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Smart thermal management of bio-based aerogels: A paradigm shift from energy localisation to zero-energy anti-icing

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Abstract

Given the global energy crises and severe climate challenges, it is urgent to develop zero-energy anti-icing technologies to ensure infrastructure security. Bio-based aerogels, due to their environmental friendliness and renewable characteristics, excellent thermal insulation properties and structural design flexibility, provide an innovative opportunity for solar-powered intelligent thermal management. Therefore, we systematically review recent developments in bio-based aerogels for intelligent thermal management. The concept of 'localisation of solar thermal energy' is proposed to highlight a paradigm shift from passive insulation to active thermal management platforms. Through a critical analysis of green interface coupling, biomimetic anisotropic structures and photothermal-phase transition sequences, the importance of rational cross-scale design in overcoming performance barriers (such as high porosity, high strength, low thermal conductivity and high photothermal efficiency) is emphasised. In addition, research gaps in dynamic energy matching, environmental durability and system integration are identified, providing a theoretical framework and development path for designing future intelligent anti-icing materials. This review demonstrates that through integrated multi-scale design, bio-based aerogels can achieve a surface temperature increase of over 60°C under 1 solar irradiance, and maintain the bulk thermal conductivity below 0.025 W/(m K). This finding indicates a promising approach to achieving zero-energy anti-icing solutions.

Keywords: Bio-based aerogel; Intelligent thermal management; Energy localisation; Zero-energy anti-icing; Paradigm shift

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1. Introduction

The global energy transition and increasing frequency of extreme weather events pose significant challenges to the sustainability and safe operation of modern infrastructure [1,2]. In cold regions, the accumulation of ice and snow on building and infrastructure surfaces will threaten the structural integrity, resulting in significant energy consumption and environmental impact [3]. Current electric heating de-icing technologies have a high energy demand, often ranging from 200 W/m to 500 W/m. Annual consumption of chemical de-icing agents exceeds 20 million tons. This practice has led to heavy metal salinisation

Nomenclature

c_p – specific heat capacity, J/(kg K)
E_b – bonding energy, eV
H – enthalpy, J
k – thermal conductivity, W/(m K)
k_i – thermal conductivity, N/m
L – latent heat of phase transition, J/kg
m – mass, kg
N – number of atomic pairs in the interfacial bond
$Q_{photothermal}$– solar heat gain, W/m^3
Q_{loss}– heat loss, W/m^3
r_i – actual bond length, pm
$r_{0,i}$ – equilibrium bond length, pm
T – temperature, K
t – time, s

Greek symbols

β – extinction coefficient, 1/m
ρ – density, kg/m^3
σ – Stefan-Boltzmann constant, 5.67×10^{-8} W/(m^2 K^4)
ϕ – porosity

Subscripts and Superscripts

eff – effective
g – gas phase
s – solid phase

Abbreviations and Acronyms

PCM – phase change material
PLA – polylactic acid

and alkalisation of soil and water [4]. Due to increased energy usage, substantial pollution and passive response, traditional methods cannot meet the requirements of dual carbon goals for green and low-carbon development [5,6]. Therefore, the development and utilisation of sustainable materials and active anti-icing technologies with near-zero external energy consumption have become a focus in the intersection of civil engineering materials, energy science and chemistry [7,8].

