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Recent Progress in Daytime Radiative Cooling: Advanced Material Designs and Applications

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Passive daytime radiative cooling (PDRC) is emerging as a promising cooling technology. Owing to the high, broadband solar reflectivity and high mid-infrared emissivity, daytime radiative cooling materials can achieve passive net cooling power under direct sunlight. The zero-energy-consumption characteristic enables PDRC to reduce negative environmental issues compared with conventional cooling systems. In this review, the development of advanced daytime radiative cooling designs is summarized, recent progress is highlighted, and potential correlated applications, such as building cooling, photovoltaic cooling, and electricity generation, are introduced. The remaining challenges and opportunities of PDRCs are also indicated. It is expected that this review provides an overall picture of recent PDRC progress and inspires future research regarding the fundamental understanding and practical applications of PDRC.

1. Introduction

Cooling is critical to humankind's life, especially in hot areas. Rapid population growth and industrialization intensify global warming and make cooling increasingly necessary for providing comfortable living environments.[1] However, traditional cooling technologies, such as air conditioners, not only have huge energy consumption but also cause environmental problems by emitting greenhouses and harmful gases.[2] Meanwhile, the heat generated from traditional cooling methods further warms the environment, thereby creating a deteriorating predicament.[3] Therefore, it is of significant importance to develop renewable and energy-saving cooling technologies.

Radiative cooling as a passive cooling scheme can cool objects without energy consumption.[4,5] Unlike conventional cooling methods such as air conditioners, it dissipates heat to the cold universe (3 K) through radiation.[6,7] According to Planck's law, the terrestrial radiation with a temperature of ≈300 K at the Earth's surface is concentrated at wavelengths ranging from 2.5 to 50 μm. Meanwhile, the combined effects from all atmospheric components result in that the special atmospheric window between 8 and 13 μm that is highly transparent. Hence, most terrestrial areas can effectively radiate heat through the transparent atmospheric window to the cold universe to maintain a relatively stable temperature. To this end, radiative coolers should have high emissivity in the transparent atmospheric window (8–13 μm), which is transparent in this region and allows infrared (IR) light to pass through. In this regard, various materials and structures have been designed in the past few decades and have exhibited promising passive cooling performance at night.[8,9] However, during the daytime, the Sun heats the radiative coolers, which seriously compromises the cooling effect. To resolve this problem, the cooler should radiate more heat to the cold universe while reflecting sunlight to avoid solar heating. Fan and co-workers[10] first designed multilayer photonic materials and achieved daytime radiative cooling to a temperature below ambient conditions when subjected to direct sunlight. Since then, various materials have been demonstrated to realize subambient daytime radiative cooling and have shown great potential for practical applications.[11–13] Before some reviews have summarized these developments in radiative cooling,[14–17] but the limited net cooling power and instability of radiative cooling hinder its practical wide applications. In this review, by summarizing the state-of-the-art research and development in passive daytime radiative cooling (PDRC), we first propose three critical components for PDRC: 1) spectral design in the mid-IR range, 2) structure design for enhancing solar reflectance, and 3) thermal management. Second, we introduce various applications of PDRC, such as building cooling, solar cell cooling, water harvesting, clothing, and electricity generation (**Figure 1**). Finally, the remaining challenges and opportunities of PDRCs are also discussed.

2. Fundamental Mechanisms of PDRC

2.1. PDRC Concept

Based on Kirchhoff's law, an object with a temperature higher than 0 K continuously exchanges heat with other objects by absorbing

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and emitting electromagnetic waves. Studies show that the Earth's atmosphere is transparent to IR radiation with a wavelength range of 8–13 μm.[25,26] Thus, terrestrial emitters can effectively dissipate heat to the cold universe (≈3 K) through this atmospheric window. In other words, the emitted radiative power can theoretically exceed the absorbed incoming radiation, thereby passively cooling the object and reaching temperatures below the ambient environment. In this feature, the heat is dissipated to the cold universe through IR emission. The average IR emittance ($\varepsilon_{8-13\,\mu m}$) in the atmospheric window (8–13 μm) can be calculated as follows

$$\varepsilon_{8-13\,\mu m} = \frac{\int_8^{13} I_{BB}(T,\lambda)\varepsilon(T,\lambda)\,d\lambda}{\int_8^{13} I_{BB}(T,\lambda)\,d\lambda} \quad (1)$$

where $I_{BB}(T,\lambda)$ is the spectral intensity emitted by a standard blackbody with temperature, and $\varepsilon(T,\lambda)$ represents the spectral emittance of a cooler.

