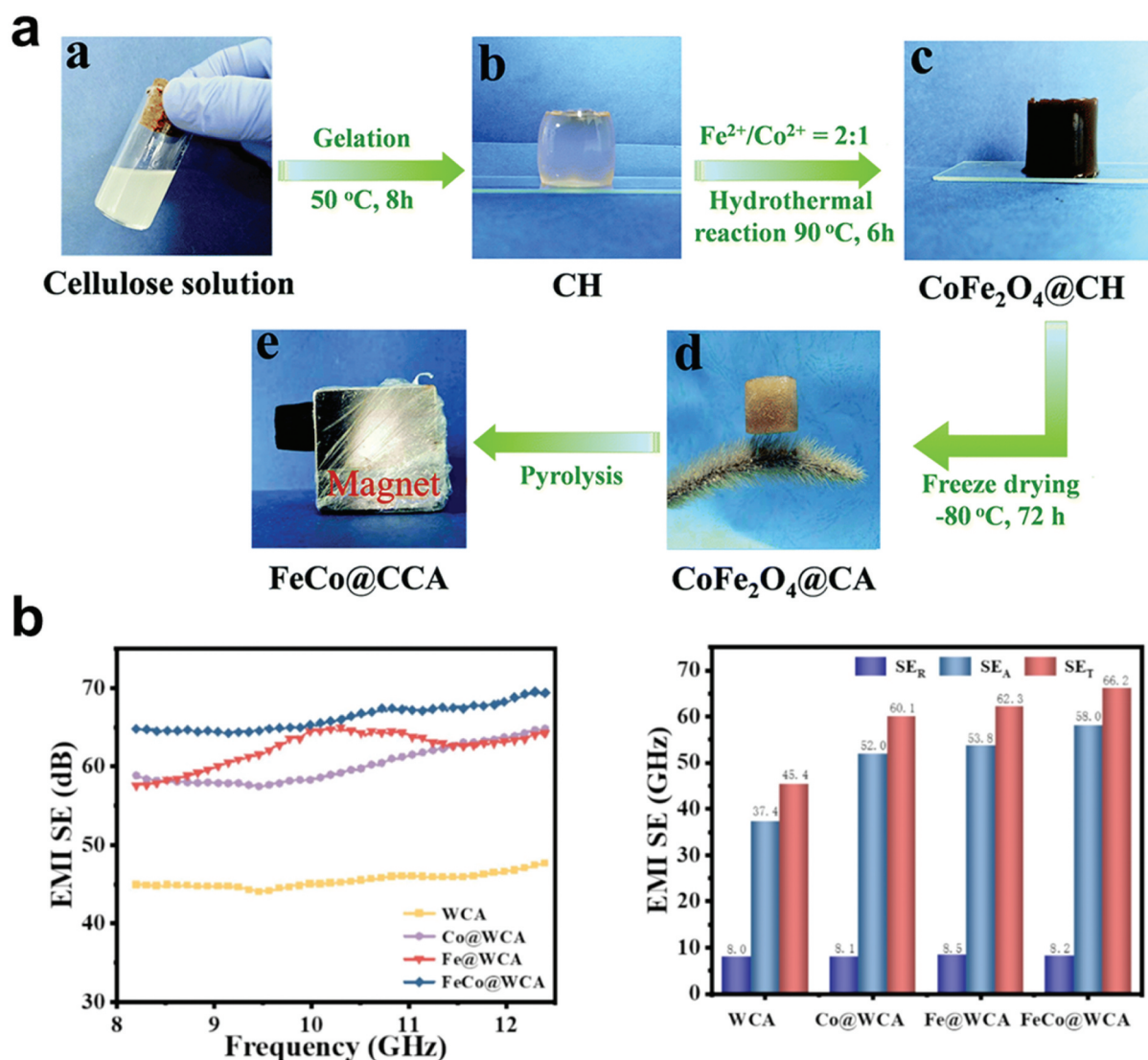


Figure 6. a) schematic illustration showing the preparation process of FeCo@CCA (Y. Guo et al. 2022), b) EMI se of WCA, Fe@WCA, Co@WCA, and FeCo@WCA (Shen et al. 2025).

Liquid metal-based aerogel

Highly conductive fillers such as metal powders, MXene, and carbon materials are widely used to build porous aerogels for high-performance EMI shielding; however, their intrinsic rigidity often leads to mechanical mismatch and interfacial stress failure within the matrix. This limits the long-term durability and remains a major challenge for flexible shielding systems. In recent years, liquid metal (LMs)-based alloys, especially gallium (Ga)-based alloys, have offered promising alternatives for wearable EMI shielding applications owing to their high conductivity, fluidity, and ability to deform synchronously with soft networks. Unlike rigid fillers, LMs minimize the stress concentrations and maintain stable electrical pathways under strain. Moreover, Ga-based LMs can generate free radicals under ultrasonic treatment, enabling in situ polymerization and the formation of ionically crosslinked structures without external initiators. These unique mechanical and chemical advantages make LMs transformative fillers for next-generation flexible and durable EMI shielding aerogels. Xu et al. created an Al₂O₃@LM/borax-crosslinked PVA (Al₂O₃@LM/BCP) aerogel with excellent EMI shielding ability. The shell coated with the Al₂O₃ shell through mechanical grinding offers better compatibility with the PVA matrix by lowering the high surface tension of the LM. It was prepared by mechanical grinding, crosslinking of the melted materials, and directional freeze-drying to form a conductive, porous structure. Consequently, the composite aerogel exhibits high

Table 2. EMI shielding performance of Representative aerogels reported in literature.