Due to nanoporous structures and excellent thermal insulation properties, aerogels have low thermal conductivity (< 0.025 W/(m K)) and high porosity (> 90%), making them an ideal platform for efficient thermal insulation [9]. However, traditional silica-based aerogels are hindered by their limited functions, high brittleness, and dependence on non-renewable raw materials. The development of bio-based aerogels, such as those derived from cellulose, chitosan, and polylactic acid, has initiated a green transformation in this field. These materials from renewable biomass have the advantage of biodegradability, excellent biocompatibility and mechanical flexibility, laying a foundation for creating environmentally friendly functional materials. In addition, early bio-based aerogels were mainly used as passive thermal insulators, lacking the ability to respond to or resist external icing [10]. Photothermal materials, such as MXene and black phosphorus [11,12], combined with bio-based aerogels, have the ability of active photothermal conversion. However, these composites show a fundamental scientific paradox: how to effectively generate, direct and spatially locate photothermal energy in an adiabatic system designed to suppress heat conduction [13]. This conflict between ‘thermal insulation’ and ‘heating’ poses a challenge to the development of intelligent thermal management systems [14]. To address this, it is essential to move away from the traditional functional layering approach and initiate a paradigm shift from passive materials to intelligent thermal management platforms. The core of this concept is to achieve surface-controlled thermal energy generation and accumulation while maintaining the overall thermal insulation performance of the system. The theoretical basis of heat conduction is expressed as follows:

$$\rho c_p \frac{\partial T}{\partial t} = \nabla(k\nabla T) + Q_{photothermal} - Q_{loss}, \tag{1}$$

where ρ represents the density of the material, c_p is the specific heat capacity at constant pressure, T is the absolute temperature and t is the time, term $\partial T/\partial t$ indicates the rate of change of temperature over time, k is the thermal conductivity of the material, $\nabla(k\nabla T)$ represents the thermal diffusion term, $Q_{photothermal}$ denotes the solar heat gain term and Q_{loss} represents the heat loss term. The key to achieving energy localisation is to maximise $Q_{photothermal}$ and minimise Q_{loss}.

To address this issue, the intelligent thermal management of bio-based aerogels is reviewed and evaluated from three fundamental mechanisms to achieve localisation of photothermal energy [15,16]:

1) Green interface energy coupling mechanism: This section investigates the effects of molecular-level interactions (such as hydrogen bonding) between bio-based frameworks and photothermal nano-units on energy injection efficiency and interface stability;
2) Biomimetic anisotropic thermal management: This analysis examines the strategy of guiding heat flow paths through microstructural design (such as unidirectional cryogenic casting) to achieve spatial localisation of surface thermal energy, while maintaining overall thermal insulation;
3) Photothermal-phase-change sequential coordination mechanism: This section elaborates on the role of phase-change materials as "thermal capacitors" in balancing energy supply and demand to promote all-weather anti-icing, especially under nighttime and low-light conditions.

We first define the main material systems and characteristics of bio-based aerogels, and explore the current state of the involved mechanisms and their relationships. Then the performance of various technical approaches is compared to identify the points of consensus, areas of disagreement, and critical gaps. Finally, a technological evolution from the principle of energy localisation to zero-energy anti-icing applications is proposed. Future challenges and research directions required for a true paradigm shift are anticipated, aiming to provide a guidance for theoretical innovation and engineering practice. The overall logical structure is shown in Fig. 1.

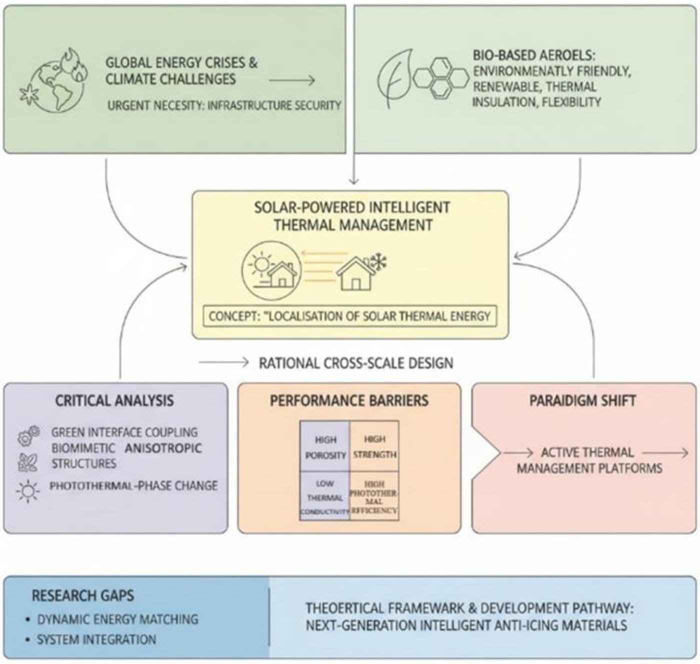

Fig. 1. Diagram of logical structure.