During the daytime, the peak solar absorbance cannot exceed the emitted surface energy and achieve a subtemperature under direct sunlight. Considering the large difference between the power density of solar irradiation and surface radiation, a radiative cooler should have a low absorption for wavelengths of solar irradiation (i.e., 0.3–2.5 μm) while maintaining a high emissivity at mid-IR wavelengths. It is not easy and requires adjusting the optical properties of a material over a very wide range of wavelengths. The average solar reflectance ($\overline{R}_{solar}$) in the full solar spectrum (0.3–2.5 μm) can be calculated using the following equation

$$\overline{R}_{solar} = \frac{\int_{0.3}^{2.5} I_{solar}(\lambda)R(\lambda)\,d\lambda}{\int_{0.3}^{2.5} I_{solar}(\lambda)\,d\lambda} \quad (2)$$

where $I_{solar}(\lambda)$ represents the solar intensity spectrum at air mass (AM) 1.5, and $R(\lambda)$ is the spectral reflectance of a cooler.

In addition, it is also important to minimize the absorbed power from incident atmospheric thermal radiation. The absorption of atmospheric radiation mainly comes from IR wavelengths outside of the atmospheric window. In addition to thermal radiation, radiative cooling surfaces are also subject to other nonradiative heat transfer processes with the surrounding environment. The nonradiative loss is heating conduction/convection, which is the collective effect owing to the contact of the radiative cooler with external surfaces and air adjacent to the radiative cooler.

2.2. Thermal Energy Flow of PDRC

In this section, the steady-state heat transfer process of a radiative cooler is analyzed (**Figure 2**),[27] which can be expressed as

$$P_{in} = P_{sun} + P_{amb}(T_{amb}) + P_{cond+conv} \quad (3)$$

$$P_{out} = P_{rad}(T_c) \quad (4)$$

$$P_{cooling} = P_{out} - P_{in} \quad (5)$$

where P_{in} is the heat transferred to the surfaces of a radiative cooler, and P_{out} is the temperature-dependent radiative power

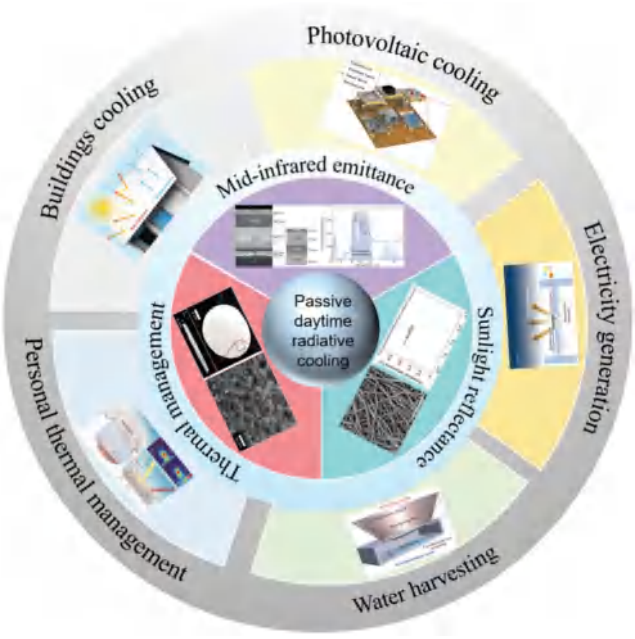

Figure 1. Schematic illustration of the development process of passive daytime radiative cooling. Reproduced with permission.[10] Copyright 2014, Springer Nature. Reproduced with permission.[18] Copyright 2021, Springer Nature. Reproduced with permission.[19] Copyright 2019, The Authors, some rights reserved; exclusive licensee AAAS. Distributed under a Creative Commons Attribution NonCommercial License 4.0 (CC BY-NC). Reproduced with permission.[20] Copyright 2019, The Authors, some rights reserved; exclusive licensee American Association for the Advancement of Science. Reproduced with permission.[21] Copyright 2020, Cell. Reproduced with permission.[22] Copyright 2019, Cell. Reproduced with permission.[23] Copyright 2019, The Authors, some rights reserved; exclusive licensee AAAS. Distributed under a Creative Commons Attribution NonCommercial License 4.0 (CC BY-NC). Reproduced with permission.[24] Copyright 2021, The Authors, some rights reserved; exclusive licensee American Association for the Advancement of Science.

