



Recent advances in spectrally selective structural designs for radiative cooling

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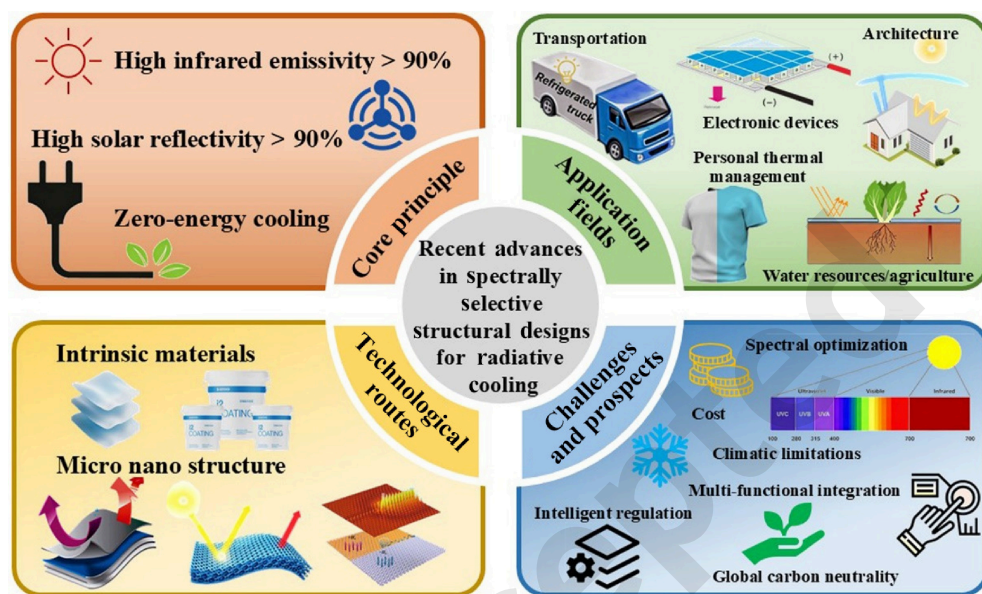
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This review classifies radiative cooling materials into random-scattering intrinsic structures and precise photonic architectures, comparing their spectral selectivity and durability. It links structural design to applications (buildings, electronics, textiles, and water harvesting) and outlines key challenges and future intelligent integration.



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ABSTRACT

Radiative cooling technology passively dissipates surface heat to outer space through the atmospheric window (8–13 μm), providing an innovative pathway for continuous cooling with zero energy consumption and zero carbon emissions. The core challenge for high-performance daytime radiative cooling lies in strict spectral selectivity: A solar reflectance exceeding 90% in the solar spectrum band (0.3–2.5 μm) is required to minimize solar heating, while an infrared emissivity higher than 90% must be maintained within the atmospheric window to maximize radiative heat dissipation. This review systematically provides the latest advances in radiative cooling materials and structures in recent years, centered on the core driving force of “spectral selective structural design”. According to the optical modulation hierarchy of structural design ranging from random to precise, existing research is categorized into two major technical pathways: (1) Random scattering structures based on intrinsic material properties, including polymer films and functional coatings. Their infrared emission relies on molecular bond vibrations or lattice phonon resonances, while micro/nano pores or fibrous structures enhance solar light reflection via multiple scattering. (2) Precise micro/nano structures based on photonic engineering, including multilayer films, photonic crystals, and metamaterials, achieve finer spectral modulation through mechanisms, such as photonic band gaps, Mie scattering and surface polaritons. This paper further summarizes the application progress of this technology in building energy conservation, personal thermal management, heat dissipation of electronic devices, atmospheric water collection and other fields, and emphatically analyzes the key design trade-offs faced in the transition from laboratory research to large-scale applications, including cost control, environmental durability, climate adaptability, as well as the synergy and constraint between color aesthetics and cooling efficiency. Finally, this paper puts forward a prospective outlook on the future development of intelligent, responsive, and multi-functionally integrated radiative cooling materials. This review aims to provide a systematic reference framework centered on structural design for researchers in the radiative cooling community, and promote the evolution of this technology towards high efficiency, practicality, and sustainability.

KEYWORDS

radiative cooling, spectral selectivity, atmospheric window, passive cooling, structural design

1 Introduction

With the growth of the global economy and the acceleration of urbanization, the share of building energy consumption within the total societal energy consumption has been steadily increasing; the resulting carbon emissions and the environmental impact of refrigerants have become critical bottlenecks in the pursuit of carbon neutrality [1]. Radiative cooling strategies typically rely on vapor-compression refrigeration systems, which are widely used in

air-conditioning and refrigeration equipment. However, these systems are not only bulky, heavy, energy-intensive, and dependent on a stable power supply, but they also drive up energy costs, increase reliance on fossil fuels, and contribute to higher carbon emissions [2].

Furthermore, common refrigerants (e.g., Freon, hydrochlorofluorocarbons, etc.) contribute to ozone depletion and possess considerable global warming potential, thereby accelerating climate change [3] and potentially triggering

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environmental issues of air pollution and acid rain [4], posing a serious threat to human production and daily life. In the building sector, heating and cooling systems account for approximately 12% of global energy consumption, representing a major contributor to peak electricity demand and a critical barrier to achieving carbon peak and neutrality targets [5, 6].

Therefore, the development of a new generation of energy-saving and eco-friendly cooling technologies has become increasingly urgent. Among such technologies, radiative cooling, which features advantages, including zero energy consumption, ecological compatibility, sustainability, and reduced fossil fuel combustion, has attracted growing attention from researchers worldwide [7, 8]. This technology leverages the atmospheric window (8–13 μm band) to allow terrestrial objects to passively dissipate long-wave infrared (LWIR) radiation into outer space, which is near absolute zero temperature, thereby achieving cooling without energy input [9]. All objects above absolute zero emit thermal radiation due to their intrinsic temperature, predominantly in the infrared range under ambient conditions [10]. At environmental temperatures, thermal emission is predominantly in the infrared spectrum. Radiative cooling exploits this physical mechanism by utilizing the transparency of the atmosphere in specific bands to directly emit terrestrial heat into cold outer space as infrared radiation, resulting in a net cooling effect between the Earth's surface and the external environment [11]. Owing to the substantial temperature difference between the Earth and the cosmos, radiative cooling has been proposed and extensively investigated as a means to cool the Earth's surface via radiation. This process allows radiation to pass through the atmosphere without being absorbed, thereby avoiding additional atmospheric heating [12]. In contrast to conventional cooling methods that consume electricity and discharge waste heat into the surrounding environment, radiative cooling requires no external energy input and is thus classified as a passive cooling technology [9]. It features extremely low operating costs [13] and demonstrates promising applications in building energy efficiency [14], thermal management of space probes [15], hybrid radiative cooling–solar heating systems [16], and beyond. Advances in materials science and engineering have enabled researchers to continually explore novel radiative cooling materials and extend their applications to diverse scenarios, including the thermal management of electronic devices, data center cooling, and personal sun protection, offering innovative solutions to heat management challenges.

Therefore, developing efficient radiative cooling technology holds significant scientific and socio-economic value in addressing current global energy and environmental challenges [17, 18]. Based on structural and material design principles, current research on radiative cooling technology primarily follows two technical pathways. The first involves intrinsically spectrally selective materials, such as polymer-based thin films and functional coatings, which offer advantages in terms of low cost and scalability. The second focuses on micro-nano photonic structures, including multilayer thin films/photonic crystals, random porous architectures, and metamaterials. These structures enable precise spectral regulation of solar and mid-IR (MIR) radiation through mechanisms, such as photonic bandgaps, Mie scattering, and surface polaritons, albeit with more complex fabrication requirements. In terms of applications, radiative cooling has shown promising potential across various fields, including building energy efficiency, thermal management of electronic devices, personal thermal comfort, transportation, and

atmospheric water harvesting. Nonetheless, challenges remain for large-scale commercialization, particularly concerning cost control, environmental durability, and diminished cooling performance under overcast or high-humidity conditions. In this context, constructing multifunctional integrated materials that combine thermal management, solar-thermal conversion, and microwave absorption offers a promising pathway toward more versatile and resilient passive thermal regulation solutions [19]. Future advancements will require breakthroughs in material design and photonic engineering to drive the technology toward smarter, more practical, and more integrated solutions, thereby contributing to global carbon neutrality goals through zero-energy cooling pathways. This review systematically summarizes the current state of radiative cooling materials and their application progress across different domains, while offering a multi-perspective outlook on the future development of this technology.

Despite rapid progress and numerous reviews on radiative cooling, existing literature typically categorizes materials by composition or application, lacking a unified framework that directly links structural design to optical performance and practical feasibility. This review centers on spectrally selective structural design as the key driver, classifying strategies into two archetypes: (1) intrinsic spectrally selective materials relying on random scattering and molecular/lattice vibrations (e.g., polymer composites, porous coatings, and fiber membranes) and (2) micro/nano photonic structures achieving precise spectral control via periodicity and resonances (e.g., multilayers, photonic crystals, and metamaterials). This taxonomy clarifies the underlying physics and outlines an evolutionary path from simple, low-cost solutions to sophisticated high-performance designs.

Focusing primarily on recent research advances while selectively incorporating foundational earlier works, this review also highlights emerging trends, such as dynamic/adaptive selectivity and multifunctional integration. This review aims to provide researchers and engineers with a practical guideline oriented toward structural design for material selection and optimization in specific applications, while identifying persistent challenges and promising future opportunities. The overall framework of this review, spanning core principles, technical approaches, application domains, and future challenges, is schematically summarized in Fig. 1.

2 Principles of radiative cooling

To understand radiative cooling, it is essential to establish a fundamental physical concept: Any object with a temperature above absolute zero ($-273.15\text{ }^{\circ}\text{C}$) continuously radiates energy outward in the form of electromagnetic waves and also absorbs energy from the surrounding environment. This mode of heat transfer is known as “radiative heat transfer”.

Due to the fact that air absorbs infrared radiation of different wavelengths to varying degrees, the atmosphere exhibits high transmittance within the 8–13 μm wavelength range, which is known as the atmospheric window [20]. It is highly transparent, and the atmospheric transparency window [21] overlaps with the wavelength range of the thermal radiation of objects on Earth [22]. Outside this atmospheric window, the atmosphere is highly absorptive or radiative. Therefore, when the thermal radiation of an object is within the atmospheric window wavelength band, it can pass through the atmosphere and enter outer space, causing its own temperature to drop. This technical principle is based on the heat radiation exchange between an object and its

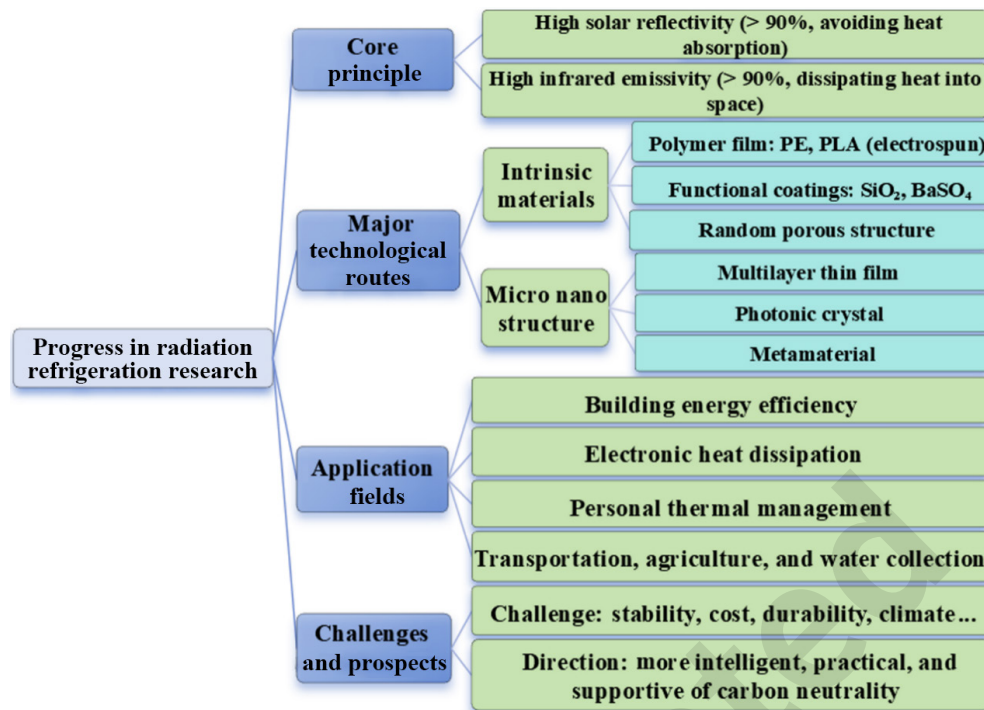


Figure 1 Schematic framework of radiative cooling technology: core principles, technical pathways, application domains, challenges, and future prospects.

environment. By using specific materials, heat is radiated in the mid-infrared band (8–13 μm) to the cold cosmic space, thereby achieving passive cooling [23–25].

An ideal radiative cooling medium [26] must simultaneously satisfy two spectral selectivity requirements. Specifically, it exhibits a high infrared emissivity of over 90% within the atmospheric window (8–13 μm), efficiently radiating heat as infrared radiation [20]. At the same time, within the solar spectrum band (0.3–2.5 μm), it should have a high solar reflectivity of over 90%, reflecting sunlight to the greatest extent and avoiding heat absorption from the environment [27]. The radiative heat-exchange processes among the sun, the Earth's surface, the atmosphere, and outer space are schematically shown in Fig. 2.

To quantitatively evaluate the net cooling performance of a radiative cooler, it is essential to consider the energy balance among solar absorption, thermal emission, atmospheric radiation, and non-radiative heat exchange. The net cooling power ($P_{\text{net}}(T)$, where P_{net} represents the net cooling power and T represents the temperature of the cooler) can be expressed by the following heat-balance equation

$$P_{\text{net}}(T) = P_{\text{rad}}(T) - P_{\text{atm}}(T_{\text{amb}}) - P_{\text{solar}} - P_{\text{non-rad}} \quad (1)$$

where $P_{\text{rad}}(T) = \int d\Omega \cos\theta \int_0^\infty d\lambda I_{\text{BB}}(T, \lambda) \varepsilon(\lambda, \theta)$ is the thermal



Figure 2 Schematic diagram of the Earth's surface radiative heat flux. Reproduced with permission from Ref. [27], © Yin, X. B. et al. 2020.

radiation emitted by the cooler, where P_{rad} represents the thermal radiation emitted by the cooler, Ω represents the solid angle, θ represents the emission angle relative to the surface normal, λ represents the wavelength of radiation, I_{BB} represents the blackbody spectral radiance, and ε represents the spectral and angular emissivity of the cooler; $P_{\text{atm}}(T_{\text{amb}})$ is the absorbed atmospheric downwelling radiation, where P_{atm} represents the absorbed atmospheric downwelling radiation and T_{amb} represents the ambient temperature; P_{solar} is the absorbed solar flux, and $P_{\text{non-rad}}$ accounts for convective and conductive heat losses. To achieve sub-ambient daytime cooling, the condition $P_{\text{net}} > 0$ must be satisfied, meaning that the emitted radiative flux must exceed the combined heating from solar irradiation, atmospheric radiation, and non-radiative exchange. The spectral selectivity of the material directly governs its performance: High emittance $\varepsilon(\lambda)$ within the atmospheric window maximizes P_{rad} , while high reflectance (i.e., low absorptance) across the solar spectrum minimizes P_{solar} . Furthermore, the atmospheric radiation term P_{atm} is strongly affected by meteorological factors, such as ambient humidity and cloud cover, which represent critical environmental constraints for practical applications of radiative cooling, as will be discussed in later sections.

Thus, by designing the absorption and emission spectra of the material, the cooler can achieve passive cooling without consuming any energy, and its temperature is expected to drop below the ambient temperature even on a sunny day.

3 The way to achieve spectral selectivity in radiative cooling

The spectral selectivity of radiative cooling is not conferred by a single approach but is the product of cross-integration among materials science, nanophotonics, and thermal engineering. According to the degree of structural order and the dominant optical mechanism, current research can be categorized into two major pathways: (1) intrinsic selective structures based on random

scattering and molecular/lattice vibrations and (2) resonance-enhanced structures based on precise photonic engineering. Ranging from low-cost and solution-processable random structures to high-performance and precisely engineered photonic architectures, this field is developing rapidly toward higher efficiency, lower cost, and greater practical applicability.

3.1 Intrinsic spectrally selective materials

This class of structures relies on the inherent molecular bonds (e.g., C–H, C–O, and C–F in polymers) or lattice vibration modes (e.g., Si–O in silicon dioxide (SiO_2) and Ti–O in TiO_2) to achieve strong absorption/emission in the mid-infrared atmospheric window. To minimize solar heating, they typically incorporate randomly distributed micro/nano pores or particles to scatter sunlight via Mie scattering. Their advantages lie in low cost and ease of large-scale preparation, such as by spraying, roll coating, or electrospinning, making them highly suitable for large-scale applications like building rooftops. However, their spectral selectivity is often not perfect, and there are inherent bottlenecks in performance improvement due to the random nature of their structures. This pathway includes polymer films/fibers, functional coatings, and random porous structures, which will be discussed in terms of their material forms and fabrication strategies.

3.1.1 Polymer films and nanofiber membranes

Radiative cooling materials in the form of films are usually formed by the mixture of inorganic micro- and nano-particle fillers and polymer matrix materials through processes, notably melting, casting, extrusion, and cooling.

Electrospinning has emerged as a pivotal technique for fabricating functional nanofiber membranes due to its straightforward process and controllable cost [28–30].