This review suggests that addressing the fundamental paradox of insulation and heat generation requires a comprehensive and multi-scale design strategy. Three main mechanisms: green interface energy coupling, biomimetic anisotropic thermal management and photothermal-phase-change sequential coordination are concentrated, not because they are the only relevant mechanisms, but because they collectively address the challenge at three essential design scales. First, at the molecular scale, interface coupling (such as through hydrogen bonds) helps to inject efficient photothermal energy into the insulating matrix. Second, at the microstructural scale, anisotropic pore architecture directs the injected heat flow to the material surface to achieve spatial localisation. Third, at the system level, phase-change coordination serves as a temporal buffer to balance energy supply and demand for all-weather operation. Therefore, these mechanisms are interrelated. They establish a hierarchical strategy, where interface coupling provides the foundation, anisotropic structures create the pathway and phase-change coordination provides assurance. Overall, they can accurately locate solar thermal energy within an adiabatic system, which is the foundation to achieve zero-energy anti-icing.

2. Material systems

The emergence of bio-based aerogels represents a significant paradigm shift in aerogels, from focusing on individual properties to emphasising balanced sustainability and multi-functionality. The continuous enrichment and evolution of these material systems provide multiple platforms for advanced thermal management technologies [17]. The preliminary research mainly aimed to replace traditional silica-based aerogels. Recent advancements have focused on the functional design based on the properties of biopolymers. Three predominant material systems are classified according to their chemical nature and functional characteristics: cellulose-based aerogels, chitosan-based aerogels and polylactic acid (PLA)-based aerogels [18] (Table 1).

Table 1. Comparative performance of key bio-based aerogel material systems.

Material systems	Precursor characteristics	Typical thermal conductivity (W/(m K))	Key advantages	Functional priorities and challenges	Applicable scenarios
Cellulose-based aerogels	Rich in hydroxyl groups, highly derivatisable	0.025–0.035	High mechanical strength, facilitating the construction of anisotropic structures	Light-heat interface coupling/prone to moisture absorption	Building envelopes
Chitosan-based aerogels	Amino groups confer pH responsiveness and antimicrobial properties	0.030–0.040	Excellent adsorption properties and biocompatibility	Bioactive function integration/ acid instability	Special environmental applications
Polylactic acid-based aerogels	Intrinsically hydrophobic, thermoplastic	0.035–0.045	Hydrophobic, easy to process and form	Superhydrophobic anti-icing coating/ relatively brittle	Surface coating

2.1. Cellulose-based aerogels

Cellulose, as the most abundant biopolymer in nature, has become the most extensively studied aerogel system due to its excellent mechanical properties and adjustable pore structure. The three-dimensional network formed by cellulose nanofibers (CNF) achieves high mechanical strength (tensile strength up to MPa level) and ultra-low thermal conductivity (ranging from 0.025 W/(m K) to 0.035 W/(m K)) [19]. In addition, the abundant hydroxyl groups on its surface are ideal reaction sites for subsequent functionalisation modifications.

The radial thermal conductivity of cellulose nanofiber aerogels produced by unidirectional freeze-casting technology is as low as 0.030 W/(m K), and the axial thermal conductivity reaches 0.060 W/(m K). This indicates significant anisotropy in thermal management, laying a structural foundation for directional thermal control. However, the hydrophilicity of cellulose aerogels limits their long-term application in humid environments, and usually requires post-treatment methods such as silane modification to improve environmental stability. The hydrophilicity of cellulose aerogels significantly reduces their thermal insulation stability in high-humidity environments. It is necessary to make modifications, such as achieving superhydrophilicity [20].