Type	Density (mg/cm ³)	SE (dB)	Mechanical Resilience	EM Mechanisms	Ref
Graphene-Based	9–30	43–130	Elastic, compressible	Absorption-dominated	Du et al. (2022); Feng et al. (2022)
CNT/CNF	<20	35–80	Stretchable, fatigue	Abs/Reflection	Lv et al. (2025); Yang et al. (2023)
MXene-Based	<50	70–130	Fatigue, fireproof	Abs/Dielectric/Magnetic	Du et al. (2022); Sambyal et al. (2019)
Metal NW/Magnetic	10–30	48–109	Flexible, transparent	Conductive, magnetic	Y. Guo et al. (2022); He et al. (2024)
Polymer Composite	<25	30–80	Tough, foldable	Percolative network	Lv et al. (2025); Sozcu et al. (2023)
Bioinspired/Cellulose	<25	40–70	Sustainable, stretchable	Hierarchical interfaces	Sozcu et al. (2023); J. Zhang et al. (2024)

electrical conductivity (312.5 S/m), high EMI shielding efficiency (80.9 dB), and a high absorption ratio (SEA/SET of 83.9%), thereby providing an efficient and simple means to design flexible, high-performance EMI shielding materials (Chen et al. 2025).

Building on this concept, Hao et al. developed a shape-memory-based liquid metal/polyimide/aramid nanofiber (LPA) composite aerogel that can switch between EM absorption and shielding, as reported in the work. This material addresses the problem of EM absorption, which requires high dielectric and conduction losses, while EM shielding typically relies on reflection and blocking, which may be difficult to combine and tune in a single system. The LPA aerogel involves reconstructing the porous structure via compression and reconfiguring the network of liquid metals to continuously tune electrical conductivity. Consequently, because of its shape-memory effect, which allows it to repeat and switch reversibly, the aerogel shows good repeatability and reversible switching. The shape memory effect allows it to become a pure EM absorption material with an effective absorption bandwidth (EAB) of up to 8.91 GHz reversibly at low compressive strains of about 20–40%. Its overall EMI shielding efficiency of approximately 28.21 dB at high strains of 50–80% is superior to most current intelligent EM materials, which have only single- or less-tunable applications (S. Wang et al. 2025).

An overview of representative literature-reported aerogels and their EMI shielding capabilities is presented in Table 2.

Future prospects

Conductive aerogel EMI shielding primarily operates through absorption-dominated mechanisms: incident waves are partially reflected at the air/aerogel interface and then attenuated within the highly porous, conductive 3D network by ohmic loss, polarization loss at heterointerfaces, and multiple internal reflections along tortuous paths, with the EM energy finally converted to heat or microcurrents. The ultra-high porosity (usually > 99%), interlaced conductive skeleton, and tunable impedance of graphene/MXene/carbon aerogels result in a significant reduction in front-surface reflection and favor an “absorption-reflection-reabsorption process,” currently of interest for next-generation low-pollution EMI shielding.

From a methodological perspective, the current effective routes of freeze-drying, supercritical drying, directional freezing, and wet spinning or filamentous assembly are powerful for engineering porosity and absorption pathways, but remain energy-intensive and difficult to scale to large or complex 3D shapes with precise gradients. Recent work on conductive filler – integrated hydrogels (CFHs) and derived aerogels emphasizes that controlled gel chemistry (double-network, ionic and covalent crosslinking), in-situ polymerization of conductive polymers, and heterointerface engineering (e.g., poly (3,4-ethylenedioxythiophene) (PEDOT): polystyrene sulfonate (PSS), polyaniline on carbon networks) can provide continuous conductive paths with improved toughness and self-healing, yet reproducibly translating these chemistries to thick, monolithic aerogels or films is still non-trivial.

Future development using conductive aerogels is therefore moving toward structure – method coupling, where fabrication methods (3D printing, filamentous aerogels, gradient dipping, and impregnation) are deliberately used to encode graded conductivity, asymmetry, and hierarchical porosity that favor absorption-dominated, low-reflection shielding. For example, filamentous aerogels and printed lattices built from MXene/CNT, carbon nanofiber – polymer, or biomass-derived carbon filaments enable the rational design of paths for “absorption – reflection – reabsorption”

and the integration of multifunctionality, such as thermal insulation, Joule heating, and sensing. At the hydrogel – aerogel level, high-impact reviews suggest combining CFHs with directional freezing, ion-triggered or photo-triggered gelation, and solvent-exchange strategies that reduce drying stresses to yield elastic, fatigue-resistant, conductive aerogels better suited for wearable and structural EMI shields.