The vibrational frequencies of molecular bonds (e.g., C–H, C–O, and C–F) in polymers exhibit high correspondence with the atmospheric window, endowing them with intrinsic infrared absorption and emission capabilities [31]. The overlap with the

atmospheric window [32] leads to the generation of high infrared emissivity [33], making them excellent infrared emitter materials. Various polymer nanofibers (e.g., polyvinylidene fluoride (PVDF), polyurethane (PU), polyvinyl alcohol (PVA), etc.) can be fabricated via electrospinning; alternatively, inorganic nanofibers (e.g., TiO_2 , SiO_2 , etc.) can be prepared by combining the electrospinning method with the sol–gel method [34]. They are usually prepared as random porous foams, fiber films, or coatings, using micrometer-scale pores to strongly scatter sunlight to achieve high reflection while retaining their inherent infrared emission capabilities. Polymer films have the advantages of low cost, good flexibility, and ease of processing, and have been widely studied in the field of radiative cooling.

In nature, many organisms have developed remarkable photothermal regulation capabilities, including adjustable reflectivity, adjustable absorption, and dynamic infrared radiation emission. These capabilities are not only crucial for their survival and evolution but also serve as inspiration for the development of biomimetic radiative cooling technologies [35]. Protein polymers derived from natural sources exhibit unique potential in the field of radiative cooling, among which research on silk fibroin has attracted particular attention. Natural white silkworm cocoons contain thousands of axially aligned nanofibrillar voids within their fibers, which enable strong broadband light scattering via the Anderson localization effect, thereby effectively protecting pupae from overheating under sunlight. However, Park et al. [36] challenged the conventional view that “evolution has optimized biological materials to their optimal performance” and pointed out that evolutionary optimization does not target a single property, and natural materials are far from optimal for specific functions. They reconstructed natural silk via conventional electrospinning, which completely destroyed the original nanofibrillar void structure. As shown in Fig. 3, by utilizing the conventional optical diffusion effect instead, they achieved a stronger solar reflectivity than that of natural raw silk.

Studies have shown that when the average diameter of

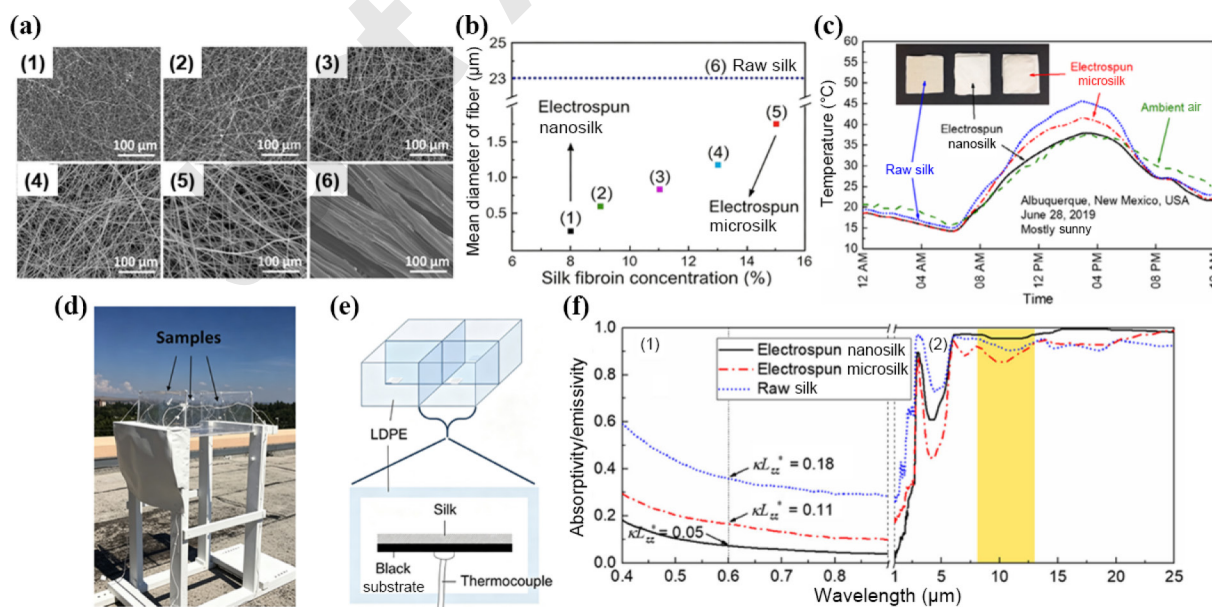


Figure 3 (a) Top view scanning electron microscopy (SEM) images of (1)–(5) electrospun silk with different mean diameters and (6) raw silk; (b) mean diameter of silk fibers as a function of fibroin solution concentration for the (1)–(5) structures; (c) measured temperature variation over a day for electrospun nanosilk, electrospun microsilks, raw silk, and ambient air; (d) photograph and (e) schematic of our outdoor experimental setup for temperature measurements; and (f) absorptivity/emissivity spectra of electrospun nanosilk, electrospun microsilks, and raw silk at a thickness of $420\ \mu\text{m}$ placed on a black substrate over the (1) visible and (2) mid-IR wavelengths. Reproduced with permission from Ref. [36], © Park, B. K. et al. 2021.

electrospun fibers is 0.25 μm , the scattering intensity in the visible (VIS) spectral region reaches the maximum, and the average emissivity in the atmospheric window (8–13 μm) reaches 0.97, which is significantly higher than the value of 0.93 for nonwoven raw silk fabrics. More importantly, the filling fraction of this electrospun film is only 0.06–0.11, which is far lower than the filling fraction of 0.35 for raw silk, yet structural optimization compensates for the disadvantage brought by the low filling fraction. Outdoor field measurements demonstrate that the average temperature of the substrate covered with the electrospun nanofiber film is 7.5 $^{\circ}\text{C}$ lower than that of the substrate covered with raw silk fabric during daytime, and its temperature throughout the day is almost consistent with the ambient temperature. This work reveals that even without relying on Anderson localization, artificial polymer fiber mats can exceed the performance limit of naturally evolved materials in terms of solar reflectivity through reasonable regulation of fiber diameter, and also points out the direction for further performance optimization by using synthetic polymers with lower ultraviolet (UV) absorption.

To further improve the radiative cooling performance of electrospun nanofiber materials, researchers have conducted microstructural design based on nanofibers and optimized the solar reflectance and atmospheric window emissivity of nanofiber materials through structural designs, such as porous, hollow, or triangular protrusion structures. Zhong et al. [37] adopted coaxial electrospinning to prepare nanofiber membrane materials with both hollow structures and surface rough structures. In this process, PVDF is used as the shell solution and PVA as the core solution. By leveraging the rapid volatilization of the shell solvent and the immiscibility between the core solution and the shell solution, the hollow fiber structure is formed in one step. Fig. 4 systematically presents the passive daytime radiative cooling (PDRC) mechanism, building-envelope thermal insulation behavior, infrared images, simulated thermal conductivity, heat-transfer processes, and spectral properties of the thermal insulating cooler (TIC). Its multi-scale micro-nano structure achieves

broadband solar reflectance of 94%. The abundant C–F bonds and C–H bonds in polyvinylidene fluoride endow the membrane material with excellent atmospheric window emissivity of 94%. Meanwhile, the hollow structure provides a still air layer, enabling the fiber membrane material to have outstanding thermal insulation performance, thus exhibiting great potential for providing both radiative cooling and thermal insulation capabilities in hot outdoor environments. Outdoor field tests demonstrate that under a solar irradiance of 900 $\text{W}\cdot\text{m}^{-2}$, TIC can achieve a cooling effect of 9 $^{\circ}\text{C}$ below the ambient temperature.

Following this “pure polymer structural design” approach, Zhong et al. selected PVDF as the base material and further extended the structural regulation from “optical scattering optimization” to “collaborative integration of optical cooling and thermal insulation”. Unlike Park et al., who focused on the single-dimensional improvement of optical performance, this work aims to simultaneously address another core bottleneck faced by radiative cooling materials in practical building applications: the degradation of cooling performance caused by environmental heat gain.

Especially suitable for electrospinning, polylactic acid (PLA) can be used to prepare random porous structures or nanofiber membranes with high solar scattering capabilities. In the research of PLA-based radiative cooling materials, the introduction of inorganic micro-nanoparticles has become an important research direction and has been proven to significantly enhance their cooling effect. For example, the developed PLA/polyethylene glycol (PEG)@ SiO_2 microfiber tent material with a bilayer heterostructure [38], composed of an upper porous polylactic-co-glycolic acid (PLGA)/ SiO_2 composite coating and a lower hydrophobic PVDF film [39], has shown potential in the field of radiative cooling.

In recent years, radiative cooling films have emerged as a novel passive thermal management material, demonstrating broad application prospects across various fields [40], particularly in building energy efficiency [41, 42], photovoltaic (PV) devices [43–45], and human thermal management textiles [46–49]. Zhang

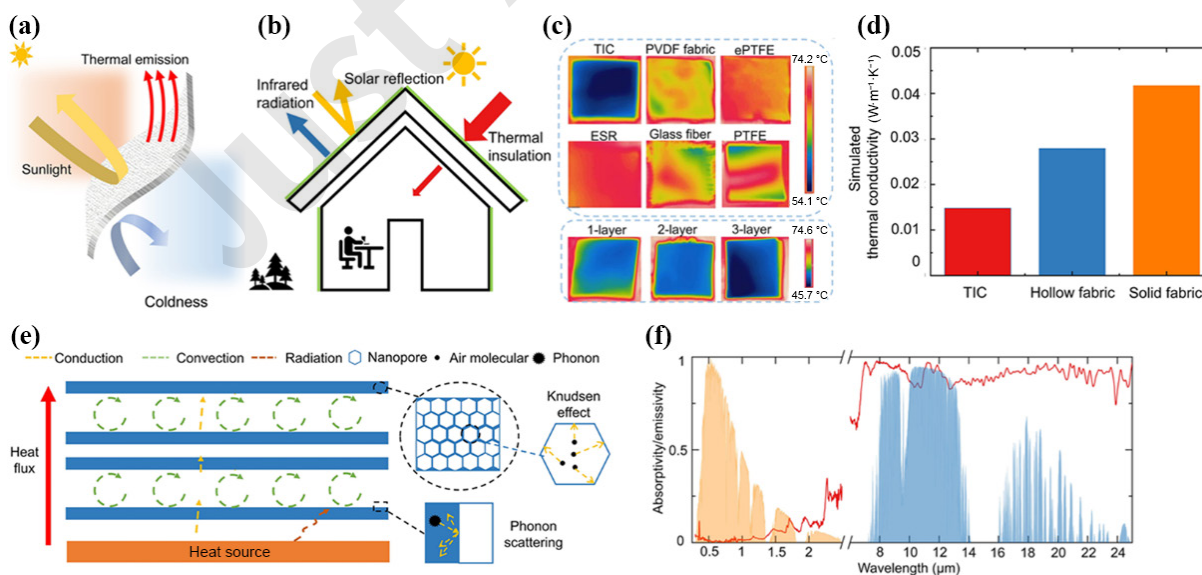


Figure 4 (a) Schematic showing passive daytime radiative cooling by solar reflection and infrared thermal emission, as well as coldness maintenance by thermal insulation; (b) when used as a building envelope, the TIC exhibits high solar reflection, high infrared emissivity, and low thermal conductivity; (c) infrared images of the TIC sample and control samples, as well as TIC with various layers. The sample surface temperatures are measured based on the infrared images taken after setting the stage temperature to 70 $^{\circ}\text{C}$; (d) simulated thermal conductivity values of the TIC, compared with hollow PVDF fabric (without nanopores in the fiber wall) and solid PVDF fabric (without a hollow structure and nanopores); (e) schematic illustration of the heat transfer process of the TIC; and (f) absorptivity/emissivity spectra of the TIC. Reproduced with permission from Ref. [37], © American Chemical Society 2021.

and co-workers [50] employed solution blow spinning combined with lamination to fabricate a hierarchical nanostructured textile composed of SiO₂ nanofiber membranes (fiber diameter: 300–1900 nm) and expanded polytetrafluoroethylene (ePTFE) films (fiber diameter: ~ 170 nm) (Fig. 5). This multi-scale fiber diameter architecture enables precise spectral management across the solar spectrum: The ePTFE film predominantly scatters ultraviolet radiation (200–300 nm), while the SiO₂ nanofibers enhance reflection in the visible to near-infrared (NIR) range (0.4–2.5 μm), thereby achieving high-efficiency broadband solar reflection.

This study addresses the critical challenges of full-spectrum radiative control, scalable manufacturing, and multifunctional integration in PDRC textiles by developing a scalable hierarchical nanofiber structure. It achieves synergistic enhancement of radiative cooling and thermoelectric conversion, thereby establishing a novel paradigm for self-powered smart textile development. The material design strategy can be extended to applications in building energy efficiency (e.g., a 5 °C reduction in temperature observed in a semi-covered wooden hut model), promoting the advancement of zero-energy thermal management technologies. Future research may focus on color integration, flexibility enhancement, and deeper integration with wearable electronics.

3.1.2 Functional particle-embedded coatings

Among the various technological pathways for radiative cooling, coatings are regarded as one of the most commercially promising approaches due to their suitability for large-area and complex surface fabrication. However, the majority of high-performance radiative cooling coatings reported to date either rely on precisely engineered photonic crystals and nanostructures [51], or employ high-cost fluoropolymers as binders. The complicated fabrication processes and exorbitant raw material costs have severely impeded their large-scale production and practical applications [52]. Therefore, the development of radiative cooling coatings using low-cost, readily available raw materials and featuring simple fabrication procedures is of critical importance to advancing the practical deployment of this technology.

In recent years, passive radiative cooling polymer coating materials have garnered significant attention due to their energy-free and sustainable characteristics [53]. To address the aforementioned challenges, researchers have begun to explore low-cost radiative cooling coatings based on common materials, including silica, calcium carbonate, and barium sulfate, which achieve daytime cooling by leveraging the intrinsic optical properties of the materials or constructing randomly scattered structures. This has, to a certain extent, verified the feasibility of the low-cost technical route. Nevertheless, most of these materials still require the use of organic polymers, and there remains room for improvement in terms of environmental stability and process complexity. Accordingly, the development of a radiative cooling coating that combines all-inorganic composition, excellent environmental stability, readily available raw materials, and simple fabrication processes remains a key research goal in this field and is also the core prerequisite for promoting its large-scale practical applications.

Inorganic fillers, notably SiO₂ [54–56] and SiC, characterized by their high chemical stability and ultraviolet aging resistance, are particularly suitable for long-term outdoor applications, particularly in building exteriors and industrial storage tanks. Against the backdrop of escalating building energy consumption, radiative cooling coatings exhibit significant energy-saving potential. To help mitigate global warming [57], there is a pressing demand for novel, efficient, and eco-friendly building cooling strategies [58].

Feng Wenjie, Zhu Wenkai, and co-workers [59] developed a universal color-imparting method for polymer-based radiative cooling coatings. By using nanoimprint lithography to tailor the optical interference of periodic surface structures on polymers, they reduced the solar absorptance of polymer films to 1.7%–3.7%. The study introduced a simple and versatile color-integration strategy involving the embedding of colored microspheres into cooling polymer films via solution processing. Fig. 6 summarizes the hemispherical emissivity, FTIR absorption spectra, field-test setup, SEM images of patterned surfaces, and the measured/simulated reflectance and emittance of structurally colored polymer films. Selective reflection from the microspheres

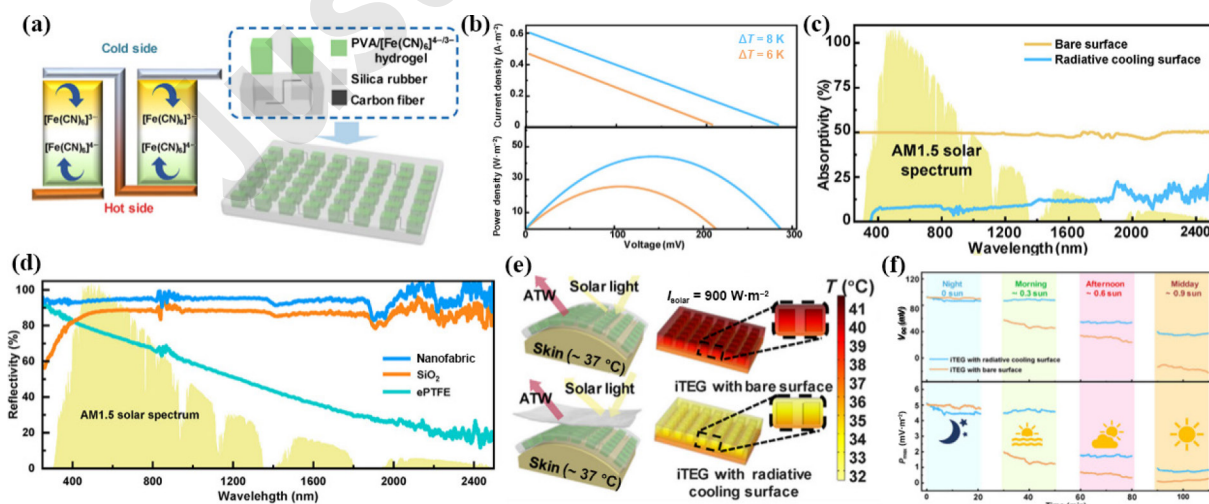


Figure 5 Thermoelectric power generation based on ionic thermoelectric generator (iTEG) and nanotextile. (a) Mechanism of the thermogalvanic effect and fabrication process of iTEG; (b) output performance of iTEG; (c) solar reflectance of SiO₂ nanofiber membrane, ePTFE film, and the resulting nanotextile; (d) absorption spectra of iTEG with radiative cooling surface and bare surface; (e) schematic illustrating heat transfer processes and temperature distributions (simulated, the real-time data of solar intensity (I_{solar}) = 900 W·m⁻²) for iTEG under direct solar irradiation with a bare surface (top) and a radiative cooling surface (bottom) under direct solar irradiance; and (f) output performance of iTEG with and without a radiative cooling surface under varying solar irradiation conditions (night, evening, afternoon, and noon). Reproduced with permission from Ref. [50], © Elsevier B.V. 2025.

