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Aerogel materials derived from waste plastics: Synthesis, structure-property relationships, and applications

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Abstract

Aerogels are a unique class of ultralight, highly porous materials distinguished by their exceptionally low density, high specific surface area, and outstanding thermal and acoustic insulation performance. Traditionally fabricated from inorganic precursors such as silica, aerogels have found applications in aerospace, construction, energy, and environmental remediation. However, high production costs, brittleness, and reliance on virgin raw materials have restricted their large-scale adoption. In recent years, the upcycling of waste plastics into polymer-based aerogels has emerged as a promising strategy that simultaneously addresses plastic pollution and enables the production of high-value functional materials. This review provides a comprehensive and critical analysis of aerogels derived from waste plastics, with a primary focus on polyethylene terephthalate (PET), polystyrene (PS), and polyethylene (PE). The fundamental principles of aerogel formation are discussed, followed by an in-depth examination of waste plastics as precursors, synthesis routes, and processing-structure-property relationships. Key physical, thermal, mechanical, and surface properties of waste plastic-derived aerogels are systematically reviewed and compared with conventional aerogels. Major application domains, including thermal and acoustic insulation, oil/water separation, gas adsorption, electromagnetic wave absorption, and emerging multifunctional uses, are discussed in detail. Finally, environmental, economic, and scalability considerations are evaluated, and critical challenges and future research directions are outlined. This review highlights the significant potential of waste plastic-derived aerogels as sustainable advanced materials within a circular economy framework.

Keywords: Waste plastics, polymer aerogels, polyethylene terephthalate, polystyrene, thermal insulation, upcycling, circular economy

Introduction

The global accumulation of plastic waste has become one of the most pressing environmental challenges of the modern era. Worldwide plastic production has exceeded 360 million tons annually, with packaging materials accounting for a significant fraction of this volume [1]. Despite increasing awareness and regulatory efforts, only a small percentage of plastic waste is effectively recycled, while the majority is landfilled, incinerated, or leaked into natural ecosystems [2]. Polyethylene terephthalate (PET), polystyrene (PS), and polyethylene (PE) dominate municipal plastic waste streams due to their widespread use in packaging, insulation, and consumer goods [3]. Conventional recycling strategies, including mechanical and chemical recycling, often face technical and economic barriers. Mechanical recycling typically leads to polymer degradation and downcycling, while chemical recycling processes can be energy-intensive and costly [4]. As a result, there is growing interest in alternative upcycling pathways that convert plastic waste into high-value materials rather than low-grade products. Aerogels represent an attractive target for such upcycling strategies. Aerogels are porous solids derived from gels in which the liquid phase is replaced by gas without collapsing the three-dimensional network. They are characterized by ultralow density, extremely high porosity, and unique thermal, acoustic, and sorption properties [5]. While silica aerogels are the most well-known, polymer-based aerogels have gained increasing attention due to their improved mechanical flexibility and durability. The transformation of waste plastics into aerogels combines environmental remediation with advanced materials engineering. By leveraging the intrinsic polymeric nature of plastic waste, researchers have demonstrated aerogels with competitive or superior performance compared to conventional insulation and sorption materials. This review aims to provide a detailed and critical overview of the current state of research on waste plastic-derived aerogels, focusing on synthesis methods, structure-property relationships, and application potential.

1. Fundamentals of Aerogel Materials

Aerogels are defined by their unique microstructure: a continuous solid network enclosing a highly porous gas-filled volume. Typical aerogels exhibit porosities exceeding 90% and densities as low as 0.003 $g \cdot cm^{-3}$ [5, 6]. The pore structure spans multiple length scales, from nanometers to micrometers, depending on the precursor material and processing route. The exceptional thermal insulation performance of aerogels arises from the suppression of all three modes of heat transfer. Solid-phase conduction is minimized due to the extremely low volume fraction of the solid skeleton. Gas-phase conduction is reduced by the Knudsen effect, which becomes significant when pore sizes are comparable to or smaller than the mean free path of gas molecules [7]. Radiative heat transfer is also attenuated through scattering and absorption within the porous network. Traditional silica aerogels are composed of rigid inorganic networks and are inherently brittle, limiting their mechanical robustness and handling. In contrast, polymer aerogels consist of flexible macromolecular chains that form entangled or crosslinked networks. This fundamental difference imparts superior toughness, elasticity, and damage tolerance to polymer aerogels [8]. These characteristics are particularly advantageous when aerogels are intended for large-area insulation, flexible devices, or mechanically demanding environments. When derived from waste plastics, polymer aerogels combine the intrinsic advantages of polymer networks with the sustainability benefits of waste valorization. Understanding the fundamental principles of aerogel formation is therefore essential for optimizing the performance of waste plastic-derived aerogels.