$P_{rad}(T_c)$ of the cooler. Note that $P_{cooling}$ denotes the net cooling power. T_{amb} is the ambient air temperature.

The power radiated by the cooler can be calculated using

$$P_{rad}(T_c) = \int d\Omega \cos\theta \int_0^{\infty} dI_{BB}(T_C,\lambda)\varepsilon(\lambda,\theta) \quad (6)$$

$$I_{BB}(T_C,\lambda) = \frac{2hc^2}{\lambda^5}\frac{1}{e^{\frac{hc}{\lambda k_B T}-1}} \quad (7)$$

Here, I_{BB} is the spectral radiance of a blackbody at temperature T, h is Planck's constant, k_B is the Boltzmann constant, c is the speed of light, and λ is the wavelength.

The power absorbed by the cooler from solar radiation, including solar radiation and diffused sunlight, can be expressed as follows

$$P_{sun} = \int_0^{\infty} d\lambda\,\varepsilon(\lambda,0)I_{AM1.5}(\lambda) + \int d\Omega \cos\theta \int_0^{\infty} dI_{solar-diffuse}(\lambda)\varepsilon(\lambda,\theta) \quad (8)$$

where $I_{AM1.5}(\lambda)$ is the standard AM 1.5 solar spectrum with a total irradiance of 1000 W m^{-2}, and $I_{solar\,-\,diffuse}(\lambda)$ is the scattering solar radiation toward the cooler.

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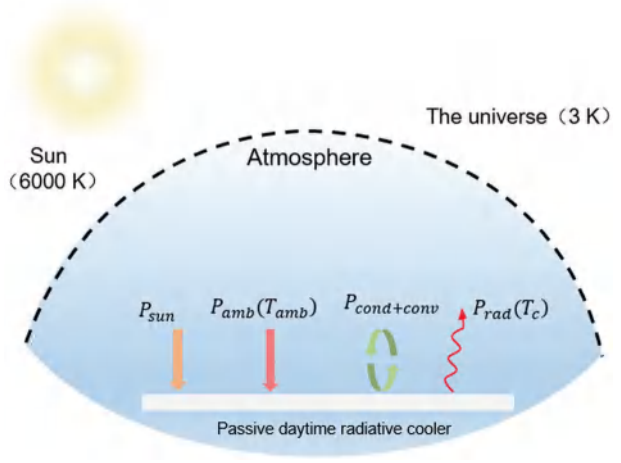

Figure 2. Thermal energy flow in a typical PDRC system. P_{sun} is the power absorbed by the cooler from solar radiation. $P_{amb}(T_{amb})$ is the power absorbed by the cooler from the atmospheric radiation. $P_{cond+conv}$ is the nonradiative power from the atmosphere. $P_{rad}(T_c)$ is the thermal radiative power.

$P_{amb}(T_{amb})$ is the power absorbed by the cooler from the atmospheric radiation, which can be described as

$$P_{amb}(T_{amb}) = \int d\cos\theta \int_0^{\infty} dI_{BB}(T_{amb},\lambda)\varepsilon(\lambda,\theta)\varepsilon_{atm}(\lambda,\theta) \quad (9)$$

$$\varepsilon_{atm}(\lambda,\theta) = 1 - t(\lambda)^{1/\cos\theta} \quad (10)$$

The power lost due to heat conduction and convection is $P_{cond+conv}$ and can be defined as

$$P_{cond+conv} = h_c(T_{amb} - T_c) \quad (11)$$

where h_c is a combined nonradiative heat coefficient that captures the collective effect of conductive and convective heating owing to the contact of the radiative cooler with external surfaces and air adjacent to the radiative cooler.