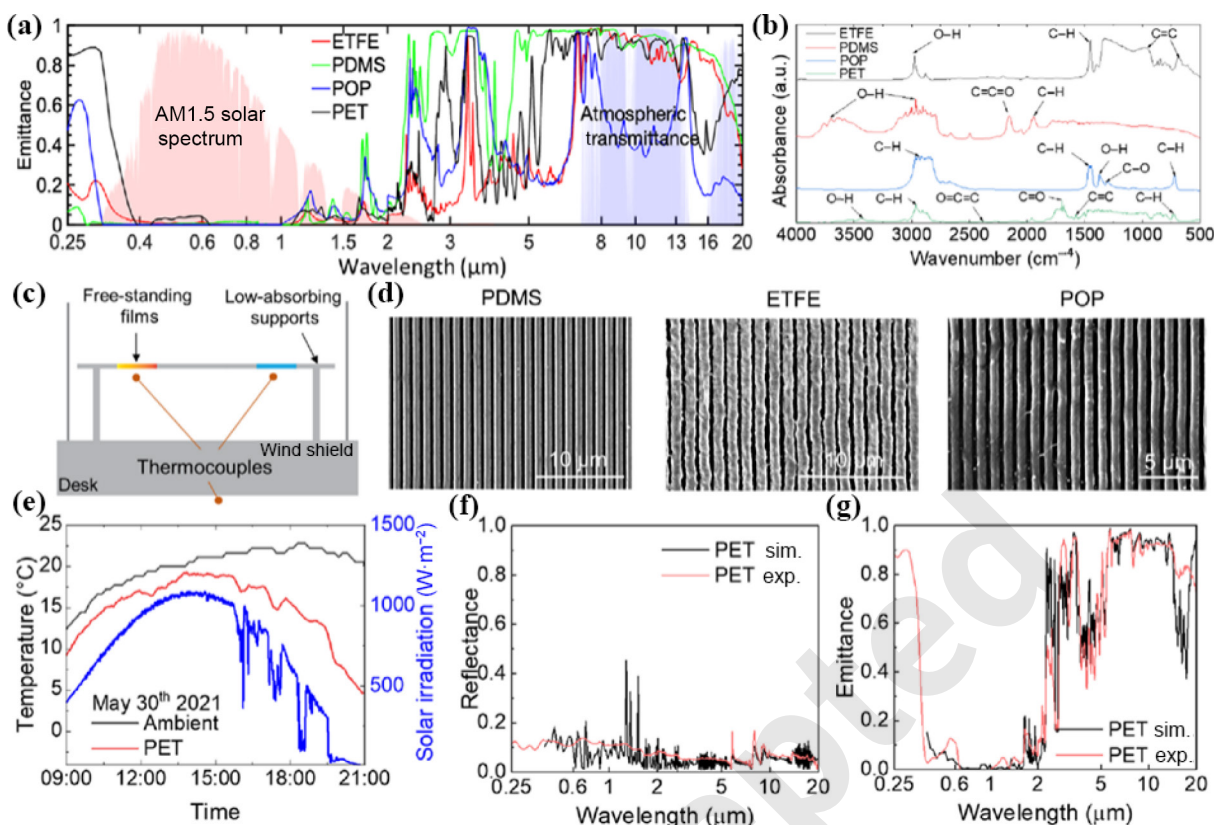


Figure 6 Optical and thermal properties of color-engineered radiative cooling polymers. (a) Hemispherical emissivity of structurally colored PDMS, ethylene tetrafluoroethylene (ETFE), polyolefin plastomer (POP), and poly(ethylene terephthalate) (PET) films from 250 nm to 20 μm ; (b) Fourier transform IR (FTIR) absorption spectra of polymer films with peak assignments corresponding to molecular vibration modes; (c) schematic of the field-test setup for suspended polymer films; (d) SEM images showing uniform and consistent patterned surfaces on PDMS, ETFE, and POP films; (e) temperature and solar irradiance recorded during field testing of nanoimprinted PET film; (f) experimental and theoretical optical reflectance of PET film based on RCWA simulation; and (g) experimental and theoretical emittance of PET film based on RCWA simulation. Reproduced with permission from Ref. [59], © American Chemical Society 2023.

enables full-color rendering while maintaining high infrared emissivity, allowing the colored films to achieve sub-ambient temperature reductions of 4.2–5.1 $^{\circ}\text{C}$ under sunlight, with a notable cooling performance (average cooling power of 85 $\text{W}\cdot\text{m}^{-2}$). This technique overcomes the limitation of monochromatic appearance in radiative cooling materials and provides a significant solution for their application in buildings, textiles, and related fields.

Yang et al. [60] developed a novel zero-energy, sub-ambient daytime radiative cooling coating composed of geopolymer/ BaSO_4 with dispersed SiO_2 nanoparticles. This material design confers dual functionality: SiO_2 microspheres enable efficient scattering and reflection of solar radiation, while the geopolymer matrix exhibits intense lattice vibrations within the atmospheric window, thereby achieving high infrared emissivity. The optimized coating demonstrates exceptional spectral selectivity, with a solar reflectance of 95.5% and an atmospheric window emissivity of 94%.

Bao et al. [61] reported a bilayer radiative cooling coating featuring a $\text{TiO}_2/\text{SiO}_2$ composite as the top reflecting layer and a TiO_2/SiC composite as the bottom emitting layer. The upper layer primarily scatters solar radiation, while the lower layer facilitates efficient radiative heat dissipation and compensates for reflection losses, synergistically achieving high spectral selectivity. This bilayered architecture enables simultaneous high solar reflectance and atmospheric window emissivity. Theoretical calculations predict that under ideal conditions, the coating can achieve a cooling effect exceeding 10 $^{\circ}\text{C}$ below ambient temperature.

Beyond color aesthetics, the development of environmentally benign, waterborne radiative cooling coatings with low volatile organic compound (VOC) content is another critical step toward practical and sustainable deployment. In this context, Huang et al. [62] reported a scalable aqueous-processing route for fabricating poly(vinylidene fluoride-co-hexafluoropropylene) (P(VdF-HFP)) coatings with hierarchically porous structures via a surfactant-assisted ball-milling strategy (Fig. 7). Contrary to the conventional expectation that ball milling merely breaks down agglomerates, the authors demonstrated that controlled energy input (e.g., 285 rpm for 2 h) induces slight plastic deformation of primary P(VdF-HFP) nanoparticles, promoting their self-assembly into uniform secondary microclusters ($\sim 2.0 \pm 0.6 \mu\text{m}$ in diameter). This bottom-up assembly creates a bimodal pore network, with micropores between secondary clusters and nanopores among primary particles, which substantially enhances broadband Mie scattering of sunlight. As a result, the optimized coating achieves a solar reflectance of 0.94 and an atmospheric-window emittance of 0.97 at a thickness of 500 μm .

Remarkably, the VOC content of the aqueous formulation is only 71 $\text{g}\cdot\text{L}^{-1}$ (including water), well below the regulatory limits set by the U.S. Environmental Protection Agency, in stark contrast to conventional organic-solvent-based porous polymer coatings that typically exceed 750 $\text{g}\cdot\text{L}^{-1}$. The coating also exhibits excellent storage stability, waterproofness (no degradation after 6 months of water immersion), and resistance to UV aging (negligible reflectance drop after 288 h of accelerated UV exposure equivalent to half-year outdoor weathering in New York City). Field tests in

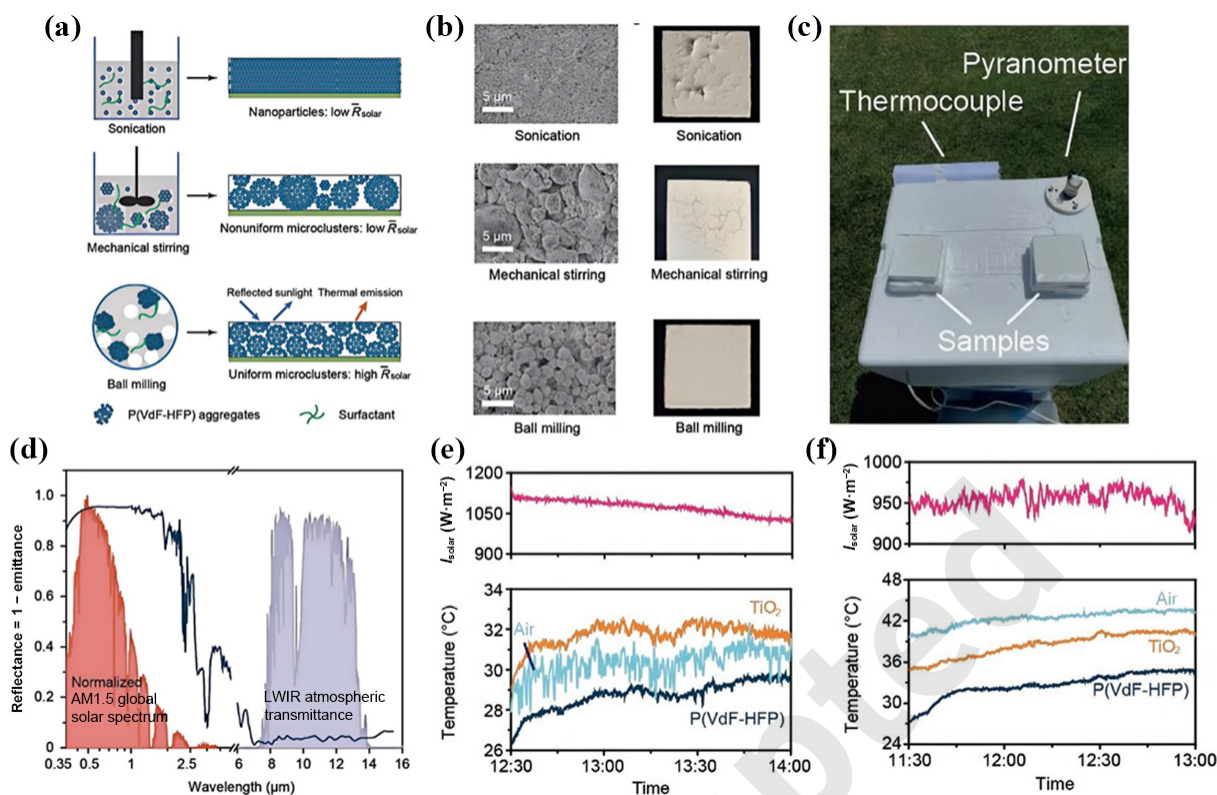


Figure 7 (a) The schematic illustrations; (b) SEM images and optical images of aqueous processing-based P(VdF-HFP) coatings with different dispersing methods, which render various morphologies; (c) a photograph of the setup for testing radiative cooling performance under sunlight; (d) the spectral reflectance of a 500 μm thick porous P(VdF-HFP) coating prepared by the ball milling approach in (a); and ((e) and (f)) I_{solar} and recorded temperatures (e) without and (f) with a polyethylene cover. Reproduced with permission from Ref. [62], © Wiley-VCH GmbH 2021.

Los Angeles under a peak solar intensity of $\sim 1100 \text{ W}\cdot\text{m}^{-2}$ show that the coating maintains an average surface temperature 1.7°C below ambient and 3.3°C cooler than a commercial TiO_2 -based white paint. This work not only provides a green and scalable manufacturing pathway for high-performance radiative cooling paints but also validates that mild mechanical deformation can be harnessed to engineer hierarchical morphologies in hydrophobic fluoropolymers, offering a versatile strategy extendable to other polymer systems, such as PVDF and PTFE.

3.1.3 Random micro/nano porous structures

By choosing matrix materials with inherent porous characteristics (e.g., foam polymers, aerogels [63], and porous ceramics), it is possible to effectively construct multi-level pore structures for radiative cooling coatings. Such structures, fabricated through phase separation, electrospinning, or foaming techniques, rely on the refractive index mismatch between the polymer matrix and air-filled pores to achieve broadband solar scattering. The randomly distributed pores and fibers efficiently scatter sunlight, while the materials themselves provide intrinsic infrared emission, achieving a good balance between performance and preparation cost. Therefore, generating porous structures in polymer materials is an important approach to achieving high-performance radiative cooling.

Similarly, a hydrophilic self-assembled monolayer (SAM) surface can also facilitate the nucleation and growth of functional films fabricated by scalable coating methods, forming a compact and uniform buried interface that enhances optical performance and thermal contact [64].

Wang et al. [65] prepared a PU-SiO₂ tandem composite fiber membrane through continuous electrospinning technology. This

membrane has a dual-layer design: The upper layer is a SiO₂ nanofiber layer that utilizes its high refractive index and fiber structure to achieve efficient solar reflection. The lower layer is an elastic PU nanofiber layer, serving as a supporting substrate, providing excellent flexibility, mechanical strength, and durability for the entire membrane structure. Meanwhile, both PU and SiO₂ materials themselves have high infrared emissivity in the 8–13 μm atmospheric window band. This synergy enables the prepared composite fiber membrane to achieve a solar reflectivity of up to 88.29% and an infrared emissivity of 94.9%. Outdoor tests show that its average cooling power can reach approximately $85 \text{ W}\cdot\text{m}^{-2}$, providing a promising solution for radiative cooling applications that require flexibility and mechanical strength.

In contrast, Zhang et al. [66] prepared porous SiO₂ aerogels and incorporated them into PTFE nanofiber membranes fabricated through electrospinning. These membranes have extremely strong hydrophobicity and chemical stability, outperforming similar materials. In terms of optical performance, the porous network structure formed by PTFE nanofibers provides efficient solar scattering, achieving a solar reflectivity of over 95.4% and a high emissivity of 95.8% in the atmospheric window. The inherent superhydrophobicity of PTFE enables its surface to form a “lotus effect”, allowing rainwater to easily wash away adhered dust particles and maintain high optical performance over the long term. More importantly, in long-term outdoor exposure experiments, this membrane demonstrated significantly better dust resistance and performance stability compared to traditional materials (e.g., polydimethylsiloxane (PDMS)), providing an effective strategy for developing radiative cooling materials suitable for harsh outdoor environments with long-term working capabilities.

Huang et al. [67] proposed a synergistic strategy of coupling radiative cooling with solar heating using an adsorbent and designed a composite hydrogel as the core material, which is a typical soft matter functional material with random micro-nano porous structures. The working principle and outdoor water-collection performance are shown in Fig. 8. Its passive atmospheric water collection is achieved by integrating multiple functional components (hygroscopic salt LiCl, photothermal material carbon black) into this porous hydrogel matrix, rather than relying on its macroscopic structural design. The prepared composite hydrogel achieved a high infrared emissivity (0.98) and high solar absorptivity (0.93), laying the foundation for its dual functions. Outdoor tests showed that the material could achieve a temperature drop of 4.2 °C below the ambient temperature at night through radiative cooling and a temperature increase of 29.3 °C above the ambient temperature under 677 W·m⁻² sunlight during the day. By ingeniously integrating the three physical processes of adsorption, radiative cooling, and solar thermal conversion into a single system, a brand-new passive technology solution that is completely independent of external energy sources has been provided for addressing the freshwater shortage problem in arid regions.

In porous media used for water evaporation or sorption, regulating the solar thermal gradient to balance heat loss and evaporation performance is equally critical for maximizing passive cooling or water harvesting efficiency [68].

By introducing a multi-scale functional filler system [69], such as hollow particles [70, 71], polymer inclusions [72, 73], and fibrous fillers, the pore structure of radiative cooling materials can be directionally designed, and their performance can be synergistically optimized. Furthermore, the chemical composition and interfacial bonding properties of the functional filler can simultaneously improve the mechanical strength, thermal stability,

and weather resistance of the material, enabling the radiative cooling performance to be maintained more durably in actual service environments, and providing a flexible and feasible regulation strategy for the design of high-efficiency, long-life, and zero-energy consumption cooling materials.

In contrast to the above filler-based strategies, melt extrusion combined with selective phase leaching offers a facile, solvent-free, and scalable route for fabricating radiative cooling polymer fibers. Sun and co-workers [74] developed polyethylene fibers containing directional microchannels (PFCDM) via melt extrusion of high-density polyethylene (HDPE)/poly(ethylene oxide) (PEO) blends followed by water leaching. The surface microgrooves (100–500 nm) and internal microchannels (0.2–2.5 μm) enable strong Mie scattering, achieving a solar reflectivity of 93.6% and mid-infrared emissivity of 93.9%. The PFCDM fabric delivers a record daytime cooling power of 104.285 W·m⁻² and a temperature drop of 27.71 °C, along with good hydrophobicity, mechanical strength, and breathability. Song et al. [75] fabricated porous PE fibers with pore and wrinkle structures via melt spinning, cold drawing, and water leaching, achieving 93.77% solar reflectance and 90.97% infrared emissivity, with a 6.8 °C sub-ambient cooling performance and an ultraviolet protection factor (UPF) of 2878. These melt-extrusion methods enable continuous, high-throughput production without organic solvents, yielding textiles with excellent radiative cooling, mechanical durability, and wearability.