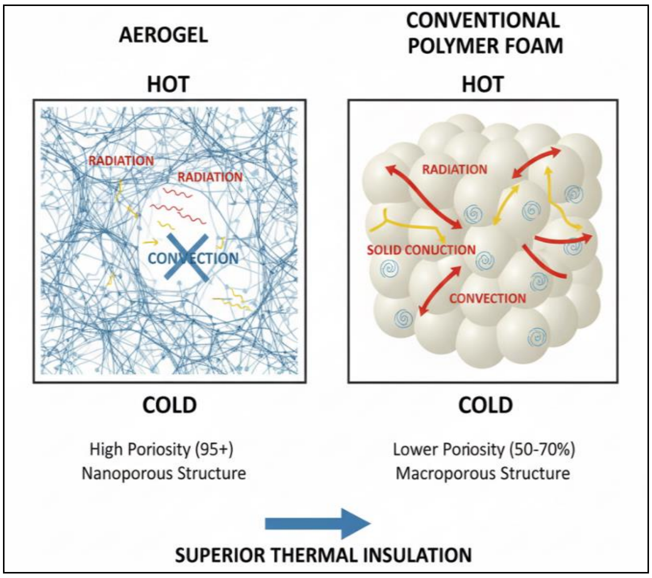

Fig 1: Schematic illustration of the thermal insulation mechanisms in aerogels compared with conventional polymer foams [7-8]

Waste Plastics as Precursors for Aerogel Synthesis

1. Polyethylene Terephthalate (PET) Waste

PET is the most extensively studied waste plastic for aerogel fabrication. Its widespread use in beverage bottles, food packaging, and textiles results in a large and relatively homogeneous waste stream [1, 2]. PET possesses high tensile strength, chemical resistance, and thermal stability, making it an attractive precursor for structural aerogels. Early work demonstrated that recycled PET fibers could be crosslinked using polyvinyl alcohol (PVA) and glutaraldehyde to form stable gel networks, which were subsequently freeze-dried to produce ultralight aerogels [9]. These rPET aerogels exhibited densities as low as 0.007 $g\cdot cm^{-3}$ and porosities exceeding 99%, rivaling conventional silica aerogels in thermal insulation performance. Subsequent studies expanded PET aerogel fabrication to post-consumer packaging waste. Dissolution-based approaches enabled homogeneous gel formation, resulting in interconnected porous networks after freeze drying [10]. These aerogels demonstrated not only low thermal conductivity but also excellent acoustic absorption, highlighting their multifunctional potential. To address mechanical limitations, researchers have introduced fiber reinforcement and nonwoven architectures. Aerogel-inspired PET materials produced via needle-punching and freeze drying exhibited improved compressive resilience while maintaining high porosity [11]. Such approaches bridge the gap between laboratory-scale aerogels and scalable industrial materials.

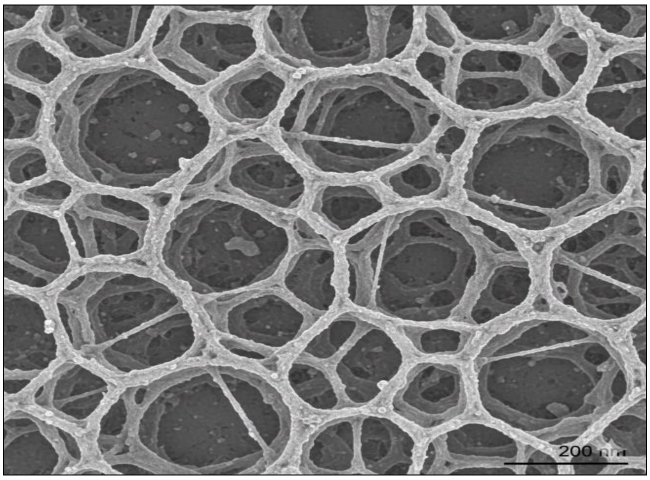

Fig 2: Representative porous microstructure of aerogels derived from recycled PET waste [8-10]

2. Polystyrene (PS)Waste

Polystyrene waste, particularly expanded polystyrene (EPS), presents a significant recycling challenge due to its low density and high volume [3]. Conventional recycling is often economically unviable, motivating interest in upcycling strategies. Recent work introduced closed-loop recyclable aerogels derived from waste PS through dynamic polymer chemistry [12]. In this approach, PS waste was converted into a reversible polymer network capable of forming aerogels with low density and intrinsic hydrophobicity. Importantly, these aerogels could be depolymerized back into monomers, enabling true circular recycling.

PS-derived aerogels exhibit competitive thermal insulation performance and improved moisture resistance compared to silica aerogels. Their closed-loop recyclability represents a significant advancement in sustainable aerogel design.