In the future, useful approaches will likely focus on (i) programmable processing (DIW/FDM/filamentous assembly to apply controlled gradients and anisotropy), (ii) robust interfacial design (conductive polymer shells, heterointerfaces, and magnetic-dielectric hybrids) to stabilize networks and tune impedance, and (iii) integrated testing and modeling to correlate processing parameters with EMI performance over extended bands. Bridging lab-scale chemistries with scalable manufacturing routes, including roll-to-roll casting of conductive aerogel films, continuous extrusion of filamentous aerogels, and low-temperature drying compatible with large-area components, will be essential for translating conductive aerogel EMI shields into practical, lightweight, and low-reflection materials for next-generation electronics and 5G/6G infrastructure.

Conclusion

The consistency between the aerogel type and the preparation methodology is central to the development of next-generation EMI shielding materials. As shown systematically in this review, neither the composition nor the processing of aerogels can be regarded as independent entities seeking optimal performance and multifunctionality in EMI management.

Graphene, MXene, CNT, metal nanowire, polymer composite, or cellulose aerogels are gleaned with a maximum of two sources of atypical properties, not only the materials that compose them, but also a sequence of structural designs enabled by the specific synthesis approaches. For example, metal nanowire aerogels prepared via controlled freeze-drying exhibit high mechanical strength and conductivity through end-to-end joining, resulting in new record values in EMI (SE) and (SSE/t), along with ultralight densities. The hierarchical porosity of graphene aerogels made by either chemical reduction or advanced additive manufacturing is tunable and enables absorption-based shielding through multiple internal reflections and variable polarization losses. Such effects can only be made possible via well-planned sol-gel methodology, directional freezing, or 3D printing- each of which introduces unique and beneficial microstructures.

The relative evaluation revealed that the best EMI-shielding aerogels were those in which the selection of the conductive filler or matrix was closely aligned with the processing strategy. For example, by combining MXene nanosheets and nanocellulose via directional assembly and freeze-drying, the conductivity and flexibility are balanced, whereas bioinspired or 3D-printed structures can be used to maximize performance and compatibility for wearable and flexible electronics. Notably, the new approach uses absorption-based, lightweight, and multifunctional shields, shifting away from traditional metallic reflectors toward sustainable, stretchable materials designed to span a wide frequency spectrum.

In conclusion, state-of-the-art EMI shielding cannot be achieved by merely selecting the best-performing aerogel, nor by using existing technologies. Rather, it requires a holistic design philosophy, in which the selection of materials, processing pathways, and end applications is considered at the outset. The future of filler chemistry, as well as hierarchically assembled, scalable 3D-adaptable production, is expected to deliver not only highly effective EMI shields but also products ready for implementation in next-generation devices. Further interdisciplinary efforts at the interface of materials chemistry, processor science, and application engineering are essential to achieve the full potential of aerogel-based EMI shielding.

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Author contributions

CRedit: **Sonali Thangavel:** Data curation, Formal analysis, Investigation, Methodology, Resources, Validation, Visualization, Writing – original draft; **Thirumalaisamy Suryaprabha:** Data curation, Resources, Visualization, Writing – review & editing; **Danhui Ren:** Visualization, Writing – review & editing; **Jun Young Cheong:** Visualization, Writing – review & editing; **Sooman Lim:** Visualization, Writing – review & editing; **Byungil Hwang:** Conceptualization, Funding acquisition, Investigation, Project administration, Resources, Supervision, Validation, Visualization, Writing – review & editing.