These melt-extrusion-based approaches offer distinct advantages over conventional electrospinning or phase-separation methods, including continuous, high-throughput production, freedom from organic solvents, and the ability to precisely control pore morphology through processing parameters, such as draw ratio and blend composition. The resultant fiber textiles not only achieve competitive radiative cooling performance but also possess

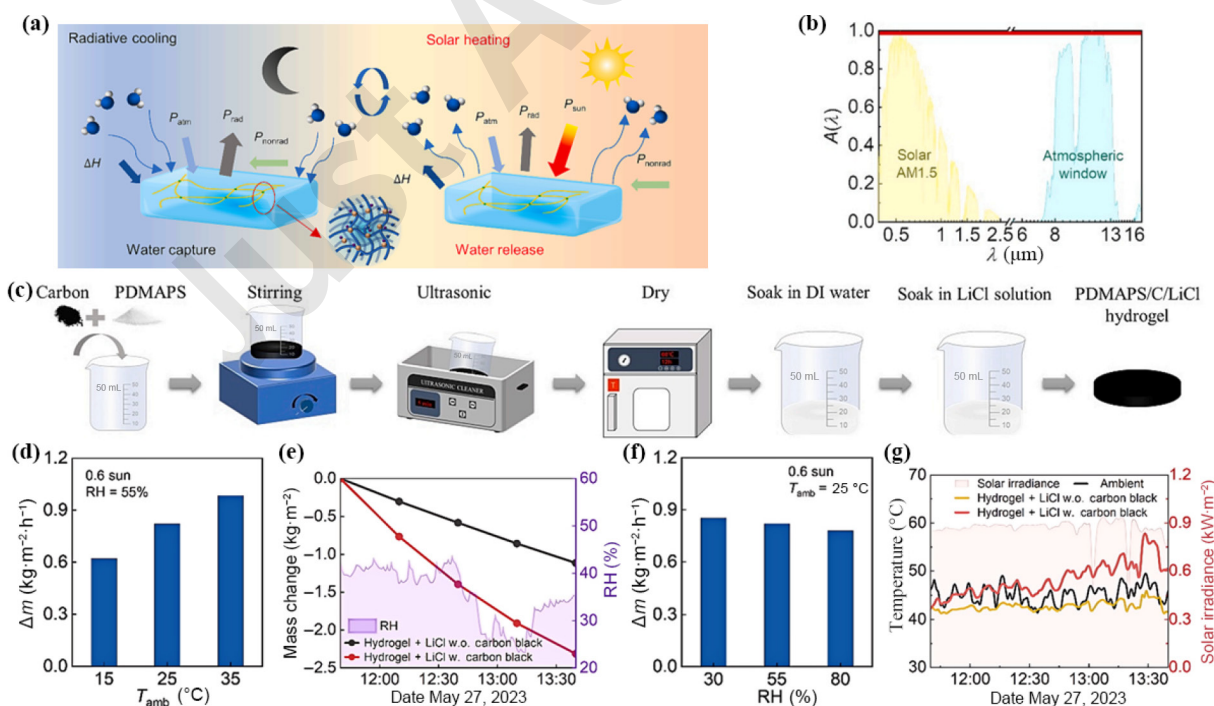


Figure 8 The principle of collecting water from the air. (a) Schematic diagram of collecting water; (b) ideal spectral absorptance of the composite hydrogel for radiative cooling in the nighttime and solar heating in the daytime; (c) schematic diagram of the composite hydrogel preparation, consisting of hydrogel PDMAAPS, hygroscopic salt LiCl, and carbon black; ((d) and (e)) Indoor mass change rate of the composite hydrogel at different (d) T_{amb} and (e) relative humidities (RH) under a solar intensity was 0.6 sun; ((f) and (g)) outdoor (f) mass change and (g) real-time temperature change of the composite hydrogel with or without carbon black. Reproduced with permission from Ref. [67], © Elsevier Inc. 2023.

the mechanical durability, air permeability, and hydrophobicity essential for practical wearable and building applications. By applying a high voltage, polymer solutions or molten substances can form fine fibers under the action of an electric field to construct a porous network. For example, a SiO_2 radiative cooling plate with an array of truncated micro-cones (top diameter $\sim 0.6 \mu\text{m}$, base diameter $\sim 1.2 \mu\text{m}$) achieves a solar-band absorptance below 2.9% and a high atmospheric-window emittance of 94.9% [76].

Theoretical simulations reveal that multimodal pore sizes are critical for enhancing solar reflectance. Chen et al. [77] showed that mixed mesopores (100 and 200 nm) yield a solar reflectance of 0.951, significantly higher than that of single-sized pores (0.811), demonstrating that hierarchical pore synergy is key to boosting reflectance.

Nevertheless, the practical deployment of these intrinsically selective materials is often compromised by environmental aging. Prolonged UV exposure degrades polymer backbones (e.g., photo-yellowing in PLA), airborne dust accumulation suppresses Mie scattering by filling air voids, and high humidity can plasticize hygroscopic matrices, altering the refractive index contrast. These synergistic effects can reduce the net cooling power by 3%–8% within the first year of outdoor exposure. Therefore, the development of intrinsic materials must integrate anti-aging additives, superhydrophobic surfaces, and standardized accelerated aging tests as essential design components.

3.2 Micro/nano photonic structures

Micro-nano photonic structures enable precise manipulation of light-matter interactions through mechanisms, including photonic bandgaps, surface phonon polaritons, and magnetic polaritons.

In photovoltaic devices, broadening the utilization of the solar spectrum is a key strategy to improve efficiency. Notably, only $\sim 46\%$ of total solar energy lies in the visible range, whereas $\sim 49\%$ is in the infrared region. This spectral distribution has driven the development of infrared-absorbing materials, such as colloidal quantum dots, and also inspires the design of micro/nano

photonic structures [78] for precise spectral control in applications like radiative cooling [79]. Representative micro/nano photonic architectures and their spectrally selective optical properties are summarized in Fig. 9.

3.2.1 Multilayer thin-film structures

These structures comprise alternating dielectric layers (e.g., $\text{SiO}_2/\text{TiO}_2$ and $\text{Si}_3\text{N}_4/\text{SiO}_2$), forming one-dimensional photonic crystals. By engineering the optical thickness of each layer, photonic structures can be constructed to exhibit high reflectance in the solar spectrum while maintaining high emissivity within the atmospheric window.

Electrospinning technology [28] has been widely used to prepare functional nanofiber membranes due to its advantages in its simple process, high production efficiency, relatively low cost, and highly controllable fiber structure parameters [29, 30]. Recent studies have shown that significant progress has been made in the spectral performance of radiation cooling fiber membranes prepared by electrospinning technology. To enhance the durability and optical performance of radiation cooling films, Li and his team [80] successfully fabricated barium strontium titanate (BST)@thermoplastic PU (TPU) composite radiation cooling films with BST nanorods as functional units and TPU as the matrix through coaxial electrospinning technology. In this structure, BST nanorods not only effectively absorb and disperse ultraviolet rays, preventing photodegradation of the TPU matrix, but also enhance visible light scattering with their high refractive index, compensating for the decrease in reflectivity caused by ultraviolet absorption. This synergistic effect enables the film to achieve a reflectivity of 97.2% and an emissivity of 93.2%, with a net cooling power of $125.21 \text{ W}\cdot\text{m}^{-2}$.

Deng et al. [81] developed a cellulose-based radiation cooling membrane that is highly efficient, environmentally friendly, and has the potential for large-scale manufacturing. Using an ethanol-water binary solvent system, they prepared a layered porous structure of ethyl cellulose/polyvinyl alcohol/polyvinylpyrrolidone/zinc oxide composite fiber membranes through electrospinning technology. The solar reflectance and mid-infrared emissivity of

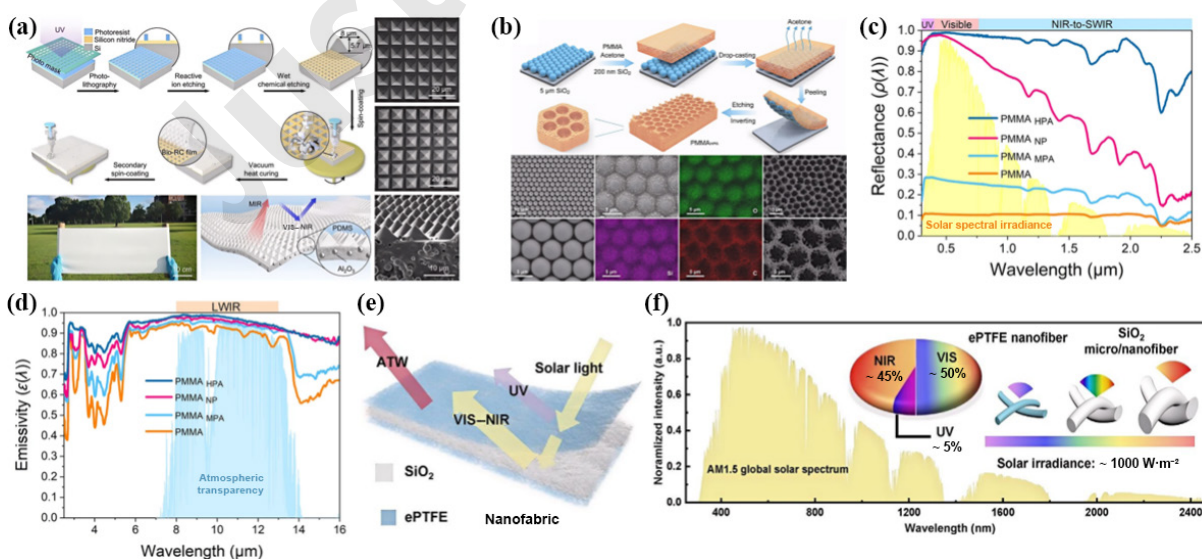


Figure 9 (a) Schematic diagram of the preparation process of PDMS/ Al_2O_3 cooling film with photonic structure. Reproduced with permission from Ref. [78], © National Academy of Sciences 2020; (b) schematic diagram and microstructure of porous PMMA film with micro-hole array for radiative cooling; (c) solar reflectance of porous PMMA in the solar spectra; (d) emissivity of porous PMMA in the infrared band. ((b)–(d)) Reproduced with permission from Ref. [20], © Wang, T. et al. 2021. (e) Hierarchical nano-microstructure design of nano fabric. VIS–NIR light; (f) nanostructure regulation of nano fabric in the solar spectrum. ((e) and (f)) Reproduced with permission from Ref. [50], © Elsevier B.V. 2025.

this fiber membrane reached 96.3% and 95.2%, respectively, achieving a cooling effect of 8.9 °C under direct sunlight. By using a low-cost and easily scalable physical method, they solved the problem of achieving high-performance optical properties in bio-based materials, providing a new green path for the practical industrialization of radiation cooling technology.

In contrast to the electrospun cellulose-based membrane described above, Zhang et al. [82] developed electrospun micropylam arrays (EMPAs) with gradient geometry via a self-assembly technology based on wet heterostructured electrified jets. The fabrication, morphology, spectral selectivity, and on-skin cooling performance of the EMPA fabric are shown in Fig. 10. The structure is ultrathin (47 μm), ultralight, and highly gas-permeable. By tuning the pyramid height, the graded refractive index effect significantly enhances phonon-polariton resonances in the mid-infrared, increasing the atmospheric-window emittance from 51.1% (for flat films) to 76.3%, while maintaining a high solar reflectance of 97.9%. Outdoor measurements demonstrate that the EMPA-based radiative cooling fabric achieves a sub-ambient temperature drop of approximately 4 °C under a solar intensity of 1 $\text{kW}\cdot\text{m}^{-2}$. Moreover, the loosely packed micro/nanofiber network endows the pyramids with excellent breathability, enabling long-term attachment to human skin without noticeable discomfort. This work offers a new pathway for personal thermal management that simultaneously achieves high cooling efficiency and wearer comfort.

3.2.2 Photonic crystals

Multilayer dielectric photonic structures [83], due to their wide absorption bands [84] of metal–oxygen bonds [85], can enhance the mid-infrared emissivity of materials [86]. Periodic structures, encompassing two-dimensional photonic crystals (e.g., SiC gratings) or three-dimensional architectures (e.g., SiO_2 microsphere arrays), achieve high solar reflectivity via Bragg

scattering or Mie resonance, while enhancing narrowband or broadband mid-infrared emission through the excitation of surface electromagnetic modes. For instance, fabricating an array of SiO_2 microspheres on a silicon substrate can create a structure that efficiently scatters or reflects visible light while emitting efficiently in the mid-infrared.

Raman et al. [87] were the first to successfully fabricate a photonic crystal film capable of achieving daytime passive cooling. This structure consists of alternating layers of hafnium dioxide (HfO_2) and SiO_2 , with a silver (Ag) reflective layer on one side. Through the optical interference effect of the photonic crystal and the intrinsic optical phonon resonance of the materials, it can reflect 97% of sunlight and selectively emit electromagnetic waves in the atmospheric window band. Under intense direct sunlight (approximately $850 \text{ W}\cdot\text{m}^{-2}$), the surface temperature of the roof with this cooler was reduced by 4.9 °C compared to the ambient air temperature, achieving a net cooling power of $40.1 \text{ W}\cdot\text{m}^{-2}$, demonstrating passive radiative cooling below the ambient temperature under direct sunlight.

Zhang et al. [88] developed a scalable and coatable polymer-based passive radiative cooling material. The inverse opal poly(methyl methacrylate) (PMMA) film was precisely controlled in pore size through a template-assisted method. This photonic crystal structure can produce extremely strong Mie scattering of sunlight, especially in the short-wave region, while the material itself has an intrinsically high infrared emissivity in the atmospheric window band. This synergy enables the material to achieve a record-breaking high solar reflectivity (up to $\sim 99\%$) and high infrared emissivity ($\sim 98\%$). The material can be directly applied to various complex-shaped substrates using conventional processes, such as spraying or brushing, making it highly suitable for large-scale practical applications and providing a technical path for low-cost, large-scale application of high-performance radiative cooling coatings.

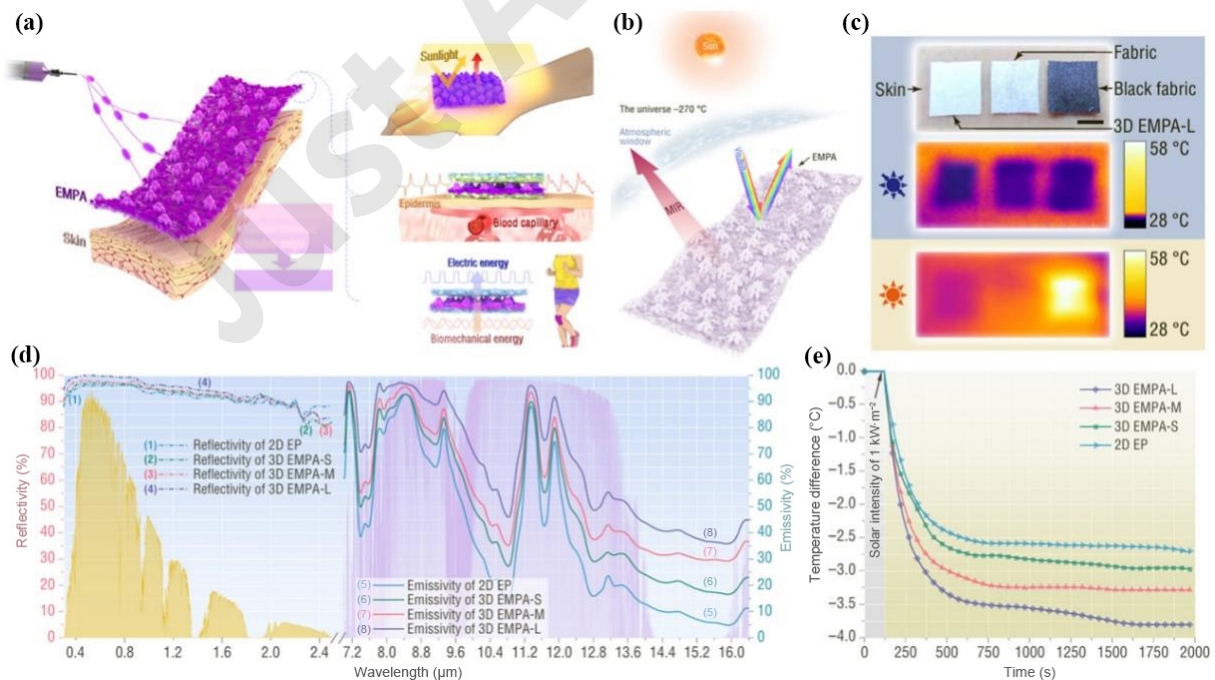


Figure 10 (a) Schematic illustration of the fabrication, structure, and application of EMPAs; (b) schematic illustration of the working mechanism of the EMPA-based passive radiative cooling fabric; (c) photograph and thermal camera images of the on-skin EMPA-based film, white cotton-containing fabric, and black cotton-containing fabric before and after solar irradiation for approximately 8 min. Scale bar, 5 mm; (d) spectral VIS–NIR/MIR reflectance/emittance of the electrospun films presented against the AM1.5 solar spectra (yellow shaded area) and the atmospheric transparency window (purple shaded area); and (e) temporal temperature difference profile measured for electrospun-film-based radiative cooling fabrics. Reproduced with permission from Ref. [82], © Zhang, J.-H. et al. 2022.

3.2.3 Metamaterials and metasurfaces

Metamaterials represent a class of artificially engineered composite materials whose optical properties can be precisely tailored through structural design, thereby achieving exceptional electromagnetic responses, including enhanced radiative cooling performance, negative refractive index, and near-zero refractive index. This offers novel pathways for advancing radiative cooling technologies. For instance, subwavelength dielectric resonant units (e.g., SiN_x cylindrical arrays) can be fabricated on metallic substrates. By exciting magnetic resonances or surface lattice resonances, strong absorption or emission peaks within the atmospheric window can be generated. Through meticulous design, these resonant peaks can be precisely positioned within the atmospheric window to realize nearly ideal spectral profiles, though their fabrication remains challenging.

Mature technologies have already been established in areas, such as transmitters capable of incorporating micro/nanoparticles [89–93], polymer-inorganic micro/nanoparticle protective coatings [94], nanoparticle-modified polymer optical waveguide films [95, 96], and polymer-micro/nanoparticle reinforced rubber materials [97]. However, research on micro/nanoparticle-embedded polymer films for radiative cooling remains relatively limited. To address current bottlenecks in radiative cooling, embedding micro/nanoparticles into polymer matrices to design thin-film structures with selective radiative characteristics is a feasible strategy. Such an approach is not only rapid and cost-effective in processing but also holds substantial application potential.