2.2. Chitosan-based aerogels

Chitosan is derived from chitin, which is the second most abundant biopolymer in nature. The amino groups in its molecular chains endow the material with unique biological activity and adsorption properties. This indicates significant antibacterial potential and makes it suitable for specialised applications that require antimicrobial suppression. Incorporating hollow glass microspheres into the chitosan matrix helps to develop low-density, high-performance thermal insulation materials. This enhancement is due to the synergistic interaction between the three-dimensional network structure of chitosan and the arrangement of microsphere frameworks. However, the instability of chitosan in acidic environments and its relatively high raw material cost have limited its large-scale engineering applications to some extent [21]. The size and surface charge of chitosan-based nanogels show pH responsiveness, and their properties will change significantly as pH decreases (under acidic conditions) [22].

2.3. Polylactic acid-based aerogels

Polylactic acid (PLA) is a biodegradable synthetic polymer with significant hydrophobicity and thermoplastic processing ability. It can develop integrated materials that combine super-hydrophobicity with photothermal properties. For example, the CFex-PLA composite aerogel has excellent hydrophobicity (with a contact angle ranging from 146.94° to 152.25°) and significant photothermal effect, effectively integrating anti-icing and de-icing functions [23]. In addition, PLA aerogels are still brittle and have limited thermal stability, highlighting the need to further improve their mechanical properties while maintaining their functions. The study on the structure-property relationship of PLA aerogels indicates they have high stiffness and elastic modulus up to 12.82 MPa [24]. This mechanical property is usually associated with low fracture strain and brittleness. Another study prepared PLA aerogel with excellent cyclic compression performance through special design, indicating that structural design can reduce its brittleness [25].

2.4. Positioning shift from 'green substrate' to 'functional platform'

Early studies usually characterised bio-based aerogels as 'green' passive thermal insulation materials. The introduction of functional fillers often damages their porous structure and mechanical properties. For example, although the physical mixing of MXene can improve photothermal performance, the stacking of nanosheets often leads to pore blockage, resulting in a significant increase in thermal conductivity. The limitation in this stage is due to a lack of understanding of the synergistic relationship between structure and function. Recent research has repositioned aerogels as a 'functional platform' that can be rationally designed. According to the strategies, such as in-situ growth and directed assembly, functional units are accurately fixed on the aerogel framework, thereby maximising functionality, while minimising performance loss. This paradigm shift lays a necessary foundation for achieving intelligent thermal management.

3. Core mechanisms and implementation pathways for energy localisation

The concept of 'energy localisation' addresses the contradiction between 'adiabatic behaviour' and 'heat generation' in aerogel systems. This concept combines multi-level synergistic mechanisms from molecular to system scales. It includes three main pathways: green interfacial energy coupling, biomimetic anisotropic structure guidance and photothermal-phase transition temporal coordination.

3.1. Green interfacial energy coupling mechanism

At the molecular scale, the design of interfaces is crucial for facilitating efficient energy transfer. The properties of the interface between bio-based aerogels and photothermal materials significantly affect the conversion and injection efficiency of light energy into thermal energy. MXene and black phosphorus, as narrow-bandgap semiconductors, can be used as excellent photothermal agents due to their ability to absorb a wide spectrum of light. However, the key determinant of their effectiveness is the nature of their interfacial interactions with the bio-based framework.