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References

- Aswathi, M., A. V. Rane, A. Ajitha, S. Thomas, and M. Jaroszewski. 2018. “EMI Shielding Fundamentals, Advanced Materials for Electromagnetic Shielding: Fundamentals, Properties, and Applications.” *Advanced Materials for Electromagnetic Shielding: Fundamentals, Properties, and Applications*. 1–9. <https://doi.org/10.1002/9781119128625>.
- Basak, S., and R. S. Singhal. 2023. “The Potential of Supercritical Drying as a “Green” Method for the Production of Food-Grade Bioaerogels: A Comprehensive Critical Review.” *Food Hydrocolloids* 141:108738. <https://doi.org/10.1016/j.foodhyd.2023.108738>.
- Błaszczczyński, T., A. Ślosarczyk, and M. Morawski. 2013. “Synthesis of Silica Aerogel by Supercritical Drying Method.” *Procedia Engineering* 57:200–206. <https://doi.org/10.1016/j.proeng.2013.04.028>.
- Bose, S., S. K. Singh, K. Sushmita, and D. Sharma. 2023. “Aerogels Containing Ionomers and Microwave Assisted Growth of Carbon Nanostructures on Carbon Urchins for Excellent Electromagnetic Interference Shielding.” *Carbon* 209: 118036. <https://doi.org/10.1016/j.carbon.2023.118036>.
- Chen, Y., Z. Luo, X. Shi, Y. Jiang, Y. Zhang, and Z. Xu. 2025. “Liquid Metal-Encapsulated Spherical Al₂O₃/PVA Aerogel Composites for High-Efficiency Electromagnetic Interference Shielding and Enhanced Mechanical Properties.” *Materials Science and Engineering: B* 314:118062. <https://doi.org/10.1016/j.mseb.2025.118062>.
- Cheng, Z., R. Wang, Y. Wang, Y. Cao, Y. Shen, Y. Huang, and Y. Chen. 2023. “Recent Advances in Graphene Aerogels as Absorption-Dominated Electromagnetic Interference Shielding Materials.” *Carbon* 205:112–137. <https://doi.org/10.1016/j.carbon.2023.01.032>.
- Chhetri, S., and T. Kuila. 2024. “Polymer Composites with 3D Graphene Architectures as High-Performance EMI Shielding Materials: A Review.” *Royal Society of Chemistry Applied Polymers* 2 (4): 507–533. <https://doi.org/10.1039/D4LP00061G>.
- Choi C, Qaiser N and Hwang B. (2024). Mechanically Pressed Polymer-Matrix Composites With 3D Structured Filler Networks For Electromagnetic Interference Shielding Application. *Facta Universitatis, Series: Mechanical Engineering* 22 4 601–614 , 601 [10.22190/FUME240601038C](https://doi.org/10.22190/FUME240601038C)
- Chongyang, W., W. Yan, Z. Fangxin, F. Bowen, Z. Jian, Z. Hong, G. Jing, J. Lichuan, and Y. Dingxiang. 2025. “Construction of Lightweight, High-Energy Absorption 3D-Printed Scaffold for Electromagnetic Interference Shielding with Low Reflection, Composites Part B.” *Engineering* 291:112043. <https://doi.org/10.1016/j.compositesb.2024.112043>.
- Deb, S. K., P. Dutta, G. M. Karim, A. Patra, P. Bera, S. Das, P. Mukherjee, et al. 2024. “Bulk Versus Surface-Limited Polymer Encapsulation: A Current Pulse-Induced Approach for Confined Polymer Coating Selectively Over Quasi-Oriented MXene Aerogel.” *Chemical Engineering Journal* 484:149617. <https://doi.org/10.1016/j.cej.2024.149617>.
- Du, Y., J. Xu, J. Fang, Y. Zhang, X. Liu, P. Zuo, and Q. Zhuang. 2022. “Ultralight, Highly Compressible, Thermally Stable MXene/Aramid Nanofiber Anisotropic Aerogels for Electromagnetic Interference Shielding.” *Journal of Materials Chemistry A* 10 (12): 6690–6700. <https://doi.org/10.1039/D1TA11025J>.
- El-Cheikh, A.-Z. F., W. Kwapinski, M. N. Ahmad, J. J. Leahy, and H. El-Rassy. 2025. “Nanoporous ZnO/SiO₂ Aerogel and Xerogel Composites via a One-Pot Sol–Gel Process at Room Temperature.” *Royal Society of Chemistry Advances* 15 (47): 39566–39577. <https://doi.org/10.1039/D5RA05345E>.