Huang et al. [98] developed a transparent, self-cleaning polymer-based micro-photonics multifunctional metamaterial (PMMM). The design concept, microstructure, and optical performance of the PMMM are illustrated in Fig. 11. Its micro-nano structure, designed based on photonic principles, consists of a PDMS matrix embedded with hollow silica nanospheres. PDMS, commonly known as silicone, is a non-polar polymer characterized by excellent hydrophobicity, stain resistance, and weather resistance; it is frequently used as a polymer coating substrate in applications, such as synthetic leather, fabric coatings, and building waterproofing [99]. These hollow silica nanospheres act as photonically engineered fillers that selectively scatter near-infrared

solar heat while maintaining up to 95% visible light transmittance. The scattering effect of the nanospheres enables uniform illumination and reduces glare. PMMM roofs exhibit reduced reflection losses and significant light-scattering effects, thereby creating a more comfortable visual environment. Plants inside buildings equipped with such roofs have been observed to grow faster and healthier. The superior radiative cooling performance of PMMM roofs enables efficient passive cooling without electrical consumption. Furthermore, the PDMS matrix not only exhibits a high emissivity of 0.98 within the atmospheric window but also possesses intrinsic hydrophobicity, imparting self-cleaning capability and helping maintain performance stability in outdoor environments. This offers an innovative multifunctional solution for energy-efficient building windows.

Lu et al. [100] have developed a metasurface-enhanced supercooling cement that can be produced on a large scale for building energy conservation. By embedding micron-sized silica particles as “meta-atoms” into the cement matrix, an efficient photonic metasurface structure is constructed, which enables more precise and powerful scattering of sunlight. This cement-based metasurface achieves strong light scattering in an extremely wide wavelength band that is independent of the incident angle, realizing a record-breaking solar reflectance of $> 96\%$ and an atmospheric window emissivity of $\sim 95\%$. This material can be produced via pressing or knife coating processes that are compatible with the existing building materials industry, with a low production cost of approximately $\$0.5\text{--}\1.0 m^{-2} . Outdoor tests demonstrated that the surface temperature of this supercooling cement can be about $8\text{ }^\circ\text{C}$ lower than the ambient temperature, with a net cooling power exceeding $100\text{ W}\cdot\text{m}^{-2}$. This work provides a high-performance, easily scalable integrated solution for zero-energy cooling of building structures. It demonstrates that, through metamaterial design principles, conventional cement can be endowed with excellent optical functionalities without relying on expensive nanofabrication techniques. This offers a viable technical pathway for achieving zero-energy building cooling directly through building materials, contributing significantly to global building energy conservation and emission reduction.

Emerging strategies also explore dynamic or self-adaptive spectral selectivity, enabling materials to switch between cooling

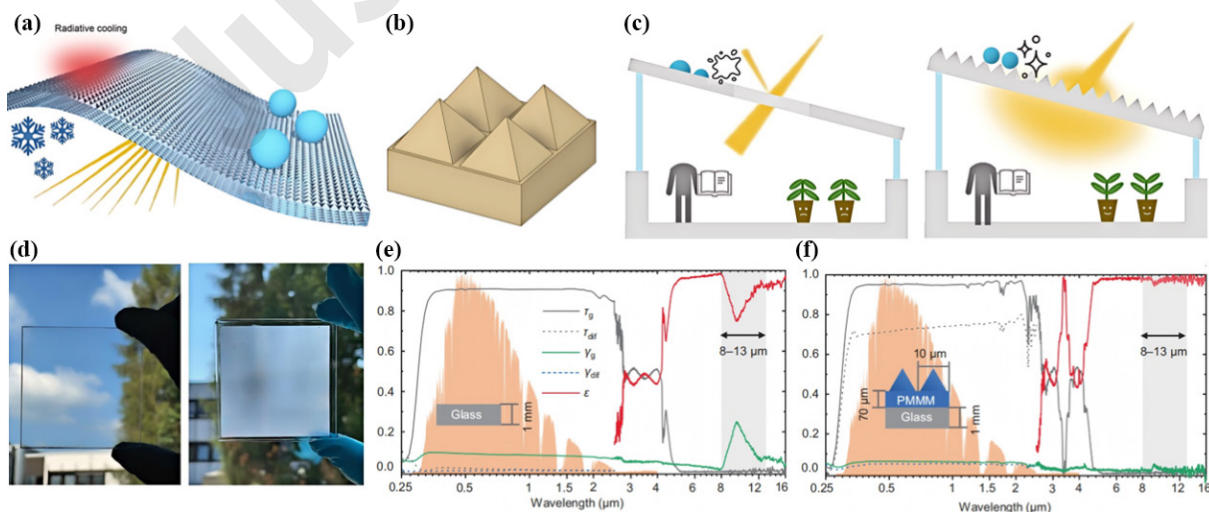


Figure 11 (a) Conceptual integration of PMMM featuring light scattering, anti-reflection, self-cleaning, and radiative cooling functions; (b) structure and dimensions of the micro-pyramid array; (c) a building with a traditional glass roof and a building with a $2\text{ cm} \times 2\text{ cm}$ PMMM roof; (d) photographs of a soda-lime glass and a PMMM film on a soda-lime glass substrate; (e) optical properties of conventional soda-lime glass; and (f) optical properties of a PMMM film coated on a 1 mm-thick soda-lime glass substrate. Reproduced with permission from Ref. [98], © Huang, G. et al. 2024.

and heating modes in response to diurnal environmental changes, thereby expanding radiative cooling toward all-day thermal management [101].

On the other hand, for polymer coatings, even with increased thickness or multilayer designs, the LWIR emittance remains limited to a saturation value of approximately 0.95 due to interface reflectance between air and the polymer. Chen et al. [102] introduced a periodic grating microstructure on the PDMS surface to suppress this interfacial reflection, successfully achieving near-perfect emittance, demonstrating that precise structural design is equally effective in overcoming the bottleneck of mid-infrared emittance.

Despite their superior spectral selectivity, precisely engineered photonic structures face formidable practical barriers. The structural periodicity essential for optical functionality is susceptible to thermal expansion mismatch, mechanical vibration, and contamination-induced refractive index changes, all of which can broaden or shift the photonic bandgaps and dampen surface polariton resonances. Moreover, cleaning these delicate micro-patterns is inherently difficult—mechanical wiping risks irreversible damage, while chemical agents may alter surface chemistry. Therefore, protective encapsulation and combined-stress durability tests are indispensable prerequisites for translating these laboratory prototypes into long-term outdoor applications.

3.3 Cross-structural comparative analysis and trade-off assessment

The above classification reveals a central principle that governs radiative cooling structural design. Spectral selectivity, fabrication cost, and long-term durability are deeply intertwined, and no single structure excels simultaneously in all dimensions.

The performance-cost trade-off is the most prominent contradiction. Polymer films and functional coatings achieve eighty to ninety-seven percent solar reflectance at the lowest processing cost, sufficient for most building energy-saving applications [50, 59, 62, 65]. However, as analyzed by Chen et al. [77] through rigorous coupled-wave analysis (RCWA) simulations, the reflectance of randomly porous polymer films is limited by the intrinsic scattering anisotropy and back-scattering losses in high-porosity media, with a theoretical ceiling around 97% under optimized multimodal pore-size distributions (e.g., 100 nm for UV, 300 nm for visible, and 1–2 μm for NIR). Further improvement would require introducing precise photonic structures, which inevitably increases fabrication complexity and cost.

Durability and environmental adaptability constitute another key differentiating dimension, which we further dissect into five critical factors: UV aging resistance, dust soiling susceptibility, moisture/humidity tolerance, cleaning feasibility, and long-term outdoor stability.

PTFE-based porous structures excel across nearly all these aspects due to their intrinsic superhydrophobicity and chemical inertness, demonstrating less than 1% reflectance degradation over six months of outdoor exposure [66]. This outstanding durability is attributed to the combination of the chemically inert PTFE backbone and the superhydrophobic surface (water contact angle $> 150^\circ$), which enables self-cleaning via rainfall. Inorganic functional coatings (e.g., geopolymer/BaSO₄ and TiO₂/SiO₂ composites) also exhibit excellent UV resistance and moisture tolerance, though their rough surfaces may trap dust particles, requiring occasional water-rinsing maintenance.

In stark contrast, most polymer films, particularly biodegradable PLA-based systems, suffer from severe photo-yellowing and chain scission under UV irradiation, while hygroscopic polymers (e.g., cellulose) undergo moisture-induced plasticization, both of which reduce the refractive index contrast between pores and matrix, thereby diminishing solar reflectance by $> 5\%$ under accelerated aging tests. For multilayers and photonic crystals, additional failure modes emerge: Thermal expansion mismatch between dissimilar layers can cause interfacial delamination, and airborne contaminants alter the local effective refractive index, damping the excitation of surface polaritons. Furthermore, cleaning these delicate micro-patterned surfaces is non-trivial, as mechanical wiping risks permanent structural damage.

A particularly encouraging breakthrough is the dual breakthrough in performance and cost recently observed in radiative cooling metamaterial research. The metasurface-enhanced supercool cement developed by Lu and colleagues simultaneously achieves a solar reflectance of 96.2% and a competitive cost-performance ratio, disrupting the conventional paradigm that high performance entails high cost [100]. However, it should be noted that this estimate is based on laboratory-scale production; the actual cost for large-scale industrial manufacturing may vary depending on local raw-material prices, production volume, and quality-control requirements. This case demonstrates that combining macroscopically scalable manufacturing with microscale structural design, rather than relying on nanoscale precision processing, may redefine the boundary between performance and cost. The generalizability of this strategy to other material systems warrants further exploration.

From the above comparison, three guiding principles can be distilled. First, for cost-sensitive large-area applications, such as building roofs and industrial storage tanks, functional coatings or polymer films should be prioritized, as their spectral performance is already sufficient for energy-saving needs. Second, for performance-critical small-area or high-value-added scenarios, such as chip-level heat dissipation and space exploration equipment, multilayers, photonic crystals, or metamaterials are more suitable choices. Third, when the application scenario is uncertain or multiple criteria must be balanced, random porous structures often serve as the most robust starting point due to their balanced performance profile. Understanding these trade-offs helps researchers and engineers make more rational decisions in material selection and structural optimization according to specific requirements.

Beyond the above engineering-oriented comparison, a mechanistic distinction between the two design pathways is essential. Random scattering structures, including films, porous membranes, and coatings, rely on Mie scattering for solar reflection. Scattering efficiency depends on pore or particle size relative to wavelength and on the refractive index contrast between matrix and air, which is approximately 0.3 to 0.5 for polymer systems. Multimodal pore sizes, such as 100 nm for ultraviolet, 300 nm for visible, and 1 to 2 μm for near-infrared, are required for broadband reflection. The reflectance ceiling is approximately 97%, limited by scattering anisotropy and back-scattering losses in high-porosity media. Mid-infrared emission arises from intrinsic molecular vibrations, including C–O, C–F, and Si–O bonds, or from phonon resonances. These modes are spectrally broad with quality factors around 5 to 20, offering robust emission but limited spectral sharpness.

Precise photonic structures, including multilayers, photonic

crystals, and metamaterials, achieve spectral control via Bragg interference or resonant modes. With 5 to 10 independent design parameters, such as layer thickness, refractive index, and periodicity, they can approach near-ideal spectra with reflectance exceeding 99% and emittance above 98%. However, sharp spectral features are angle-sensitive and are easily degraded by surface contamination or structural disorder. More importantly, solar reflection and infrared emission can be decoupled in photonic designs by assigning different layers or resonances to each function, whereas in random structures these two optical functions are coupled through the same material volume.

Random scattering structures provide a robust, fabrication-tolerant, and cost-effective solution for most building and textile applications. Photonic structures offer superior spectral precision for performance-critical, small-area, or high-value applications, but at the cost of fabrication complexity, angular sensitivity, and environmental fragility. The key to rational material selection lies in matching the optical mechanism to the specific demands of each application.

The quantitative ranges presented in Tables 1 and 2, as well as in the textual discussion of Section 3.3, are compiled from the peer-reviewed literature cited throughout this review. For each structural category, we have taken the reported values from multiple representative studies and summarized them as typical ranges rather than absolute benchmarks. The following principles were applied:

(1) Solar reflectance and infrared emittance are reported as hemispherical values measured over the 0.3–2.5 and 8–13 μm bands, respectively, under standard AM1.5 solar spectrum (ASTM G173) or equivalent laboratory/outdoor setups. Where studies reported values over slightly different wavelength ranges, we normalized them to the standard bands wherever possible.

(2) Cooling power and temperature reduction are compiled from outdoor field tests under typical summer conditions (solar irradiance: 900–1000 $\text{W}\cdot\text{m}^{-2}$, ambient temperature: 25–35 $^{\circ}\text{C}$, relative humidity (RH): 20%–60%, and low wind speed: $< 2 \text{ m}\cdot\text{s}^{-1}$). Values may differ significantly under other climatic conditions; readers are referred to the original studies for detailed experimental parameters.

(3) Cost estimates are approximate material costs derived from reported raw-material prices and typical processing costs in the cited studies. These estimates exclude substrate materials, packaging, installation labor, equipment depreciation, and transportation, and they should be interpreted as order-of-magnitude indicators rather than precise market prices. For actual industrial production, total system costs may differ considerably.

(4) Durability and scalability assessments are qualitative ratings based on the reported performance in accelerated aging tests (e.g., UV exposure, damp-heat, and thermal cycling) and outdoor exposure studies, as well as the compatibility of the reported fabrication methods with existing large-scale manufacturing infrastructure (e.g., roll-to-roll, spray coating, and doctor-blading).

By providing these notes, we aim to enhance the transparency and traceability of the cross-structural comparisons while acknowledging the inherent variability and context-dependence of the reported data.

4 Application fields

In recent years, radiative cooling technology has witnessed substantial progress in material design and photonic structure modulation, greatly enhancing spectral selectivity and cooling efficiency. Related achievements are gradually transitioning from laboratory validation to engineering prototyping and outdoor field testing. Radiative cooling technology, with its “zero energy

Table 1 Comparison of fabrication methods and optical properties across different radiative cooling structural types

Structure type	Typical fabrication methods	Solar reflectance (%)	Atmospheric-window emittance (%)	References
Polymer films/fibers	Electrospinning, phase separation, melt extrusion	88–97	82–96	[36, 37]
Functional coatings	Spraying, doctor-blading, brushing	93–99	94–97	[59–62]
Multilayer thin films	Sputtering, e-beam evaporation, coaxial electrospinning	90–97	93–95	[80, 81]
Photonic crystals	Template assembly, nanoimprinting, self-assembly	97–99	95–98	[87, 88]
Random porous structures	Electrospinning, phase separation, foaming	88–96	94–96	[65, 66, 131]
Metamaterials	Solution blending, compression molding, doctor-blading	> 96	95–98	[98, 100]

Table 2 Comparison of cooling performance, durability, scalability, and cost across different radiative cooling structural types

Structure type	Cooling performance ($\Delta T/\text{power}$) ^a	Durability ^b	Scalability ^c	Cost estimate ^d
Polymer films/fibers	3–22 $^{\circ}\text{C}/40\text{--}85 \text{ W}\cdot\text{m}^{-2}$	Moderate (UV aging, moisture)	High	Low–medium
Functional coatings	4–10 $^{\circ}\text{C}/> 100 \text{ W}\cdot\text{m}^{-2}$	Medium–high (inorganic fillers)	High	Low
Multilayer thin films	2–10 $^{\circ}\text{C}/40\text{--}125 \text{ W}\cdot\text{m}^{-2}$	Medium (interfacial adhesion)	Low	High
Photonic crystals	$\sim 5 \text{ }^{\circ}\text{C}/\sim 40 \text{ W}\cdot\text{m}^{-2}$	Medium (structural integrity)	Low–medium	High
Random porous structures	8–20 $^{\circ}\text{C}/\sim 85 \text{ W}\cdot\text{m}^{-2}$	High (PTFE, self-cleaning)	Medium–high	Medium
Metamaterials	$\sim 8 \text{ }^{\circ}\text{C}/> 100 \text{ W}\cdot\text{m}^{-2}$	Medium–high (matrix protection)	Medium–high	Low–medium

^a ΔT represents the temperature difference between the cooler and the ambient environment. Cooling performance values are compiled from multiple references under typical outdoor conditions (solar irradiance: 900–1000 $\text{W}\cdot\text{m}^{-2}$, ambient temperature: 25–35 $^{\circ}\text{C}$, relative humidity: 20%–60%, and wind speed: $< 2 \text{ m}\cdot\text{s}^{-1}$). Actual performance is highly dependent on local climate, device geometry, and measurement setup. ^bDurability ratings are qualitative assessments based on reported accelerated aging tests, outdoor exposure studies, and material properties as summarized from the cited literature. Detailed mechanistic discussions are provided in Section 3.3. ^cScalability reflects compatibility with existing industrial processes (e.g., roll-to-roll, spray coating, and doctor-blading) and the technological readiness level of the reported fabrication methods. ^dCost estimates are approximate material costs only (US dollars per square meter for the radiative cooling functional layer), excluding substrate, packaging, installation, and equipment amortization. Cost ranges are derived from reported raw-material prices and typical processing costs in the cited studies. For large-scale production, total system costs may differ significantly.

consumption” feature of achieving spontaneous cooling without any external energy input, has broad and significant application prospects in energy conservation, emission reduction, mitigating urban heat island effects, extending the lifespan of outdoor electronic devices, and developing comfortable functional textiles. Moreover, its low-carbon operational model also provides a highly promising technological solution for addressing global climate change and advancing sustainable development.

4.1 Building energy conservation

Building operational energy consumption (particularly for cooling and heating) constitutes a critical component of global energy use and carbon emissions [103]. In the context of summer building space cooling, passive radiative cooling technology has rapidly evolved and garnered significant attention [104], offering a revolutionary passive cooling solution for building envelopes [105]. Its core advantage lies in achieving sustained cooling without external energy input, thereby substantially reducing air-conditioning system loads and electricity consumption. Field validations have demonstrated the potential of radiative cooling in building applications. For instance, field measurements on rooftops coated with radiative cooling materials have shown surface temperature reductions of 4–8 °C. Building energy simulations for office buildings in hot and dry climates (e.g., parts of the southwestern United States) predict that the integration of such coatings can reduce annual cooling energy consumption by 15%–30%, although actual savings are highly dependent on factors, such as local climate, building insulation levels, and heating, ventilation, and air conditioning (HVAC) system efficiency. While the technology holds promise for large-scale implementation, its practical contribution to the “dual carbon” goals requires further validation through long-term, real-world

building performance studies across diverse climatic conditions. Notably, a recently reported triple-mode device integrating evaporative cooling, solar modulation, and thermal radiation regulation achieved a tripled annual heating/cooling energy saving (979 MJ) compared with conventional dual-mode designs (276 MJ) in building simulations [106].