3. Polyethylene (PE)and Other Plastic Wastes

Polyethylene waste, including low-density and high-density PE, has been explored primarily for sorption and separation applications. Aerogel membranes fabricated from waste PE via solvent swelling and freeze drying demonstrated ultralow density, high porosity, and strong hydrophobicity [13]. These materials exhibited excellent oil absorption capacity and oil/water separation efficiency, making them promising candidates for environmental remediation. Although PE aerogels are less commonly studied for thermal insulation, their chemical inertness and hydrophobicity expand the functional scope of waste plastic aerogels.

Synthesis Strategies for Waste Plastic-Derived Aerogels

The synthesis of waste plastic aerogels typically involves polymer dissolution or dispersion, gelation, network stabilization, and solvent removal. Each step plays a critical role in determining the final structure and properties.

1. Dissolution and Gelation

Dissolution-based methods allow for homogeneous polymer distribution and controlled network formation. Chemical crosslinking agents stabilize the gel network but may compromise recyclability. Physical gelation methods based on chain entanglement or crystallization offer alternative routes with reduced chemical additives [9, 10].

Freeze Drying

Freeze drying is the most widely used technique for drying waste plastic gels. By sublimating frozen solvents under vacuum, capillary stresses are minimized, preserving the porous structure. However, freeze drying is energy-intensive and time-consuming, posing challenges for large-scale production.

2. Ambient Pressure and Hybrid Drying Methods

To reduce energy consumption, ambient pressure drying and Sol-gel hybrid approaches have been developed, particularly for composite aerogels incorporating inorganic fillers such as fly ash or silica [14, 15]. These methods offer a compromise between performance and scalability.

3. Surface Functionalization

Surface modification enhances hydrophobicity, thermal stability, and adsorption capacity. Functionalization strategies include silane treatment, polymer coatings, and ceramic deposition [16]. Such modifications expand the application range of waste plastic aerogels.

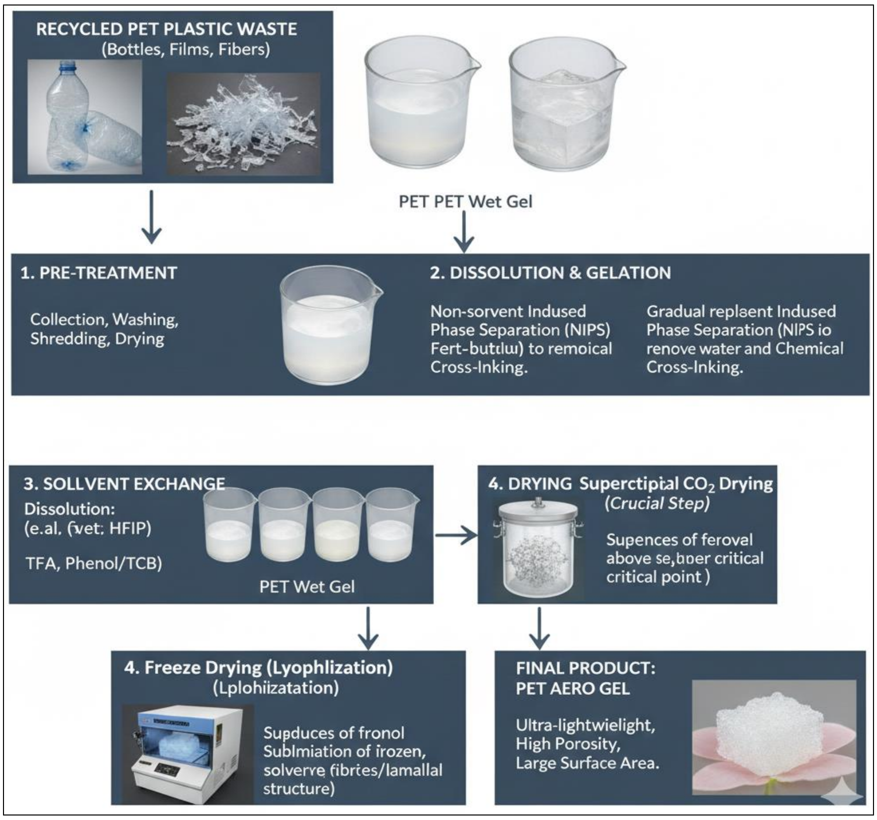

Fig 3: General synthesis pathways for aerogels derived from waste plastics [4-15]

4. Structure-Property Relationships

The performance of waste plastic-derived aerogels is strongly governed by their microstructure. High porosity and interconnected pore networks are essential for thermal insulation and acoustic absorption. Pore size distribution influences gas-phase conduction and sound attenuation, while network connectivity affects mechanical strength. PET aerogels typically exhibit hierarchical pore structures combining micro- and macropores, which balance insulation performance and mechanical stability [9, 11]. PS aerogels often display closed or semi-closed pore structures that enhance hydrophobicity and moisture resistance [12]. Mechanical properties are influenced by polymer chain flexibility, crosslink density, and reinforcement strategies. Compared to silica aerogels, polymer aerogels demonstrate superior elasticity and damage tolerance, making them more suitable for practical applications [8].