- Elshehsah, K. A. A. A., Z. A. Noorden, and N. M. Saman. 2024. "Graphene Aerogel Electrodes: A Review of Synthesis Methods for High-Performance Supercapacitors." *Journal of Energy Storage* 97:112788. <https://doi.org/10.1016/j.est.2024.112788>.
- Evers, C., M. Kurilich, J. G. Park, C. Jolowsky, K. Thagard, and Z. Liang. 2024. "Multifunctional Properties of Carbon Nanotube Yarn/Aerogel Laminate Composites, Composites Part B." *Composites Part B Engineering* 280:111495. <https://doi.org/10.1016/j.compositesb.2024.111495>.
- Feng, L., P. Wei, Q. Song, J. Zhang, Q. Fu, X. Jia, J. Yang, et al. 2022. "Superelastic, Highly Conductive, Superhydrophobic, and Powerful Electromagnetic Shielding Hybrid Aerogels Built from Orthogonal Graphene and Boron Nitride Nanoribbons." *American Chemical Society Nano* 16 (10): 17049–17061. <https://doi.org/10.1021/acsnano.2c07187>.
- Fu, C., Z. Sheng, and X. Zhang. 2022. "Laminated Structural Engineering Strategy Toward Carbon Nanotube-Based Aerogel Films." *American Chemical Society Nano* 16 (6): 9378–9388. <https://doi.org/10.1021/acsnano.2c02193>.
- Fu, J., W. Lian, Y. Deng, Z. Fang, and Q. Cheng. 2025. "Isotropic Thermal Insulating Cuttlebone-Inspired MXene Aerogel." *National Science Review* 12 (10): nwaf342. <https://doi.org/10.1093/nsr/nwaf342>.
- Gu, W., A. Xia, C. Jin, H. Zhang, H. Li, and G. Ji. 2024. "An Ultralight, Eco-Friendly 3D Porous Carbon Aerogel Derived from Cotton Nano-Cellulose for Infrared Stealth and Microwave Absorption." *Carbon* 229:119565. <https://doi.org/10.1016/j.carbon.2024.119565>.
- Guo, H., T. Hua, J. Qin, Q. Wu, R. Wang, B. Qian, L. Li, and X. Shi. 2022. "A New Strategy of 3D Printing Lightweight Lamellar Graphene Aerogels for Electromagnetic Interference Shielding and Piezoresistive Sensor Applications." *Advanced Materials Technologies* 7 (9). 202101699 <https://doi.org/10.1002/admt.202101699>.
- Guo, P., L. Su, S. Jia, Z. Ni, Z. Dai, J. Guo, X. Wang, K. Peng, and H. Wang. 2024. "Strong SiC@ Carbon Nanowire Aerogel Metamaterials for Efficient Electromagnetic Interference Shielding." *Carbon* 229:119492. <https://doi.org/10.1016/j.carbon.2024.119492>.
- Guo, Y., D. Wang, Y. Tian, J. Wang, T. Bai, H. Liu, Z. Guo, C. Liu, and C. Shen. 2022. "FeCo Alloy Nanoparticle Decorated Cellulose Based Carbon Aerogel as a Low-Cost and Efficient Electromagnetic Microwave Absorber." *Journal of Materials Chemistry C* 10 (1): 126–134. <https://doi.org/10.1039/D1TC04494J>.
- Ha H, Mueller S, Guriyanova S and Hwang B. (2025). Surface Energy Characterization of a Single Microsphere Particle Using PeakForce Quantitative Nanomechanical Mapping Mode of Atomic Force Microscope. *Facta Universitatis, Series: Mechanical Engineering* 23 1 171–181 , 171 [10.22190/FUME250114012H](https://doi.org/10.22190/FUME250114012H)
- Ha H, Müller S, Baumann R and Hwang B. (2024). PeakForce Quantitative Nanomechanical Mapping for Surface Energy Characterization on the Nanoscale: A Mini-Review. *Facta Universitatis, Series: Mechanical Engineering*, 22(1 001–012), 001 [10.22190/FUME221126001H](https://doi.org/10.22190/FUME221126001H)
- Han, L., K. Li, H. Liu, Y. Jiao, X. Yin, H. Li, Q. Song, and L. Qi. 2023. "Heterogeneous Stacking Strategy Towards Carbon Aerogel for Thermal Management and Electromagnetic Interference Shielding." *Chemical Engineering Journal* 465:142839. <https://doi.org/10.1016/j.cej.2023.142839>.
- Hareesh, M., P. Joseph, and S. George. 2025. "Electromagnetic Interference Shielding: A Comprehensive Review of Materials, Mechanisms, and Applications, Nanoscale Advances." *Nanoscale Advances* 7: 4510–4534. <https://doi.org/10.1039/D5NA00240K>.
- He, Z., W. Zhang, J. Zhang, J. Xie, F. Su, Y. Li, D. Yao, Y. Wang, and Y. Zheng. 2024. "Enhancing the Electromagnetic Interference Shielding of Epoxy Resin Composites with Hierarchically Structured MXene/Graphene Aerogel, Composites Part B." *Composites Part B Engineering* 274:111230. <https://doi.org/10.1016/j.compositesb.2024.111230>.
- Iqbal, A., J. Kwon, M.-K. Kim, and C. Koo. 2021. "MXenes for Electromagnetic Interference Shielding: Experimental and Theoretical Perspectives." *Materials Today Advances* 9:100124. <https://doi.org/10.1016/j.mtadv.2020.100124>.
- Iqbal, A., P. Sambyal, and C. M. Koo. 2020. "2D MXenes for Electromagnetic Shielding: A Review." *Advanced Functional Materials* 30 (47): 2000883. <https://doi.org/10.1002/adfm.202000883>.
- Jiang, X., Z. Zhao, S. Zhou, H. Zou, and P. Liu. 2022. "Anisotropic and Lightweight Carbon/Graphene Composite Aerogels for Efficient Thermal Insulation and Electromagnetic Interference Shielding." *ACS Applied Materials and Interfaces* 14 (40): 45844–45852. <https://doi.org/10.1021/acsaami.2c13000>.
- Kefeni, K. K., and B. B. Mamba. 2020. "Photocatalytic Application of Spinel Ferrite Nanoparticles and Nanocomposites in Wastewater Treatment." *Sustainable Materials and Technologies* 23:e00140. <https://doi.org/10.1016/j.susmat.2019.e00140>.
- Kim, S., and J. Byun. 2024. "Research Trends in Electromagnetic Shielding Using MXene-Based Composite Materials." *Journal of Korean Powder Metallurgy Institute* 31 (1): 57–76. <https://doi.org/10.4150/kpmi.2024.31.1.57>.
- Li, T., L. Ma, Y. Huang, C. Wang, W. Fang, C. B. Park, E. Kumacheva, and H. E. Naguib. 2025. "Direct Ink Writing of Flexible Conductive Polymer Aerogels with Exceptional Electromagnetic Shielding Efficiency." *ACS Applied Electronic Materials* 7 (19): 8871–8881. <https://doi.org/10.1021/acsaelm.5c01221>.
- Li, Y., L.-D. Peng, D.-P. Bao, G.-T. Zhu, L. Ma, Z.-Y. Chen, C.-F. Cao, et al. 2025. "Recent Progress of Multifunctional Silica Aerogel Composite Materials: From Fabrication Strategies to Versatile Applications." *ACS Applied Materials and Interfaces* 17 (23): 33296–33317. <https://doi.org/10.1021/acsaami.5c00606>.