Building exterior wall and roof cooling represents the most direct and widespread application [107–109]. Representative building-integrated radiative cooling designs, including cooling wood, transparent bamboo, and colored low-emissivity films, are summarized in Fig. 12. Adding thermal insulation materials to the building envelope is a conventional method for building energy efficiency retrofits in hot summer and warm winter regions, facilitating a reduction in outdoor heat ingress. Applying high-reflectivity, high-emissivity radiative cooling films or coatings (e.g., SiO_2 -based paints or polymeric films) to external building surfaces can significantly lower surface temperatures, with field measurements indicating reductions of 4–10 °C below ambient air temperature for rooftops. This effectively blocks solar heat transmission, thereby reducing the cooling load and energy consumption of air conditioning systems. In recent years, radiative cooling technology has witnessed substantial progress in material design and photonic structure modulation, gradually advancing from laboratory research to real-world applications. Large-scale deployment of radiative cooling materials across urban rooftops can effectively reflect sunlight and radiate heat into space, thereby lowering the overall urban environmental temperature. This macro-scale application not only reduces building energy consumption but also yields significant ecological benefits, contributing to the alleviation of the urban heat island effect.

A critical challenge in the practical deployment of radiative cooling is the intrinsic trade-off between optical performance and

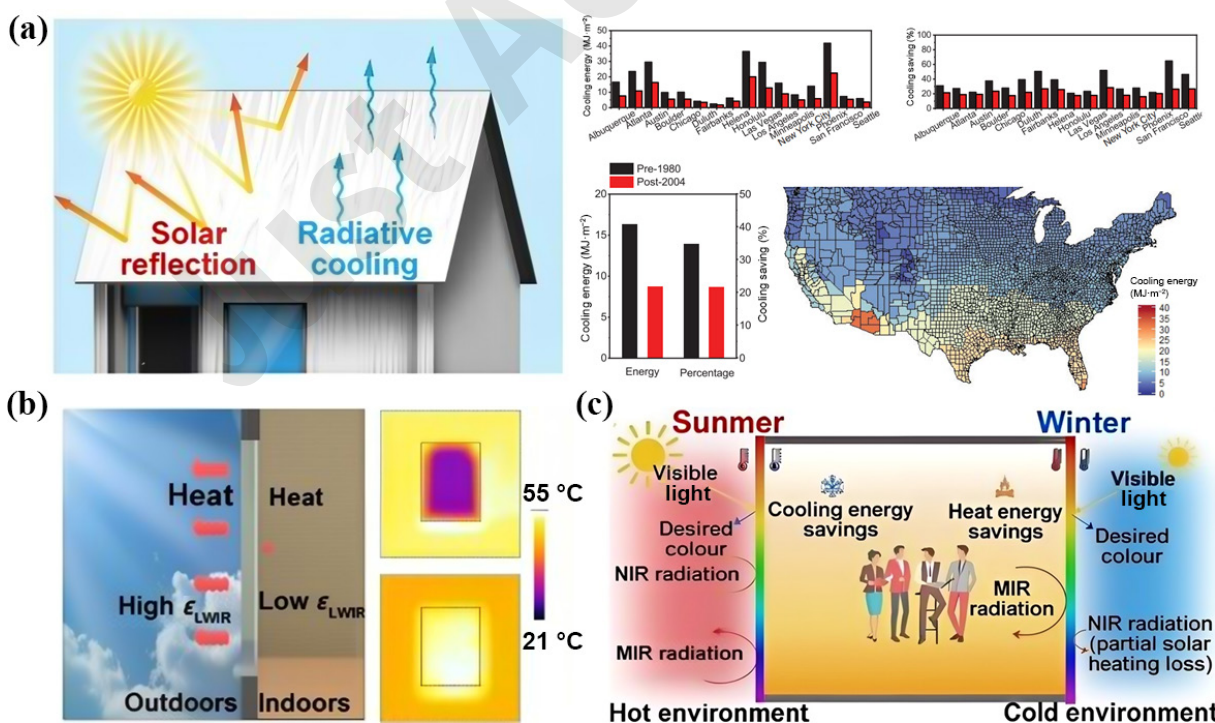


Figure 12 (a) Schematic diagram of energy-saving modeling using cooling wood with high solar reflectivity and infrared emissivity on the roof and exterior wall panels of a mid-rise apartment building. Reproduced with permission from Ref. [107], © Li, T. et al., some rights reserved; exclusive licensee American Association for the Advancement of Science 2019; (b) schematic diagram of the working mechanism of transparent bamboo for building radiative cooling. Reproduced with permission from Ref. [108], © American Chemical Society 2021; (c) schematic diagram of colored low radiation film for buildings to meet the requirements of thermal modulation programs and aesthetics. Reproduced with permission from Ref. [109], © Peng, Y. C. et al. 2021.

aesthetic requirements, particularly when introducing color or transparency. While color rendering and see-through features are essential for building facades, automotive glazing, and textiles, they inevitably compromise solar reflectance or transmittance, and thus the net cooling power.

For colored coolers, achieving a specific chromaticity inherently requires selective absorption of visible light, which directly reduces solar reflectance. State-of-the-art strategies mitigate this penalty by decoupling the color-rendering function from the primary solar-reflecting layer, for example, using structurally colored photonic films [59] or bilayer coatings where a thin colored top layer sits atop a highly reflective porous substrate. However, a residual trade-off persists: Darker shades inevitably absorb more visible light, limiting the practical palette to pastel or moderately saturated colors if sub-ambient cooling is required.

For transparent coolers, the conflict is more stringent. High visible transparency demands minimal scattering and absorption, which runs counter to the need for strong solar reflection. These devices must instead selectively transmit visible light while blocking near-infrared heat and maintaining high infrared emissivity, all while carefully controlling haze to preserve visual clarity. Transparent designs based on polymer micro-photonic metamaterials [98] have shown that such spectral management is feasible, yet their cooling power remains significantly lower than that of opaque white coolers, and their performance is strongly dependent on the angle of incidence.

These trade-offs dictate application-specific design strategies: (1) for building walls and roofs, opaque white or structurally colored coolers are preferred, prioritizing solar reflectance over color saturation; (2) for windows, transparency is non-negotiable, so designs should optimize the haze ratio and selective NIR blocking, accepting lower cooling power; and (3) for textiles, color and breathability are key, with less stringent angular dependence. Future work should aim for flexible platforms that allow independent tuning of reflectance, transmittance, chromaticity, and emittance, supported by quantitative metrics to facilitate systematic comparison and engineering selection.

The development of radiative cooling panels, as an alternative or supplement to air conditioning systems, involves integrating radiative coolers into building envelopes or connecting them to the building's water circulation systems (such as radiant ceilings and fan coil units), which can directly cool the circulating water for use in indoor fan coil units or radiant floors/ceilings, significantly reducing the electricity consumption of traditional compressor-based cooling. This "compressor-free" cooling method can significantly reduce the cooling load and electricity consumption of traditional compressor-based air conditioning systems. In suitable climate zones with low humidity and high atmospheric transparency (e.g., arid and semi-arid regions), it may serve as a primary cooling strategy for well-insulated buildings, potentially supplementing or partially replacing conventional air conditioners. However, in hot and humid climates, its cooling power is insufficient to fully replace active cooling systems, especially during peak daytime hours, due to the attenuation of the atmospheric window by water vapor.

Microphotonic structures (e.g., micro-cubes, micro-pyramids, and micro-grooves) have been proven to enhance the mid-infrared emissivity of radiative cooling. Although most radiative cooling materials are opaque, research in recent years has focused on the development of translucent radiative cooling materials. In response to the heat ingress problem of architectural glass curtain walls and windows, researchers are developing transparent or

translucent radiative cooling materials (e.g., polymer-based microphotonic metamaterials) that combine high visible light transmittance and strong mid-infrared radiation capability. Transparent aerogels have recently emerged as a promising candidate for energy-saving windows, as they combine superinsulation with high visible transparency and can be retrofitted onto existing glazing or inserted into multi-pane insulating glass units [110]. While allowing natural light to enter the interior, such materials can dissipate indoor heat through radiative emission and reflect part of the solar near-infrared thermal radiation, achieving "transparent heat insulation", which is of great significance for improving the energy-saving performance of building curtain walls. To meet the demands of architectural aesthetics, breakthroughs have been made in the research of colored radiative cooling coatings and thin films. Through technologies, such as photonic structure coloring (e.g., nanoimprinting and structurally colored microspheres), selective reflection in the visible light band is achieved to present different colors while maintaining high infrared emissivity. This breaks the limitation that traditional materials are only available in white, and greatly broadens their application prospects in architectural facade design.

Building applications require balancing cooling performance against aesthetics and functionality. Color rendering inherently reduces solar reflectance through selective visible light absorption. Bilayer architectures or structurally colored photonic films can partially mitigate this penalty, but darker shades inevitably retain lower reflectance, restricting the viable palette to pastel or moderately saturated colors if subambient cooling is required. Transparency for windows presents a more stringent conflict. High visible transmittance opposes strong solar reflection. Transparent coolers must selectively transmit visible light while blocking near-infrared radiation and maintaining high longwave infrared emittance, with careful haze control. Their cooling power remains substantially lower than that of opaque white coolers, and performance is angle-dependent. Design strategies must therefore be tailored: Opaque walls and roofs should prioritize solar reflectance, while windows should optimize the trade-off between visible transmittance, near-infrared blocking, and longwave infrared emittance, accepting lower cooling power for transparency.

In summary, building applications favor cost-effective solutions. Low-cost functional coatings (Section 3.1.2) and random porous structures (Section 3.1.3) are most promising, combining solar reflectance of about 95% with material costs below \$5 m⁻². For windows, microphotonic metamaterials (Section 3.2.3) offer a viable alternative; for colored facades, bilayer architectures (Section 3.1.2) provide the best compromise between aesthetics and cooling efficiency.

4.2 Thermal management in electronic devices and communications

The escalating performance demands of electronic devices have exacerbated thermal accumulation issues, making radiative cooling an efficient and passive supplemental solution for high-power-density equipment. In thermal management applications, integrating radiative cooling technology with servers, communication base stations, and electronic chips offers an effective passive cooling strategy that compensates for the limitations of conventional air and liquid cooling systems, thereby enhancing device performance and reliability. Radiative cooling

provides a passive, zero-energy alternative to alleviate heat accumulation in high-power devices, especially where conventional methods are inadequate.

In parallel with radiative dissipation, integrating thermochromic phase change materials (TCCPMs) into device thermal management systems offers an alternative passive strategy. It not only stores thermal energy via reversible solid-liquid phase transitions but also dynamically modulates solar absorption through a reversible black-to-colorless transition upon heating. This dual functionality enables both thermal buffering and self-adaptive optical modulation, effectively mitigating transient heat surges and improving the stability of outdoor electronic enclosures under intense sunlight.

With the rapid advancement of fifth-generation (5G)/sixth-generation (6G) communications, artificial intelligence, and Internet of Things (IoT) technologies, thermal management has become a critical bottleneck constraining the performance and reliability of high-power electronic devices. Communication infrastructure of 5G base stations and servers operates continuously, resulting in substantial energy consumption for cooling. Applying radiative cooling materials to device housings or dedicated heat sinks provides an additional passive cooling pathway, reducing reliance on air conditioning and fans, cutting energy usage and operational costs, and improving equipment durability. Field tests demonstrate that under high summer temperatures, the internal temperature of base stations can be reduced by up to 15 °C, significantly enhancing operational stability and prolonging service life. However, such performance is contingent upon factors, including local solar irradiance, ambient humidity, and the base station's internal heat load. This passive cooling approach is particularly attractive for base stations in remote, off-grid areas, where it can substantially reduce maintenance costs and reliance on active cooling. Nevertheless, its performance in tropical, humid climates requires further investigation.

In the domain of photovoltaics, solar panels experience a decline in conversion efficiency due to heating during operation, with a temperature coefficient of approximately 0.4 to 0.5 %·°C⁻¹. Integrating radiative coolers on the rear surface of photovoltaic modules allows waste heat from the cells to be directly emitted into outer space, enabling active temperature reduction. This approach increases the power output and long-term stability of solar panels, proving especially beneficial for concentrated photovoltaic systems and solar farms in high-temperature regions. Research indicates that such integrated photovoltaic-radiative cooling designs can enhance the overall power generation efficiency of PV systems by 5%–8%, effectively addressing the industry-wide challenge of efficiency degradation under elevated temperatures. While promising, this benefit is most pronounced in high-irradiance and high-temperature environments and has been validated primarily through short-term outdoor testing.

In addition to steady-state overheating, intermittent thermal loads also stress devices. Thermal energy storage (TES) heat exchangers with HDPE as PCM buffered temperature swings to ±4.6 °C under 2 min on/off cycles, versus ±12.1 °C under 7 min cycles, suggesting shorter-period cycling improves PCM responsiveness.

For chip-level integrated thermal management in consumer electronics, such as smartphones, laptops, and light-emitting diode (LED) lighting fixtures, the direct integration of micro/nano-scale radiative cooling structures into chip packaging or device enclosures facilitates efficient heat dissipation within confined

spaces, thereby enhancing device performance and longevity. The development of flexible radiative cooling films, which can be integrated inside chip packages, exemplifies this trend. In parallel with radiative cooling, flexible thermoelectric coolers (F-TECs) based on the Peltier effect offer an alternative pathway for precise on-demand temperature management at small scales, particularly in chip-level hotspots and wearable electronics, without the need for mechanical compressors [111]. For instance, a flexible radiative cooling film with a thickness of only 150 μm can lower the junction temperature of chips by over 10 °C, offering a viable thermal management strategy for next-generation high-performance computing chips.

Developing advanced multifunctional materials that integrate thermal management, solar-thermal conversion, and microwave absorption is highly promising for solving the problems that electronic devices cannot work normally due to excessive heating or cooling and electromagnetic interference [112].

For electronics cooling, multilayer thin films and metamaterials are well suited despite costs exceeding \$100 m⁻², as they offer solar reflectance above 97% and precisely tailorable infrared emission. The incorporation of high thermal conductivity fillers (e.g., hexagonal boron nitride (hBN) and graphene) represents a promising direction for hotspot mitigation.

4.3 Personal thermal management

For human individuals engaging in activities under hot weather conditions, the development of effective personal thermal management technologies [113] that effectively regulate the microclimate around the human body represents a primary pathway [114] to achieving thermal comfort. By utilizing specialized materials or structures, textiles can be engineered to efficiently emit body heat (in the form of infrared radiation) to outer space while strongly reflecting sunlight, thereby realizing passive cooling. By applying radiative-coupled evaporative cooling (REC) through perspiration on textiles, different passive cooling textiles can be fabricated [115]. The development of fabrics or apparel with radiative cooling functionality, such as infrared-transparent nanopolyethylene and fibers coated with spectrally selective metamaterials, can provide personal cooling for outdoor workers, athletes, and pedestrians exposed to high-temperature environments without energy consumption, improving both thermal comfort and personal safety. For instance, nanofiber membranes fabricated via electrospinning technology not only retain excellent radiative cooling performance, achieving a cooling effect that is 3.6 °C lower than that of white cotton fabrics, but also possess favorable air and moisture permeability, guaranteeing high wearing comfort.

Ideal outdoor radiative cooling textiles [116] require high solar reflectance and high emissivity within the atmospheric window [116]. The ideal spectral characteristics of indoor and outdoor radiative cooling textiles are compared in Fig. 13. These optical characteristics are achieved through the doping of high-reflectance nanoparticles, the design of porous structures, or the stacking of nanofibers to enhance solar reflectivity. Common dopants include titanium dioxide (TiO₂) and aluminum oxide (Al₂O₃).

In military and medical applications, multilayer composite structures for protective clothing show significant potential. For instance, these structures may comprise an inner layer for moisture-wicking, a middle layer for thermal emission, and an outer layer for solar reflection, enhancing wearer comfort without compromising protective performance. In medical settings, radiative cooling bandages can provide continuous cooling for burn victims, alleviating pain and promoting wound healing.

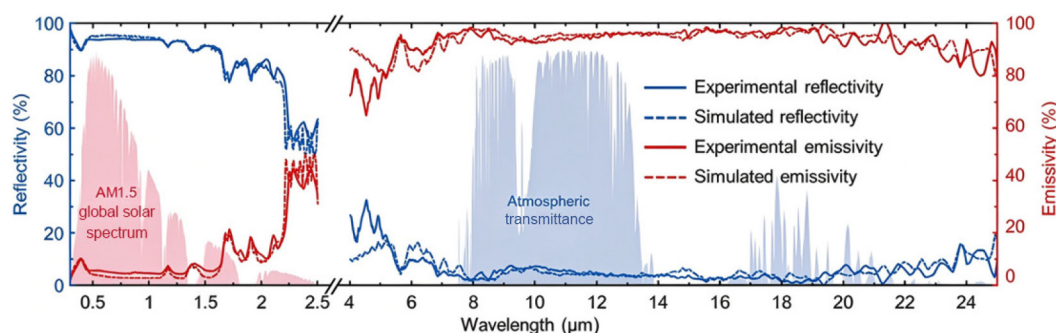


Figure 13 Measured reflectivity and emissivity spectra of the metafabric (0.3 to 25 μm). AM, air mass. Reproduced with permission from Ref. [116], © Zeng, S. N. et al. 2021.