The interfacial structure formed by strong hydrogen bonds between cellulose and MXene can promote efficient phonon transport and improve photothermal conversion efficiency, as well as has a significantly higher interfacial bonding energy compared to physical adsorption. These hydrogen-bond-based 'green interfaces' pass complex chemical coupling steps, while providing stable and highly efficient energy transfer paths [26]. The hydroxyl groups in the cellulose framework form a molecular-level interfaces with terminal groups, such as –O and –F, on the MXene surface. The strength of these interactions can be quantified as follows:

$$E_b = \frac{1}{2N}\sum_{i=1}^{N} k_i\left(r_i - r_{0,i}\right)^2, \tag{2}$$

where E_b denotes the bonding energy, N represents the total number of atomic pairs involved in forming the interfacial bond, k_i is the force constant, r_i and $r_{0,i}$ denote the actual and equilibrium bond lengths, respectively.

Different bio-based backbones will significantly influence the interfacial properties. Cellulose is characterised by its linear molecular chains and densely distributed hydroxyl groups. Compared with branched-chain chitosan (–1.7 eV), it has a higher bonding energy with MXene (–2.1 eV). This difference results in a higher photothermal conversion efficiency of cellulose (88.5%) compared to chitosan (76%). This difference highlights the profound impact of molecular architecture on interfacial energy transfer behaviours, thereby providing a theoretical foundation for the accurate design of interfacial engineering.

3.2. Biomimetic anisotropic structures for thermal management

At the micro- and nanoscale, structural design plays a crucial role in directed thermal flow. Anisotropic structures can promote heat accumulation at material surfaces rather than internal diffusion, resulting in local 'external heat and internal cooling' effects. The unidirectional cryo-casting technology produces aerogels with highly oriented pore structures, forming a 'directional channel' of heat flow. The thermal conductivity along the axis of the hole (in-plane) significantly exceeds that perpendicular to it (out-of-plane), allowing for selective surface heat enrichment [27]. Thermal conductivity anisotropy can be significantly achieved by controlling the direction of ice crystal growth:

$$k_{eff} = \phi k_s + (1-\phi)k_g + \frac{16\sigma T^3}{3\beta\rho}, \tag{3}$$

where k_{eff} denotes the effective thermal conductivity, ϕ represents the porosity, k_s and k_g denote the thermal conductivities of the solid and gas phases, respectively, σ is the Stefan-Boltzmann constant, T is the absolute temperature, ρ is the material density, and β is the extinction coefficient.

This method achieves an in-plane to out-of-plane thermal conductivity ratio of 2:1, making the surface temperature rapidly increase to 85.2°C under illumination, and the substrate temperature increases slightly. Further structural comparisons reveal that the radial honeycomb structure exhibits an in-plane/out-of-plane thermal conductivity ratio of 2.5:1, which is significantly higher than the 1.8:1 ratio of the layered structure. This indicates that under the same solar thermal conditions, the surface thermal localisation is optimal. It is noteworthy that structural selection should be consistent with practical applications: planar anti-icing systems should prioritise the in-plane thermal conductivity through radial structures to promote rapid de-icing. Vertically channels are more effective in ensuring uniform thermal distribution on curved surfaces.

3.3. Photothermal-phase transition temporal coordination

At the system level, achieving all-weather anti-icing requires the adoption of a time-sequenced energy management mechanism. The integration of phase change materials (PCM) into aerogels provides the ability of 'thermal energy storage'. This allows aerogels to absorb excess heat during sunny periods and release latent heat under low-light or sub-zero conditions. This process reduces surface temperature fluctuations and solves the intermittent nature of solar thermal energy supply [28]. The introduction of phase change materials (PCMs) allows for the redistribution of energy over time. The thermal behaviour of composite PCMs can be calculated as follows:

$$\frac{dH}{dt} = mc_p\frac{dT}{dt} + mL\frac{df}{dt}, \tag{4}$$

where H denotes the enthalpy, m represents the mass, L denotes the latent heat of phase transition, and f is the liquid fraction.