- Liu, A., H. Qiu, X. Lu, H. Guo, J. Hu, C. Liang, M. He, et al. 2025. "Asymmetric Structural MXene/PBO Aerogels for High-Performance Electromagnetic Interference Shielding with Ultra-Low Reflection." *Advanced Materials* 37 (5): 2414085. <https://doi.org/10.1002/adma.202414085>.
- Liu, H., Y. Xu, D. Han, J.-P. Cao, F. Zhao, and Q. Yang. 2022. "Leaf-Structured Carbon Nanotubes/Graphene Aerogel and the Composites with Polydimethylsiloxane for Electromagnetic Interference Shielding." *Materials Letters* 313:131751. <https://doi.org/10.1016/j.matlet.2022.131751>.
- Liu, J., M.-Y. Yu, Z.-Z. Yu, and V. Nicolosi. 2023. "Design and Advanced Manufacturing of Electromagnetic Interference Shielding Materials." *Materials Today* 66:245–272. <https://doi.org/10.1016/j.mattod.2023.03.022>.
- Liu, X., W. Ma, Z. Qiu, T. Yang, J. Wang, X. Ji, and Y. Huang. 2023. "Manipulation of Impedance Matching Toward 3D-Printed Lightweight and Stiff MXene-Based Aerogels for Consecutive Multiband Tunable Electromagnetic Wave Absorption." *American Chemical Society Nano* 17 (9): 8420–8432. <https://doi.org/10.1021/acsnano.3c00338>.
- Liu, Y., Y. Wang, N. Wu, M. Han, W. Liu, J. Liu, and Z. Zeng. 2023. "Diverse Structural Design Strategies of MXene-Based Macrostructure for High-Performance Electromagnetic Interference Shielding." *Nano-Micro Letters* 15 (1): 240. <https://doi.org/10.1007/s40820-023-01203-5>.
- Lv, Y., Q. Li, W. Yang, Z. Zhang, and Y. Li. 2025. "Recent Advances in Functional Design of Nanocellulose and Their Intelligent Application." *International Journal of Smart and Nano Materials* 16 (2): 245–283. <https://doi.org/10.1080/19475411.2025.2483819>.
- Ma, J., R. Yan, X. Wo, Y. Cao, X. Yu, A. Li, J. Huang, F. Li, L. Luo, and Q. Zhang. 2024. "Synthesis of Superelastic, Highly Conductive Graphene Aerogel/Liquid Metal Foam and Its Piezoresistive Application." *Chemistry–A European Journal* 30 (17): e202303594. <https://doi.org/10.1002/chem.202303594>.
- Ma, Y., Z. Zhu, H. Zhang, M. Kallel, Z. Yang, J. Ren, S. M. El-Bahy, et al. 2025. "Synthesis of Superhydrophobic Crack-Free Monolithic Silica Aerogels via a Vacuum Freeze-Drying Process." *Journal of the American Ceramic Society* 108 (6): e20401. <https://doi.org/10.1111/jace.20401>.
- Peng, F., W. Zhu, Y. Fang, B. Fu, H. Chen, H. Ji, X. Ma, C. Hang, and M. Li. 2023. "Ultralight and Highly Conductive Silver Nanowire Aerogels for High-Performance Electromagnetic Interference Shielding." *ACS Applied Materials and Interfaces* 15 (3): 4284–4293. <https://doi.org/10.1021/acsmi.2c16940>.
- Pisarek, A. M., B. Nowak, R. Jobda, and J. M. Gac. 2025. "VTMS-Based Aerogel Structure Preservation: The Influence of the Sol–Gel Synthesis Composition, Aging Process, and Double-Crosslinking." *New Journal of Chemistry* 49 (26): 11397–11411. <https://doi.org/10.1039/D5NJ00656B>.
- Pyo, S., Y. Eun, J. Sim, K. Kim, and J. Choi. 2022. "Carbon Nanotube-Graphene Hybrids for Soft Electronics, Sensors, and Actuators." *Micro and Nano Systems Letters* 10 (1): 9. <https://doi.org/10.1186/s40486-022-00151-w>.