Textiles face unique constraints beyond spectral selectivity. Breathability and moisture permeability require interconnected pore networks for vapor transport, which can conflict with dense structures needed for optimal solar reflection. Porous nanofiber membranes provide both scattering centers and moisture pathways, yet increasing porosity reduces mechanical strength and reflectance. Mechanical robustness and washability are critical, as laundering can fracture delicate photonic structures or delaminate coatings, favoring intrinsically flexible and durable materials. Ultraviolet and soiling durability are more severe than in building coatings, necessitating ultraviolet absorbers, fluorinated polymers, or superhydrophobic surfaces. Textile design must therefore achieve a balanced optimization of optical performance, thermophysiological comfort, and user-centric durability, often at the expense of attaining the absolute highest spectral selectivity.

Textiles require breathability, flexibility, and washability. Electrospun nanofiber membranes and random porous coatings strike the best balance, delivering 88% to 95% solar reflectance with good comfort. Photonic structures are less competitive due to angular sensitivity and mechanical fragility.

4.4 Transportation sector

The energy consumption for temperature control in transportation vehicles, especially the range anxiety of electric vehicles, provides a promising application field for radiative cooling technology. By applying radiative cooling materials to the roof, hood, or exterior of the vehicle, the interior temperature can be reduced under intense summer sun exposure, thereby reducing the initial load and continuous energy consumption when the air conditioning is turned on. This is particularly important for extending the range of electric vehicles. Studies have shown that under summer sun exposure, the interior temperature of electric vehicles with radiative cooling coatings can be 15–20 $^{\circ}\text{C}$ lower than that of traditional vehicles, significantly reducing the energy consumption burden when the air conditioning is turned on, and extending the range of electric vehicles by 10%–15%. For electric vehicles, this means a valuable extension of their range. It also helps protect the instruments and electronic devices inside the vehicle. Nevertheless, these range extension figures are initial estimates, and the actual benefit will depend on factors, such as vehicle insulation, HVAC system efficiency, and driving conditions. It is also important to distinguish between the demonstrated cooling of the cabin air (from tests) and the inferred benefit to the vehicle's battery and overall range.

Applying radiative cooling materials to the exterior of refrigerated logistics boxes and containers can serve as an auxiliary cooling method. It can reduce the energy consumption of active cooling equipment during transportation, provide additional

temperature buffering when there is a power outage or when the door is opened and closed, and better ensure the quality of temperature-sensitive goods, such as food and medicine. Studies have shown that the application of radiative cooling boxes can reduce the energy consumption of refrigeration equipment by more than 30% and provide a temperature buffer of 6–8 h during power outages, effectively ensuring the quality and safety of temperature-sensitive goods, such as medicines and food. This makes it particularly suitable for vaccine distribution and food supply chains in remote areas.

Design priorities diverge across transportation applications. For electric vehicles, the goal is to reduce cabin temperature and extend driving range, analogous to buildings, but with additional constraints: aerodynamic integration (conformal films), impact resistance, and aesthetic compatibility with paint finishes. The aesthetic constraint directly conflicts with maximizing solar reflectance, often requiring thin topcoats that sacrifice cooling power for color. For refrigerated transport, thermal buffering against door openings and power outages is prioritized over continuous subambient cooling, favoring integration with phase change materials for thermal energy storage. This system-level integration adds weight and cost, and the overall performance depends on thermal coupling between the phase change material, the radiative cooler, and the cargo. Transportation thus demands a system-level trade-off between cooling power, thermal mass, weight, mechanical durability, and aesthetics that is more complex than static building applications.

For vehicles, superhydrophobic PTFE-based porous membranes excel in self-cleaning, chemical inertness, and conformability. For refrigerated transport, integrating radiative cooling coatings with phase change materials provides thermal buffering against power outages, a priority that outweighs maximizing solar reflectance alone.

4.5 Water resources and the agriculture sector

By utilizing radiative cooling technology, the temperature of the surface can be lowered below the dew point at night, thereby condensing water vapor in the air and achieving passive atmospheric water collection. This is of significant strategic importance for areas with water scarcity in arid regions and islands. Experiments have shown that in an environment with a relative humidity of 30%, each square meter of radiative cooling surface can collect 2–3 L of drinking water per night. It is crucial to emphasize that this represents a peak performance figure achieved under specific laboratory conditions; the actual collection rate in real-world applications is highly sensitive to ambient humidity, air temperature, dew point, and the overall efficiency of the water collection system. In arid climates with RH below 20%,

the yield would be considerably lower, or even negligible. This technology provides a new solution for obtaining fresh water in water-scarce areas and has strategic significance.

Recently, researchers have further combined radiative cooling with directional thermal management strategies to significantly enhance passive water harvesting efficiency through system-level structural designs. Chen et al. [117] designed a V-shaped coupled structure that integrates directional solar heating (solar absorptance ~ 0.94) with directional radiative cooling (atmospheric window emittance ~ 0.92), reducing heat and mass transfer resistance by enhancing internal natural convection, achieving an indoor water collection rate of $2.62 \text{ kg}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$ under one sun. Furthermore, Chen et al. [118] proposed a macropatterned decoupled design that physically separates the evaporation and condensation ends, employing a selective solar absorber and a radiative cooling coating for spectral regulation, respectively. Combined with interface engineering of a hydrophilic water-supply layer and a hydrophobic condensation surface, this design achieved an average outdoor water collection rate of $1.85 \text{ kg}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$, far exceeding that of traditional single-stage structures ($0.2\text{--}1.0 \text{ kg}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$). These two distinct figures underscore the importance of distinguishing between high-performance proof-of-concept studies conducted in the laboratory and the more realistic, yet still impressive, performance validated in the field. These studies demonstrate that integrating radiative cooling with directional thermal management and system-level architectural innovation is an effective pathway to enhance passive water harvesting.

Research has developed a composite hydrogel system integrating moisture absorption, radiative cooling, and solar regeneration, achieving all-weather water collection. Therefore, balancing heat loss and evaporation performance by regulating the solar thermal gradient is also critical for efficient water collection in systems that couple radiative cooling with solar evaporation [119].

Beyond material-level designs, Li et al. [120] coupled radiative cooling with sorption thermal effects and thermoelectric modules, achieving simultaneous 24 h power generation (up to $685 \text{ mW}\cdot\text{m}^{-2}$) and atmospheric water production ($750 \text{ g}\cdot\text{m}^{-2}$), demonstrating a promising system-level synergy to overcome the intermittency of passive cooling.

Using selective radiative cooling films on the outer covering membranes of agricultural greenhouses can regulate the microclimate for crops. They can reflect part of the near-infrared thermal radiation in sunlight during the day (which has little contribution to plant photosynthesis but generates a lot of heat), and isolate part of the solar heat, thereby reducing the temperature inside the greenhouse, reducing the heat stress on crops, and reducing irrigation requirements, creating a more suitable growth environment for specific crops, and saving energy used for cooling. For example, smart greenhouse radiative cooling films can dynamically adjust the solar spectral transmittance according to the needs of crops, reducing the temperature inside the greenhouse by $8\text{--}12^\circ\text{C}$ in summer and reducing irrigation water consumption by $20\%\text{--}30\%$. This technology is particularly suitable for promotion in water-scarce areas, providing new technical support for water-saving agriculture.

Based on the case studies reviewed in Sections 4.1 to 4.5, we summarize the structure–property–application mapping to guide material selection. Four key design principles are extracted from this mapping. First, for cost-sensitive large-area applications, functional coatings and random porous structures offer the best

performance–cost balance. The marginal benefit of photonic precision does not justify the cost premium when the target temperature reduction is moderate. Second, when spectral precision is critical, such as in small-area or high-value devices, photonic structures are defensible despite higher costs. Their ability to decouple solar reflection from infrared emission provides unique advantages that random structures cannot replicate. Third, for outdoor applications, durability considerations, including ultraviolet resistance, self-cleaning, and mechanical robustness, should be prioritized from the initial design stage. Retrofitting protective measures onto vulnerable structures is rarely effective. Fourth, the growing demand for colored or transparent coolers requires decoupling aesthetic functions from cooling functions through layered architectures or structural coloration. This decoupling mitigates the inevitable application-specific design trade-offs. These applications often require non-conventional spectral profiles. For atmospheric water harvesting, sorbent-based systems that couple radiative cooling with solar heating require high longwave infrared emittance for nighttime cooling and high solar absorptance for daytime desorption, a contradiction resolved through material architecture and system design rather than purely spectral selectivity. For agricultural greenhouses, the key trade-off is between photosynthetic active radiation transmission and near-infrared reflection. The ideal material transmits 400 to 700 nm light for plant growth while reflecting near-infrared radiation to minimize overheating, shifting the performance metric from solar reflectance to the ratio of photosynthetic transmission to near-infrared reflection. These applications demand scenario-specific spectral strategies tailored to the underlying physical processes of condensation, adsorption, and photosynthesis.

For water harvesting, broadband infrared emitters (4 to $25 \mu\text{m}$) can outperform narrowband atmospheric window emitters by maximizing total radiative heat loss. Spectral design must be application-specific, informed by local humidity, dew point, and sorbent properties, rather than adopting a universal spectral target.

5 Outlook

Although the prospects are broad, the large-scale practical application of radiative cooling technology is still hindered by the high costs of its key materials, including spectrally selective films and micro/nano photonic structures [121]. To move from laboratory to real-world deployment, the following key challenges need to be overcome.

To transcend these barriers and chart a concrete roadmap for the field, we propose a multi-tiered strategic framework that addresses material selection, standardized evaluation, environmental resilience, and integrated design. This framework moves beyond problem identification to offer actionable pathways for transitioning radiative cooling from academic prototypes to robust engineering solutions.

5.1 Thermal resistance and high-temperature stability

Currently, the vast majority of radiative cooling research focuses on sub-ambient cooling scenarios, where the core optimization targets are maximizing solar reflectance and atmospheric window emittance. However, when radiative cooling technology is applied to real-world scenarios with continuous high heat generation—such as 5G communication base stations, power electronics, and outdoor charging piles—the device operating temperature is often above ambient. Under such above-ambient

heat dissipation conditions, the thermal resistance and high-temperature service stability of the materials themselves become critical determinants of cooling effectiveness. This issue has not yet received systematic attention in existing studies.

From a thermophysical perspective, the thermal management performance of radiative cooling materials is governed by three factors. The first is interfacial thermal resistance: the contact thermal resistance between the radiative cooling coating/film and the heat-generating substrate directly affects the efficiency of heat conduction from the heat source to the cooling layer. The second is thermal diffusion capability: Local hot spots can cause severe temperature non-uniformity; insufficient in-plane thermal diffusivity can shorten device lifespan and increase the risk of thermal runaway. The third is high-temperature service stability: Conventional polymer-based radiative cooling materials may undergo degradation, yellowing, or softening under sustained high temperatures, which not only weakens cooling performance but may also pose fire hazards.

Recently, researchers have begun to explore solutions to these challenges from a heat-transport perspective. Ye et al. [122] designed a radiative-evaporative cooling hydrogel that, during high-workload daytime hours, synergistically couples evaporative latent heat with radiative dissipation, achieving a temperature 12.0 °C lower than that of a pure radiative cooling film, while its high water content imparts excellent flame retardancy. Liu et al. [123], utilizing the high intrinsic thermal conductivity ($\sim 1.82 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$) and superhydrophobic self-cleaning surface of hBN, developed an ultrathin radiative cooling paint of only 150 μm thickness, which maintains a high solar reflectance (0.963) while effectively reducing coating thermal resistance and ensuring long-term outdoor durability. Furthermore, Ye et al. [124] constructed a bilayer thermally conductive radiative cooling film, wherein the bottom graphene layer with high in-plane thermal diffusivity ($185.7 \text{ mm}^2\cdot\text{s}^{-1}$) rapidly spreads localized hotspot heat across the entire film, significantly reducing the hotspot temperature from 130.6 to 63.3 °C under the same local heating power.

Collectively, these explorations reveal a crucial trend: For above-ambient heat dissipation applications, radiative cooling material design must move beyond the single-dimensional optimization of spectral selectivity toward a multi-dimensional synergistic design of “spectral selectivity–heat transport management–high-temperature stability”. Future research urgently requires systematic breakthroughs in reducing interfacial thermal resistance, enhancing in-plane thermal spreading, and improving material stability under high-temperature and high-humidity conditions.

To address these challenges, we recommend a multi-pronged strategy. (1) Incorporate high thermal conductivity fillers (e.g., hBN, AlN, and graphene) into polymer matrices to enhance in-plane heat spreading, as demonstrated by recent bilayer designs that reduce hotspot temperatures by over 60 °C. (2) Engineer interfacial thermal contacts via self-assembled monolayers or thin metallic interlayers to minimize contact resistance. (3) Prioritize inorganic or high-T_g polymer binders that maintain structural integrity above 100 °C. Future work should systematically report the thermal conductivity and long-term stability under sustained high-temperature operation to guide material selection for electronics cooling applications.

5.2 Cost and large-scale production

The supermaterials or photonic crystal structures with excellent

performance in the laboratory often have complex preparation processes and high costs, making it difficult to achieve large-scale and low-cost production. Developing new processes, such as nanoimprinting, self-assembly, and roll-to-roll processing, that are cost-effective and easy to apply or adhere to, to reduce the manufacturing cost of precise photonic structures is currently a research focus.

Based on our comparative analysis (Table 1), we identify polymer/inorganic composite coatings (e.g., geopolymers/BaSO₄ and waterborne PVDF-HFP with fillers) and PTFE-based porous membranes as the most promising candidates for low-cost and large-scale deployment, with estimated material costs below \$1–5 m⁻² and compatibility with roll-to-roll, spray, or doctor-blade coating processes. For performance-critical applications where higher cost is acceptable (over \$100 m⁻²), multilayer films and metamaterials remain the gold standard, and research should focus on improving manufacturing yield through nanoimprint lithography and self-assembly techniques. To bridge the gap, random porous structures offer a balanced compromise at roughly \$10–50 m⁻² with 90%–96% reflectance. We encourage future studies to report a clear cost-per-area estimate and processing throughput to facilitate industrial assessment.

5.3 Environmental durability and mechanical properties

Materials used in practical applications need to withstand long-term exposure to sunlight, rain, wind, sand, pollution, and temperature changes. Their performance in terms of UV aging resistance, wear resistance, anti-fouling, self-cleaning, and adhesion to the substrate is crucial. Performance degradation can significantly affect the cooling effect. Attention should be paid to the full-cycle energy consumption and environmental impact from production, use, to disposal, to truly achieve sustainable “green cooling”.

Beyond the durability considerations for static radiative cooling materials, the emerging category of dynamic radiative cooling systems presents additional stability challenges, as these materials must sustain consistent and reversible spectral switching over extended periods of outdoor exposure [125]. The repeated actuation cycles inherent to dynamic regulation, which may be driven by temperature variations, mechanical deformation, or electrochemical reactions, can accelerate material degradation. This degradation manifests as diminished optical modulation amplitude, retarded switching kinetics, and ultimately reduced energy-saving performance throughout the service lifetime. Moreover, the integration of multiple functional layers, electrolytes, or mechanically compliant components in dynamic systems introduces additional failure mechanisms, including interfacial delamination, electrolyte leakage, and mechanical fatigue, which are less frequently encountered in conventional static coolers. Consequently, durability-oriented material selection and standardized accelerated aging protocols under realistic outdoor conditions are essential for assessing the practical viability of both static and dynamic radiative cooling technologies. For large-scale deployment, protective strategies, such as ultraviolet-resistant coatings, encapsulation layers that inhibit moisture and oxygen ingress, and mechanically robust composite architectures should be incorporated at the initial design stage. Addressing these environmental durability challenges is a prerequisite for bridging the gap between laboratory demonstrations and real-world engineering applications, thereby ensuring that radiative cooling technologies can deliver sustained energy savings across their intended operational lifespan.

Durability under outdoor conditions must be addressed from the design stage, not as an afterthought. We recommend the following strategies. (1) Superhydrophobic surface engineering (contact angle over 150°) enables self-cleaning, allowing rainfall to wash away dust and maintain high reflectance. (2) UV-blocking strategies, such as incorporating inorganic UV absorbers (e.g., BST, TiO_2 , and ZnO) or using intrinsically UV-stable fluorinated polymers (e.g., PTFE and PVDF), prevent photo-yellowing and chain scission. (3) Encapsulation layers (e.g., thin SiO_2 or Al_2O_3 coatings) protect delicate photonic structures from moisture and mechanical abrasion. Furthermore, we advocate for the adoption of standardized accelerated aging tests, including UV exposure (ASTM G154), damp-heat ($85^\circ\text{C}/85\% \text{ RH}$), thermal cycling, and dust soiling/cleaning cycles, to be reported alongside initial optical performance. This will provide a realistic benchmark for long-term outdoor service life.

5.4 Spectral performance optimization

The ideal material should have extremely high reflectivity in the solar spectrum band (especially in the near-infrared) and extremely high emissivity in the atmospheric window. How to balance and optimize these two characteristics, especially maintaining stable performance under complex angles and climatic conditions, remains a continuous technical challenge. To address this challenge, decoupling the interdependency between solar reflectance and infrared emittance enables their simultaneous enhancement [126].

A case in point is the hybrid water harvester reported by Xu et al. [127]. They deliberately used a broadband infrared emitter (PDMS, $4\text{--}25 \mu\text{m}$) rather than a narrowband atmospheric-window selective emitter. Their thermal analysis showed that for exothermic condensation, broadband emission provides higher net cooling power because it dissipates heat across a wider spectral range. This finding suggests that the optimal spectral profile is application-dependent, not universally fixed. They also identified a practical issue: condensed water droplets scatter sunlight and degrade cooling performance. By introducing a hydrophilic underlayer that flattens the water into a thin film, they suppressed scattering and maintained stable radiative cooling. This work demonstrates that spectral design must consider both the thermodynamic nature of the target process and the dynamic optical interference from operational byproducts, moving beyond static ideal targets toward scenario-specific strategies.