Paraffin@silica microcapsules (latent heat > 180 J/g) can extend the anti-icing time of the system by 40−200%. However, the selection of phase change temperatures for phase change materials remains a controversial topic. On the one hand, some studies advocate for PCMs with a phase change temperature between 5°C and 10°C to achieve rapid de-icing. On the other hand, others propose that PCMs with a phase transition temperature between –3°C and 0°C can provide prolonged anti-icing protection by releasing latent heat during crystallisation. This disagreement fundamentally reflects the different energy management requirements in different applications. In addition, the hysteresis of phase transition may last for up to 30 min, thereby limiting the performance of PCMs under dynamic climatic conditions. As a result, developing systems with graded phase-change temperatures or moulded composite PCMs to optimise thermal release kinetics has become an important research area.

Achieving energy localisation is a systemic challenge that spans multiple scales. It requires an integrated design with three dimensions: interface coupling, structure-guided orientation and temporal coordination. This combination aims to reconcile the conflict between thermal insulation and heat generation. This method will advance bio-based aerogels to be intelligent thermal management platforms.

3.4. Synergistic integration of multi-scale mechanisms

Three core mechanisms are introduced independently. To achieve true 'energy localisation' and overcome the contradiction between 'insulation and heating', they should be integrated into a unified and multi-scale design paradigm. These mechanisms are not just cumulative; on the contrary, they form a hierarchical and functionally complementary system, each addressing a specific scale of challenge.

First, the coupling of the green interface lays a molecular foundation. By generating strong and stable interactions (such as hydrogen bonds) between the bio-based matrix and photothermal units, efficient phonon transfer is ensured. The incident light is maximally converted into thermal energy in the material. This step solves the main problem of 'how to efficiently generate heat in an insulator'. Without such efficient injection, any subsequent thermal management would prove ineffective.

Second, biomimetic anisotropic structures provide essential microstructural features. The directional pore channels and layered structure designed by techniques, such as unidirectional freeze-casting, create a preferential pathway for heat flow. This design strategically directs the heat generated internally to the material surface, while suppressing backward diffusion into the bulk. Consequently, it converts molecular-scale energy input into a spatial local thermal distribution characterised by ‘hot surface, cool interior’, thereby achieving surface-specific anti-icing and de-icing functions.

Third, the coordination of photothermal-phase change is a system-level guarantee for temporal stability. It solves the intermittency of solar energy by combining thermal energy storage. Phase change materials absorb excess heat during peak irradiation and release it at night or low-light conditions. This mechanism can buffer fluctuations in energy supply and ensure sustained thermal output from the surface. It maintains the functionality of the entire system over time, making all-weather, zero-energy anti-icing operation possible.

This integration follows a logical sequence: interface coupling injects energy; anisotropic structures direct it to the surface; and phase-change coordination stabilises it over time. This collaborative multi-scale approach transforms the bio-based aerogel from a simple insulating material to an intelligent thermal management platform that can achieve active, local and lasting anti-icing performance.

4. Challenges of performance synergy and cross-scale design

Integrating mechanisms, such as green interface coupling, anisotropic structures, and photothermal-phase transition synergies into a single material system requires a thorough examination of their synergistic effects and inherent conflicts. This analysis elucidates the fundamental challenges associated with achieving high-performance bio-based aerogels.

4.1. Paths to overcoming the impossible triangle

In the design of bio-based aerogels, the goal of achieving high porosity to obtain excellent thermal insulation, high strength, and high light heat conversion efficiency often leads to an impossible triangle of conflicting objectives. Most studies that focus on enhancing one property often sacrifice others. For example, increasing the loading of photothermal agents often leads to a decrease in porosity and an increase in thermal conductivity. Conversely, excessive emphasis on achieving high porosity often damages the mechanical strength of the material.

A feasible approach to achieve breakthroughs is to achieve collaborative optimisation of multiple attributes through reasonable cross-scale design [29,30]. For example, a synergistic approach of combining cryogenic casting with in-situ cross-linking can develop cellulose/MXene composite aerogels with radial pore structures. At the molecular level, hydrogen-bonded interfaces make MXene disperse stably, resulting in a porosity of over 90%, a thermal conductivity of 0.023 W/(m K), a tensile strength of 1.3 MPa and a photothermal efficiency of 88%. Success depends on achieving multi-scale collaborative regulation from molecular interfaces to macroscopic structures. This emphasises that future material design should move away from simplistic ‘stir-fry-style’ composite strategies and adopt a rational design paradigm that unifies structure and function [31], as shown in Fig. 2 and Table 2.