- Qi, C.-Z., P. Min, X. Zhou, M. Jin, X. Sun, J. Wu, Y. Liu, H.-B. Zhang, and Z.-Z. Yu. 2025. "Multifunctional Asymmetric Bilayer Aerogels for Highly Efficient Electromagnetic Interference Shielding with Ultrahigh Electromagnetic Wave Absorption." *Nano-Micro Letters* 17 (1): 291. <https://doi.org/10.1007/s40820-025-01800-6>.
- Qiao, S., H. Chen, Y. Zhao, Z. Wang, and J. Yan. 2025. "Bioinspired Polyimide/Carbon Nanotube Aerogels with Core-Radiating and Omasum-Like Morphology Toward Excellent Electromagnetic Shielding and Superior Elasticity." *Advanced Materials* 37 (44): e13423. <https://doi.org/10.1002/adma.202513423>.
- Sambyal, P., A. Iqbal, J. Hong, H. Kim, M.-K. Kim, S. M. Hong, M. Han, Y. Gogotsi, and C. M. Koo. 2019. "Ultralight and Mechanically Robust Ti3C2Tx Hybrid Aerogel Reinforced by Carbon Nanotubes for Electromagnetic Interference Shielding." *ACS Applied Materials and Interfaces* 11 (41): 38046–38054. <https://doi.org/10.1021/acsmi.9b12550>.
- Shen, M., X. Li, J. Qi, J. Sun, W. Cao, H. Xiu, J. Li, Z. Zhang, X. Zheng, and Z. Shang. 2025. "Magnetic Metal-Loaded Wood Carbon Aerogel Composites for Electromagnetic Shielding and Microwave Absorption, Composites Part A: Applied Science and Manufacturing." *Composites Part A, Applied Science and Manufacturing* 198:109070. <https://doi.org/10.1016/j.compositesa.2025.109070>.
- Shi, Y., M. Wu, S. Ge, J. Li, A. S. Alshammari, J. Luo, M. A. Amin, et al. 2025. "Advanced Functional Electromagnetic Shielding Materials: A Review Based on Micro-Nano Structure Interface Control of Biomass Cell Walls." *Nano-Micro Letters* 17 (1): 3. <https://doi.org/10.1007/s40820-024-01494-2>.
- Song, J., S. Zheng, S. Jiao, N. Wu, Z. Sui, Y. Zhang, F. Pan, J. Liu, and Z. Zeng. 2025. "Recent Progress on MXene-Based Aerogels for Electromagnetic Interference Shielding." *Rare Metals* 44 (11): 8356–8375. <https://doi.org/10.1007/s12598-025-03548-9>.
- Sozcu, S., M. Venkataraman, J. Wiener, B. Tomkova, J. Militky, and A. Mahmood. 2023. "Incorporation of Cellulose-Based Aerogels into Textile Structures." *Materials* 17 (1): 27. <https://doi.org/10.3390/ma17010027>.
- Suryaprabha T, Choi C, Lal S, Seo M, Kim T, Wang E and Hwang B. (2026). Hierarchical MXene/ZnO Nanorods: WO3/CNT Trilayer Coatings on Cotton for High-Performance Multifunctional Wearable Fabrics. *Advanced Science* e21175 , [10.1002/advs.202521175](https://doi.org/10.1002/advs.202521175)
- Tang, C., J. Yang, J. Liu, Y. Mao, and S. Fu. 2025. "A Scalable, Efficient, and Facile Ambient Drying Approach for Preparing Low Shrinkage, Compressive, and Superporous Nano-Cellulose-Based Aerogels via a Physicochemical Crosslinking Strategy." *Green Chemistry* 27 (3): 804–814. <https://doi.org/10.1039/D4GC05106H>.
- Wang, L., P. Song, C.-T. Lin, J. Kong, and J. Gu. 2020. "3D Shapeable, Superior Electrically Conductive Cellulose Nanofibers/Ti3C2Tx MXene Aerogels/Epoxy Nanocomposites for Promising EMI Shielding, Research."