Applications of Waste Plastic-Derived Aerogels

1. Thermal and Acoustic Insulation

Thermal insulation is the most mature application area. Waste PET aerogels exhibit thermal conductivities typically between 0.030 and 0.045 $W\cdot m^{-1}\cdot K^{-1}$, outperforming conventional polymer foams and rivaling silica aerogels [9, 11]. Their lightweight and flexible nature makes them attractive for building insulation, refrigeration, and transportation. The porous structure of polymer aerogels also enables efficient acoustic absorption. Sound energy is dissipated through viscous losses and multiple scattering within the pore network, resulting in high sound absorption coefficients across a broad frequency range [10].

2. Oil/Water Separation and Environmental Remediation

Hydrophobic waste plastic aerogels demonstrate strong affinity for nonpolar liquids, enabling efficient oil absorption and oil/water separation. PE-derived aerogel membranes exhibit high separation efficiency and reusability, making them suitable for spill cleanup and wastewater treatment [13].

3. Gas Adsorption and Carbon Capture

Functionalized PET aerogels have been investigated for gas adsorption, including CO_2 capture. While adsorption capacities are generally lower than those of activated carbons, polymer aerogels offer advantages in terms of low density, flexibility, and processability [16].

4. Electromagnetic Wave Absorption and Emerging Applications

Aerogel-inspired polymer composites incorporating conductive fillers such as carbon nanotubes exhibit broadband electromagnetic wave absorption and lightweight characteristics, opening opportunities in shielding and stealth applications [17].

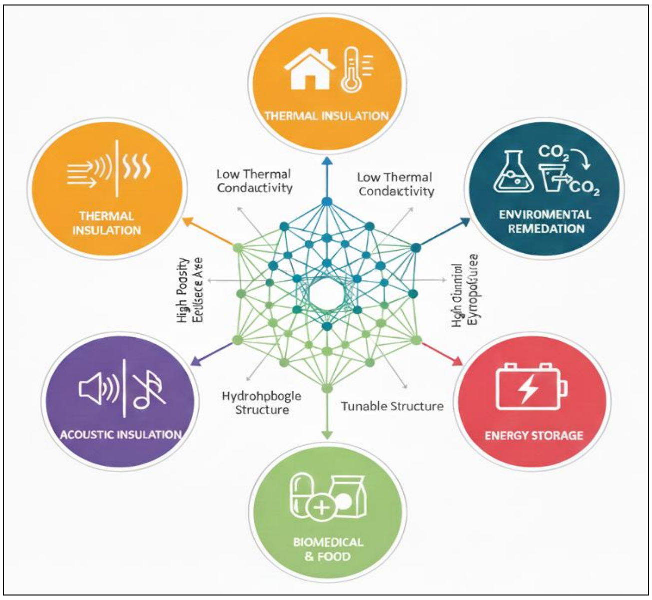

Fig 4: Application areas of waste plastic-derived aerogels [9-17]

Environmental and Economic Considerations

Upcycling waste plastics into aerogels offers significant environmental benefits by diverting waste from landfills and reducing reliance on virgin materials. However, energy-intensive processing and solvent use remain key challenges. Life-cycle assessment and techno-economic analysis are essential for evaluating sustainability and guiding commercialization [4, 18].

Challenges and Future Perspectives

Key challenges include scalability, cost reduction, long-term durability, and standardization. Future research should focus on low-energy drying techniques, closed-loop recyclability, hybrid composites, and integration into commercial products [12, 19].

Conclusions

Waste plastic-derived aerogels represent a promising class of sustainable advanced materials that effectively couple plastic waste valorization with high-performance functionality. By converting post-consumer polymers such as polyethylene terephthalate, polystyrene, and polyethylene into ultralight, highly porous aerogel structures, this approach offers a viable pathway to reduce plastic pollution while generating value-added materials. Compared with conventional inorganic aerogels and polymer foams, waste plastic-derived aerogels exhibit a favorable combination of low density, high porosity, mechanical flexibility, and tunable surface properties, enabling their use in diverse application domains. Recent progress in synthesis strategies and processing techniques has significantly enhanced the structural robustness and multifunctionality of these materials, expanding their potential beyond thermal insulation to include acoustic absorption, oil/water separation, gas adsorption, and electromagnetic interference shielding. Nevertheless, challenges related to energy consumption, solvent use, long-term durability, and cost competitiveness remain. Addressing these issues through low-energy fabrication methods, life cycle assessment-guided design, and scalable processing will be critical for the successful transition of waste plastic-derived aerogels from laboratory-scale studies to practical, real-world applications within a circular economy framework.

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