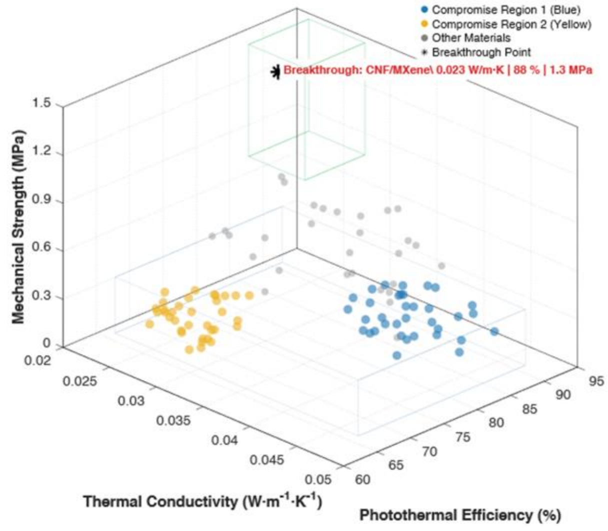

Fig. 2. Thermal conductivity-photothermal efficiency-mechanical strength three-dimensional relationship diagram.

Table 2. Performance synergy analysis of representative studies.

Research framework systems	Preparation strategies	Thermal conductivity (W/(m K))	Photothermal temperature rise (°C)	Mechanical strength	Synergy assessment
CNF/MXene physical mixture	Simple blend	0.038 (up by approximately 35%)	~60	Decline	Performance-sacrificing type: Deterioration in thermal insulation properties
CS/PCM composite foam	In-situ encapsulation	0.033	PCM-controlled temperature only	Good	Single-function type: Lacking active solar thermal capabilities
CNF/MXene anisotropy	Chilled casting + interface engineering	0.023 (radial)	~65	Enhance	Synergistic breakthrough approach: Achieving all three objectives simultaneously

4.2. Performance gap between laboratory and engineering

A significant issue is the disconnect between the standards for evaluating material performance and actual applications. Performance is often assessed under constant solar irradiance and dry, idealised conditions. In contrast, high-altitude cold environments in the real world often have complex factors, including low light levels (solar irradiance < 300 W/m², i.e. < 0.3 sun), high humidity and frequent freeze-thaw cycles.

Key engineering parameters, including structural integrity under repeated freeze-thaw cycles, thermal insulation retention in high-humidity environments, and activation efficiency under low-light conditions, are often overlooked in current research. This 'performance gap' significantly hinders the practical application of materials with excellent performance in laboratory settings. Therefore, future performance evaluations should establish testing standards that more accurately reflect real-world conditions. Such standards should systematically assess engineering indicators, including long-term durability, cycling stability and substrate compatibility. This approach will promote the transformation of bio-based aerogels from 'high-performance materials' to becoming truly 'available technologies'.

5. Pathways and future prospects of paradigm shift

The analysis indicates that bio-based aerogels are experiencing a significant paradigm shift in intelligent thermal management. This shift includes a transition from passive insulation to active thermal management, an evolution from single-function applications to system integration, and a shift in focus from performance demonstration to application-driven development.

5.1. Evolutionary trajectory of research paradigms

The development of this field follows a unique three-stage evolutionary path:

1) Early stage (prior to 2015): The research mainly focused on environmentally friendly preparation processes and fundamental thermal insulation properties of bio-based aerogels.
2) Mid-term phase (2016−2020): This stage marks the beginning of functional exploration, introducing single functional units, such as photothermal agents or phase change materials. These simple physical mixing methods bring challenges for performance trade-offs.
3) Recent phase (2021 to present): At this stage, multi-mechanism synergy has emerged, such as Janus structures and anisotropic design.