Beyond the pursuit of ideal broadband reflectivity and emittance, we emphasize that the optimal spectral profile is application-specific. For opaque building envelopes, maximizing solar reflectance (especially in the NIR) and atmospheric-window emittance remains the priority. For colored coolers, bilayer designs that decouple the color-rendering top layer from the highly reflective bottom layer can preserve over 90% NIR reflectance while achieving moderate color saturation. For transparent windows, the goal shifts to high visible transmittance, low haze, and selective NIR blocking, while maintaining sufficient LWIR emittance, a challenging multi-objective trade-off that requires precise photonic engineering. Structurally, we highlight hierarchical porous architectures (combining mesopores and micropores) as a powerful strategy to enhance Mie scattering across the entire solar spectrum. Theoretical and experimental evidence shows that multimodal pore size distributions yield significantly higher reflectance than single-sized pores. Future research should employ rigorous coupled-wave analysis or finite-difference time-domain simulations to guide pore-size engineering for specific spectral bands.

The ideal spectral profile is not universally fixed but depends on the specific application. In atmospheric water harvesting, a broadband infrared emitter (4 to $25 \mu\text{m}$) may outperform a narrowband atmospheric window emitter because broader emission provides higher net radiative dissipation. Spectral design must therefore be grounded in the thermodynamic requirements of each application and must account for dynamic operational interferences, such as sunlight scattering by condensed water droplets. Researchers are encouraged to adopt scenario-specific spectral engineering strategies informed by the unique demands of each end use.

5.5 Environmental and climatic constraints

The efficiency of radiative cooling is highly dependent on atmospheric conditions. On cloudy, hazy, or high-humidity days, water vapor, carbon dioxide, and clouds in the atmospheric window will absorb and scatter infrared radiation, significantly weakening the cooling effect or even rendering it completely ineffective. Beyond these atmospheric dependencies, radiative cooling also suffers from inherent intermittency, which provides abundant cold energy at night but insufficient supply during peak daytime hours. This limitation further undermines its practical reliability under real-world climatic fluctuations. To address this temporal mismatch, recent studies have integrated PCMs with radiative cooling coatings. For instance, Wang et al. [128] developed a bifunctional phase-change composite film that stores excess nighttime cold energy in a flexible PCM layer and releases it during the day to compensate for solar-induced cooling losses. This approach smooths diurnal cooling-power fluctuations and maintains sub-ambient temperatures throughout the day, demonstrating that thermal energy storage can effectively counter both weather variability and the intermittency issue.

Future research is expected to focus on smart regulation strategies that integrate electrochromism, thermochromism, or photochromism into radiative cooling devices, which could further enhance their adaptability for all-climate and all-season thermal management [129]. A recently reported self-adaptive cooling/heating film [130] achieves autonomous mode switching via shape memory polymers and buffers weather fluctuations with phase change materials, delivering 8.2°C sub-ambient cooling in summer and 14°C heating in winter. This provides a zero-energy solution to overcome the seasonal mismatch of conventional static materials. Such intelligent, self-regulated systems, combined with ongoing advances in cost reduction and scalable fabrication, are poised to propel radiative cooling technology from laboratory demonstration toward practical, all-weather, year-round thermal management solutions.

The inherent dependence on clear, dry atmospheric conditions is a major barrier to global deployment. To overcome this, we propose two complementary approaches. (1) Multi-mode passive cooling synergy integrates radiative cooling with evaporative cooling (via hydrogels or hygroscopic salts) or with PCMs that store nighttime “cold” and release it during cloudy or humid daytime periods. Recent hybrid systems have demonstrated that such coupling can maintain sub-ambient temperatures even under reduced atmospheric transmittance. (2) Application-tailored spectral design suggests that for scenarios where high heat dissipation is required regardless of atmospheric window transparency, such as condensation-based water harvesting, a broadband infrared emitter ($4\text{--}25 \mu\text{m}$) may outperform narrowband atmospheric-window emitters, as it maximizes total radiative heat loss. This indicates that the “ideal” spectrum is not

fixed; researchers should consider the thermodynamic nature of their target application. We further recommend that studies report cooling performance under simulated high-humidity (e.g., 80% RH) or overcast conditions to provide a realistic assessment of annual energy-saving potential in diverse climate zones.

Beyond these atmospheric dependencies, a further constraint arises from the unregulated nature of radiative cooling. The same high-emissivity surface that provides daytime cooling continues to radiate heat at night or during cold seasons, potentially leading to overcooling. This issue manifests in three practical forms: (1) increased heating penalty that offsets summer energy savings in buildings and vehicles, (2) condensation and frost formation when surface temperature drops below the dew point, degrading optical performance and causing structural damage, and (3) thermal discomfort for wearable textiles in cooler environments.

To address this dilemma, adaptive spectral regulation strategies are gaining attention. Thermochromic materials, mechanically tunable photonic structures, and phase change material integration offer pathways to dynamically modulate solar reflectance or infrared emittance in response to environmental changes, transforming radiative cooling from a static “always-on” technology into a versatile all-season thermal regulation solution. Recent demonstrations of self-adaptive cooling/heating films exemplify this promising direction and highlight the need for future research on intelligent systems that balance cooling and heating demands across diurnal and seasonal cycles.

5.6 Potential solutions and strategic pathways

To address the above challenges, researchers have explored corresponding strategies from multiple dimensions. The following provides a systematic elaboration from five aspects: material innovation, surface and interface engineering, multi-mode passive cooling synergy, smart responsive design, and standardized evaluation.

In terms of material innovation, exploring novel material systems with intrinsically superior spectral selectivity and environmental tolerance is a fundamental pathway. Inorganic dielectric materials (e.g., SiO_2 , Al_2O_3 , TiO_2 , BaSO_4 , and hBN) exhibit intrinsically low solar absorption due to their wide bandgap characteristics, while their strong lattice vibrations can generate high infrared emittance within the atmospheric window. They also possess excellent UV resistance and chemical inertness, making them an important direction for replacing conventional polymer matrices. Furthermore, incorporating high-thermal-conductivity fillers (e.g., hBN, AlN, and graphene) into radiative cooling matrices can enhance thermal diffusion capability while maintaining spectral selectivity, effectively reducing heat accumulation within the coating and improving heat dissipation efficiency under above-ambient operating conditions. Biomass-derived materials (e.g., cellulose and lignin) also show promise in balancing cooling performance with environmental sustainability due to their renewability and biodegradability.

In terms of surface and interface engineering, superhydrophobic surface designs (with water contact angles exceeding 150°) can endow radiative cooling materials with self-cleaning functionality, enabling dust and contaminants to be readily removed by rainfall or wind, thereby maintaining high solar reflectance without manual maintenance. Meanwhile, superhydrophobic surfaces can effectively inhibit moisture retention on material surfaces, mitigating optical degradation caused by pollutant adhesion and microbial growth under high-

humidity environments. Additionally, introducing thermal interface modification layers between the radiative cooling coating and the substrate can significantly reduce contact thermal resistance, ensuring efficient heat conduction from the heat source to the cooling layer. Interfacial molecular engineering (e.g., self-assembled monolayers) can also be employed to regulate the bonding strength and thermal transport efficiency between the coating and the substrate.

In terms of multi-mode passive cooling synergy, the performance of a single radiative cooling mechanism is inherently dependent on meteorological conditions, such as atmospheric transparency, humidity, and cloud cover, which impose significant limitations in practical applications. Integrating radiative dissipation with other heat transfer pathways—including thermal conduction, convection, and evaporative latent heat release—within a single system enables complementary synergy among different mechanisms under varying environmental conditions. Specifically, during high-workload daytime hours with reduced atmospheric transmittance, evaporative cooling can utilize the latent heat of water evaporation to provide an additional cooling channel, compensating for the attenuation of radiative cooling power; enhanced thermal conductive designs (e.g., constructing in-plane high-thermal-conductivity pathways) can rapidly spread localized hotspot heat across the entire cooling surface; and optimized convective structures (e.g., three-dimensional fin architectures or microchannel designs) can improve air-side heat exchange efficiency. At night or under low-load conditions, radiative cooling-dominated heat dissipation can be coupled with adsorption–desorption processes to achieve cyclic water regeneration, sustaining the system’s continuous operation. This multi-mechanism synergistic design enables passive cooling systems to maintain stable thermal management performance across a broader range of climatic regions and weather conditions.

In terms of smart, responsive, and dynamic regulation, the spectral properties of conventional radiative cooling materials are statically fixed, incapable of adapting to changes in environment and season. Developing smart radiative cooling materials with dynamically tunable spectral selectivity represents a frontier direction to overcome this limitation. Thermochromic, electrochromic, and photochromic materials can dynamically regulate their solar reflectance and infrared emittance in response to changes in ambient temperature, light intensity, or external electric fields, thereby achieving adaptive thermoregulation of “cooling in summer and warming in winter”. For example, they can automatically enhance radiative dissipation in hot weather to reduce temperature while attenuating heat loss in cold weather to retain warmth. Furthermore, responsive micro/nano structures (e.g., tunable photonic crystals and phase change material composite structures) can achieve dynamic switching of spectral selectivity across different wavelength bands, providing new design freedom for all-weather and all-season thermal management. This dynamic regulation capability is essential for addressing the overcooling dilemma discussed in [Section 5.5](#). By enabling autonomous mode switching, these smart systems can eliminate the heating penalty and condensation risks associated with static coolers. Recent demonstrations of self-adaptive cooling/heating films, which achieve seasonal mode switching via shape memory polymers, exemplify this promising direction.

In terms of standardized evaluation and accelerated aging testing, the current performance evaluation in the radiative cooling field lacks unified standards. Laboratory measurement conditions (e.g., spectral range, ambient temperature and

humidity, and solar simulator spectral match) vary considerably across studies, making direct comparison of cooling performance among different research works difficult. Establishing standardized evaluation systems and accelerated aging test protocols tailored to real-world operating conditions is a critical step in promoting technological maturation. This should include: developing outdoor testing specifications covering different climatic regions (tropical, temperate, arid, humid, etc.); establishing accelerated experimental standards for environmental factors, such as UV aging, thermal cycling, damp-heat alternation, salt spray corrosion, and wind-sand abrasion; and unifying reference conditions for measuring net cooling power and temperature reduction. The establishment of a standardized system will greatly facilitate the engineering validation and market promotion of radiative cooling technology.

These five pathways are not independent of each other but rather mutually reinforcing and complementary. The future development of radiative cooling technology urgently requires a paradigm shift from single-dimensional spectral selectivity optimization toward a system-level design framework of “intrinsic material innovation–interface and surface engineering–multi-mode synergy–smart dynamic regulation–standardized evaluation”, advancing this technology from laboratory research toward true zero-energy engineering applications.

Beyond color aesthetics, fire safety and end-of-life recyclability are critical yet underexplored constraints for building applications. Most polymer-based coolers, such as PU, PMMA, and PLA, are flammable. While flame-retardant additives can mitigate this issue, they often compromise optical performance. Balancing fire safety with high solar reflectance remains an unmet challenge. Regarding sustainability, biodegradability, as exemplified by PLA, is

insufficient, as it requires specific composting conditions and may release harmful byproducts. A circular approach that designs for chemical or mechanical recyclability should take priority. Full lifecycle assessments are essential to validate the genuine environmental benefits of radiative cooling technologies. For example, Kong et al. [131] constructed a PVDF composite film by anchoring ZrO_2 nanoparticles onto electrospun fibers via PDMS. The proposed composite film was denoted as ZrPF. As shown in Fig. 14, this film simultaneously achieved superhydrophobicity, enhanced mechanical properties, high solar reflectance (> 95%) and atmospheric-window emissivity (> 96%), and a 21.8 °C outdoor temperature drop, demonstrating a scalable route toward durable and self-cleaning radiative cooling films.

In summary, the transition from laboratory to practical application requires a system-level integration of the strategies discussed above. We propose a staged development roadmap: (1) material selection: prioritize systems with inherent durability and low-cost processability, such as inorganic–organic composites or PTFE-based structures; (2) structural design: tailor porosity, layering, or photonic patterns to achieve the required spectral selectivity for the specific application, guided by simulation; (3) durability engineering: embed self-cleaning, UV-blocking, and protective encapsulation into the structural design from the outset; (4) standardized testing: subject prototypes to accelerated aging protocols (UV, damp-heat, thermal cycling, and dust) and report results alongside initial performance; and (5) field validation: deploy in diverse climate zones to evaluate performance under real-world weather fluctuations, including humidity, cloud cover, and dust accumulation, and benchmark annual energy savings. By following this roadmap, radiative cooling technology can evolve from a laboratory curiosity into a robust, economical, and

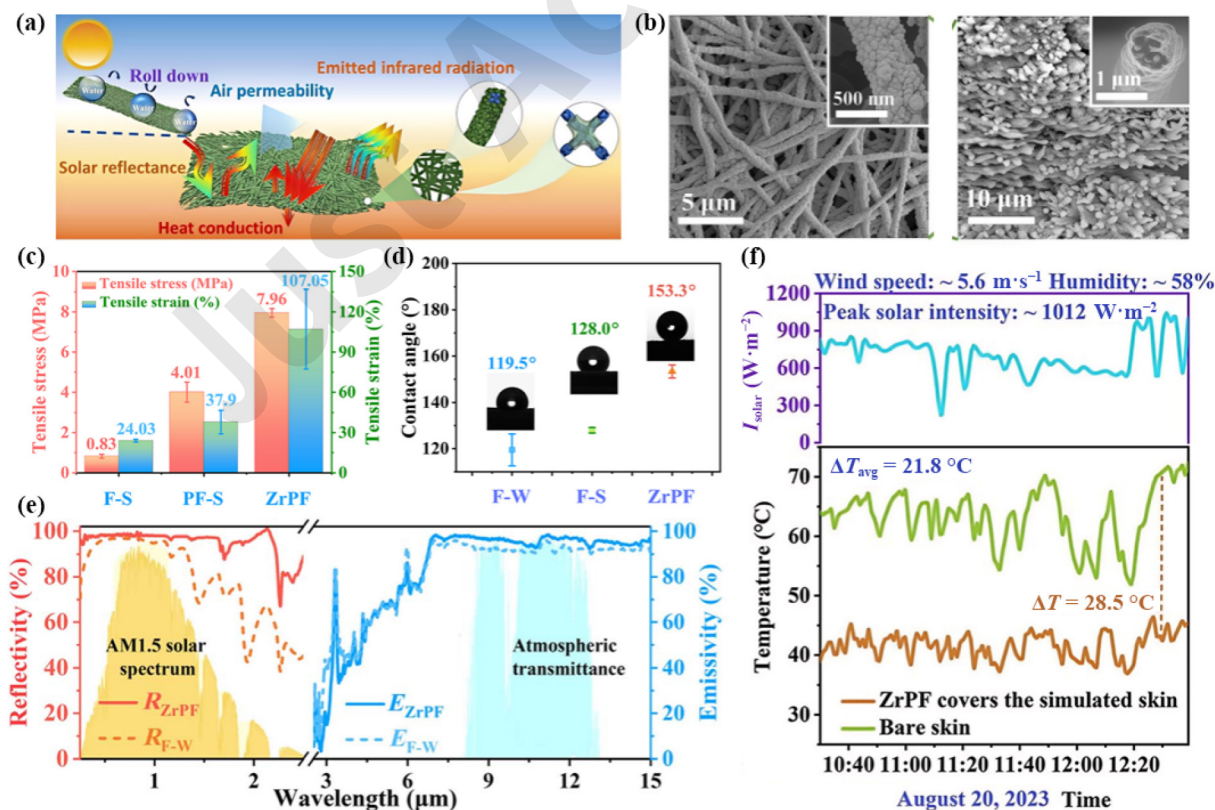


Figure 14 (a) Working principle of the superhydrophobic ZrPF film; (b) microscopic morphology of 5 μm PVDF composite membrane and 10 μm PVDF composite membrane; (c) mechanical tensile of PVDF composite membrane; (d) contact angle of PVDF composite membrane; (e) optical properties of PVDF composite membrane; and (f) cooling performance of PVDF composite membrane. Reproduced with permission from Ref. [131], © The Royal Society of Chemistry 2024.

sustainable zero-energy cooling solution for buildings, electronics, textiles, and beyond.

Radiative cooling technology, with its unique advantages of zero energy consumption, zero carbon emissions, and passive operation, has rapidly emerged as a transformative frontier technology in the global context of striving for “carbon neutrality” and “sustainable development”. It not only provides a brand-new path to address the increasingly severe problems of cooling energy consumption and global warming, but also opens up a new direction for the development of materials science and engineering technology, with extremely profound research significance and application prospects.

Spectral selective structural design is the core engine driving the development of radiative cooling technology. From random scattering spectra to precise photon engineering, research has demonstrated that through structural design, it is possible to approach the ideal spectral model infinitely. In conclusion, spectrally selective structural design has brought radiative cooling from theory to reality and is rapidly advancing towards more intelligent, practical, and integrated directions, playing a key role in areas, particularly in building energy conservation, personal thermal management, and climate change response. With the continuous development of technology and the reduction of costs, radiative cooling is expected to profoundly change our production and lifestyle in the future.

In summary, this review has presented a structural-design-centric framework for understanding and advancing radiative cooling technology. Unlike prior comprehensive reviews, our contribution lies in three aspects: (1) a hierarchical taxonomy that organizes the field by structural engineering complexity, revealing the underlying evolution from random-scattering materials to precision photonic architectures; (2) a systematic structure–property–application mapping that provides actionable guidance for material selection in specific end-use scenarios; and (3) a critical assessment of scalability and durability challenges that are often overlooked in laboratory-focused studies. By framing spectral selectivity as a designable structural property rather than a passive material attribute, we hope to inspire continued innovation at the intersection of nanophotonics, materials science, and thermal engineering, ultimately accelerating the translation of radiative cooling from research laboratories into real-world zero-energy cooling solutions.

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Declaration of conflicting interests

The authors declare no conflicting interests regarding the content of this article.

Data availability

All data needed to support the conclusions in the paper are presented in the manuscript and/or the Supplementary Materials.

Additional data related to this paper may be requested from the corresponding author upon request.

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