- Wang, S., Z. Cheng, Y. Yan, J. Yao, Y. Liu, J. Tao, L. Duan, et al. 2025. "Programmable Electromagnetic Switching in Shape-Memory-Driven Liquid Metal/Polyimide/Aramid Nanofiber Aerogels for Intelligent Wave Management." *Advanced Functional Materials* 36 (22): e21612. <https://doi.org/10.1002/adfm.202521612>.
- Wang, W., Z. Sheng, Y. Chen, C. Wei, S. Li, X. Geng, X. Li, et al. 2025. "Preparation of UO₂ Aerogel by Sol-Gel Method Combined with Supercritical Drying and Its Catalytic Properties." *Journal of Alloys and Compounds* 1043:184305. <https://doi.org/10.1016/j.jallcom.2025.184305>.
- Xiang, X., Y. Zhu, C. Gao, H. Du, and C. Guo. 2022. "Study on the Structure of Reduced Graphene Oxide Prepared by Different Reduction Methods." *Carbon Letters* 32 (2): 557–566. <https://doi.org/10.1007/s42823-021-00287-6>.
- Yang, K., H. Chen, Z. Han, C. Yin, H. Liu, D. Li, H. Yang, W. Sun, Q. Guan, and S. Yu. 2023. "Bioinspired Multifunctional High-Performance Electromagnetic Shielding Coatings Resistant to Extreme Space Environments." *The Innovation Materials* 1 (1): 100010. <https://doi.org/10.59717/j.xinn-mater.2023.100010>.
- Yue, J., M. Qin, H. Yu, Q. He, and W. Feng. 2025. "Superelastic Graphene-Based Composite Aerogel for Thermal and Electromagnetic Protection in Extreme Temperature Environments." *Advanced Functional Materials* 35 (42): 2508319. <https://doi.org/10.1002/adfm.202508319>.
- Zaed, M., K. Tan, R. Saidur, N. Abdullah, and A. Pandey. 2024. "Invited Viewpoint: Pathways to Low-Cost MXene Synthesis." *Journal of Materials Science* 59 (18): 7575–7594. <https://doi.org/10.1007/s10853-024-09666-6>.
- Zeng, Z., C. Wang, G. Siqueira, D. Han, A. Huch, S. Abdolhosseinzadeh, J. Heier, F. Nüesch, C. Zhang, and G. Nyström. 2020. "Nanocellulose-MXene Biomimetic Aerogels with Orientation-Tunable Electromagnetic Interference Shielding Performance." *Advanced Science* 7 (15): 2000979. <https://doi.org/10.1002/advs.202000979>.
- Zhan, Y.-J., N. Yu, T. Wang, J. Xu, W.-L. An, L. He, Z.-C. Fu, J.-N. Deng, H.-B. Zhao, and M.-J. Chen. 2024. "Ambient-Pressure-Dried Biomass Aerogel Toward Robust Cross-Linked Networks and Exceptional Mechanical Performances During Combustion." *American Chemical Society Sustainable Chemistry & Engineering* 12 (30): 11218–11230. <https://doi.org/10.1021/acssuschemeng.4c01929>.
- Zhang, C., Y. Zhang, Y. Wang, and Y. Huang. 2025. "Advances in Conductive Filler-Integrated Hydrogels and Derived Aerogels: Innovative Strategies for Electromagnetic Interference Shielding." *Materials Horizons* 12 (18): 7066–7100. <https://doi.org/10.1039/D5MH00577A>.
- Zhang, J., W. Guo, S. Shen, Q. Zhang, X. Chen, Z. Wang, K. Shao, Q. Sun, and C. Li. 2024. "High-Compressive, Elastic, and Wearable Cellulose Nanofiber-Based Carbon Aerogels for Efficient Electromagnetic Interference Shielding." *ACS Applied Materials and Interfaces* 16 (13): 16612–16621. <https://doi.org/10.1021/acsami.3c16559>.
- Zhang, T., S. Wang, H. Liu, X. Yang, and F. Zhu. 2025. "A Facile Method to Fabricate Syndiotactic Polystyrene Aerogels by Freeze-Drying." *Soft Matter* 21 (17): 3331–3339. <https://doi.org/10.1039/D5SM00090D>.
- Zhang, Y., A. Liu, Y. Tian, Y. Tian, X. Qi, H. Qiu, M. He, K. Zhou, and J. Gu. 2025. "Direct-Ink-Writing Printed Aerogels with Dynamically Reversible Thermal Management and Tunable Electromagnetic Interference Shielding." *Advanced Materials* 37 (35): e2505521. <https://doi.org/10.1002/adma.202505521>.
- Zhang, Y., P. Min, G. Yue, B. Niu, L. Li, Z. Z. Yu, and H. B. Zhang. 2024. "Emulsion-Based Multiscale Structural Design Realizes Lightweight and Superelastic Graphene Aerogels for Electromagnetic Interference Shielding." *Small* 20 (48): 2405950. <https://doi.org/10.1002/smll.202405950>.
- Zheng, S., W. Xu, J. Liu, F. Pan, S. Zhao, Y. Wang, Z. Zeng, and N. Wu. 2024. "One-Hour Ambient-Pressure-Dried, Scalable, Stretchable MXene/polyurea Aerogel Enables Synergistic Defense Against High-Frequency Mechanical Shock and Electromagnetic Waves." *Advanced Functional Materials* 34 (38): 2402889. <https://doi.org/10.1002/adfm.202402889>.
- Zhu, E., K. Pang, Y. Chen, S. Liu, X. Liu, Z. Xu, Y. Liu, and C. Gao. 2023. "Ultra-Stable Graphene Aerogels for Electromagnetic Interference Shielding." *Science China Materials* 66 (3): 1106–1113.
- Zhu, L., Y. Wang, S. Cui, F. Yang, Z. Nie, Q. Li, and Q. Wei. 2018. "Preparation of Silica Aerogels by Ambient Pressure Drying without Causing Equipment Corrosion." *Molecules* 23 (8): 1935. <https://doi.org/10.3390/molecules23081935>.