This evolutionary trajectory marks a fundamental shift from material innovation to system integration. Research focus shifts from pursuing individual performance metrics to emphasising overall system efficacy.

5.2. Key directions for future development

There are still several important gaps and challenges:

1) Insufficient understanding of potential mechanisms: Existing research has not yet elucidated the quantitative contribution of hydrogen bonding to energy transfer. There is still a substantial disconnect between the simulation of thermal-mechanical coupling in anisotropic structures and the study on the dynamics of ice layer separation.
2) Lack of performance data: There is almost no available data on the sustained anti-icing performance at temperatures close to 0°C. Environmental durability testing, such as ultraviolet (UV) aging for 3000 h, is cited in less than 5% of the literature.
3) System integration challenges are significant: There is no research on optimising green interface, anisotropic structure, and phase transition timing at the same time. The key characteristics of architectural applications, such as adhesion to substrates, have not received enough attention.

The following three issues require urgent attention:

1) Dynamic matching mechanism of energy chain: There is a lack of understanding of the dynamic coupling mechanism in the 'solar thermal-energy storage-thermal insulation' energy chain. There are also no performance prediction and optimisation models that take into account the fluctuations of real-world weather.
2) Systemic gaps in multiscale theory: From nanoscale interface behaviour to microscale pore structure and macroscopic device performance, there is a lack of 'structure-property' transfer theories and design principles.
3) Integration of durability and sustainability: Long-term service of materials under extreme conditions, including resistance to aging and fatigue, as well as their environmental footprint throughout the entire lifecycle (such as biodegradability and recyclability) are key factors affecting their final application. These factors are under-researched in current studies.

5.3. Proposed ways to drive paradigm shift

To address the earlier limitations and promote a true paradigm shift, three essential developmental directions are proposed: First, it is crucial to develop application-oriented in-situ characterisation techniques tailored to operating conditions. This method aims to establish a performance evaluation system for materials in real-world environments, thereby bridging the gap between laboratory performance and engineering. Second, a closed-loop system that integrates 'intelligent design' with advanced manufacturing should be established. This system combines artificial intelligence with multi-scale simulations for reverse material design. This will guide advanced manufacturing processes, such as cryogenic 3D printing and atomic layer deposition. Finally, a comprehensive lifecycle assessment system should be established. This system should incorporate life cycle assessment and life cycle cost analysis in the early stages of material development to ensure the true sustainability of technologies. These developments can signify technological advancements and indicate a fundamental paradigm shift from performance-driven to application-driven approaches. This transition will elevate bio-based aerogels from 'laboratory curiosities' to 'engineering realities' that support future green and resilient infrastructure.

6. Conclusions

The intelligent thermal management of bio-based aerogels is experiencing a significant paradigm shift from passive materials to active functional systems. We systematically present the mechanism of achieving 'localised photothermal energy' through green interface coupling, bio-inspired structural orientation, and photothermal-phase change synergy. This approach provides a promising technical way for zero-energy anti-icing. However, transitioning from laboratory research to engineering applications will overcome critical challenges, including dynamic energy matching, environmental durability and system integration. Future advancements will establish a new paradigm of multiscale rational design that combines artificial intelligence, advanced manufacturing and life-cycle assessment systems. These developments will make smart materials a key technology to support green infrastructure. Bio-based aerogels provide a highly promising green way for zero-energy anti-icing. The paradigm shift framework in this review includes energy localisation and system integration. It provides a clear perspective for understanding existing technologies, highlights the limitations of current research and identifies future directions through critical analysis. This method provides an accurate roadmap for future investigation. Developing this trajectory has the potential to transform these smart materials from outstanding laboratory performance into engineering reality, thereby supporting future green and resilient infrastructure.

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