3. Development of Advanced PDRC Devices

Based on the basic cooling principles of PDRC, there are two key parameters to meet the requirements for efficient daytime radiative cooling: 1) high-emittance value in the atmospheric transparent window (8–13 µm) and 2) high solar reflectance in the entire solar spectrum range (0.3–2.5 µm).[28] First, the radiative cooler should radiate as much heat as possible to the cold universe. Second, sunlight absorption should be minimized to avoid heating intake and increase cooling efficiency. Significant efforts have been devoted to enhancing cooling performance from enhanced solar reflectance to optimized IR radiation. In this section, several design concepts with highly efficient PDRC by enhancing mid-IR emittance and solar reflectance are discussed.

3.1. Spectral Design in the Mid-IR Range

Numerous studies have attempted to enhance coolers' radiative cooling performance by seeking new materials with mid-IR radiation or modifying already-known materials, including inorganic dielectric materials and organic polymer materials.

It is difficult for inorganic dielectric materials to achieve daytime radiative cooling on their own. Many efforts have been devoted to developing superior PDRC structures with high mid-IR emittance through the delicate design of multilayer coatings and surface/integral structure engineering. Strong IR emittance can be achieved with a wide absorption band of metal–O, nonmetal–O, and nonmetal–nonmetal bonds of inorganic dielectric materials.[29,30] Among these materials, silicon-related materials, such as SiO,[31] SiO_2,[32] and Si_xN_yO,[33] have been widely used in radiative cooling applications. Specifically, in 2013, Rephaeli et al.[34] presented a theoretical calculation model and revealed that a metal–dielectric photonic structure is capable of radiative cooling in outdoor daytime conditions. Considering the heat transferred through conduction and convection mechanisms, the net cooling power of this structure exceeds 100 W m^{-2} at ambient temperature. The structure was constructed using silicon carbide and quartz photonic crystal layers and a silver substrate. This structure can strongly radiate heating in the transparent atmospheric window while simultaneously reflecting sunlight in the entire solar spectrum. Moreover, Raman et al.[10] combined seven layers of HfO_2 and SiO_2 and proposed an integrated photonic solar reflector and thermal emitter (**Figure 3**a). This tailored photonic crystal achieved a high reflection (97%) in the solar spectrum, avoiding heating and sternly emitting in the atmospheric transparency window (8–13 µm). Consequently, this cooling device can be applied to reach a cooling power of 40.1 W m^{-2} and reach a temperature up to 4.9 °C below the ambient temperature.

In addition, more dielectric particles have also been reported to enhance the mid-IR emittance of cooling devices. Most bulk multilayer dielectric layer films are fabricated by photolithography or electron beam evaporation, which requires stringent, nanometer precision fabrication. Dielectric particles can be easily applied in different textures and geometries to create scalable cooling devices. For example, a cooling device consisting of a periodical array of SiO_2 microspheres has achieved outstanding daytime cooling performance.[29,35] The optimized media could maximize optical scattering in the solar spectrum, thereby improving the thermal emission (Figure 3b). Incorporating dielectric microspheres in a polymer has also been widely adopted as an effective approach for dielectric microsphere-based PDRC devices. These dielectric microspheres can preserve polymers' excellent IR emittance and intrinsic physical properties (flexibility, permeability, and water repellency). Owing to the combinatory effect, hybrid materials offer opportunities for these dielectric microspheres to enhance antiabrasion. For instance, Zhai et al.[12] randomly embedded 8 µm SiO_2 microspheres in a polymeric matrix and achieved a daytime radiative cooling metamaterial with a high thermal emissivity (>0.93) for wavelengths varying from 8 to 13 µm (Figure 3c). Moreover, this high-efficiency and economical manufacturing method meets commercial applications' low-cost and large area requirements. More importantly, the phonon-polariton resonances of dielectric microspheres with 8 µm diameter lead to a strong emissivity in the mid-infrared ray (MIR). Wang and co-workers[36] designed SiO_2 spheres with sub-micrometer sizes and random distributions into polyamide 6 nanofibers, enabling a high mid-IR emittance and enhancing radiative cooling

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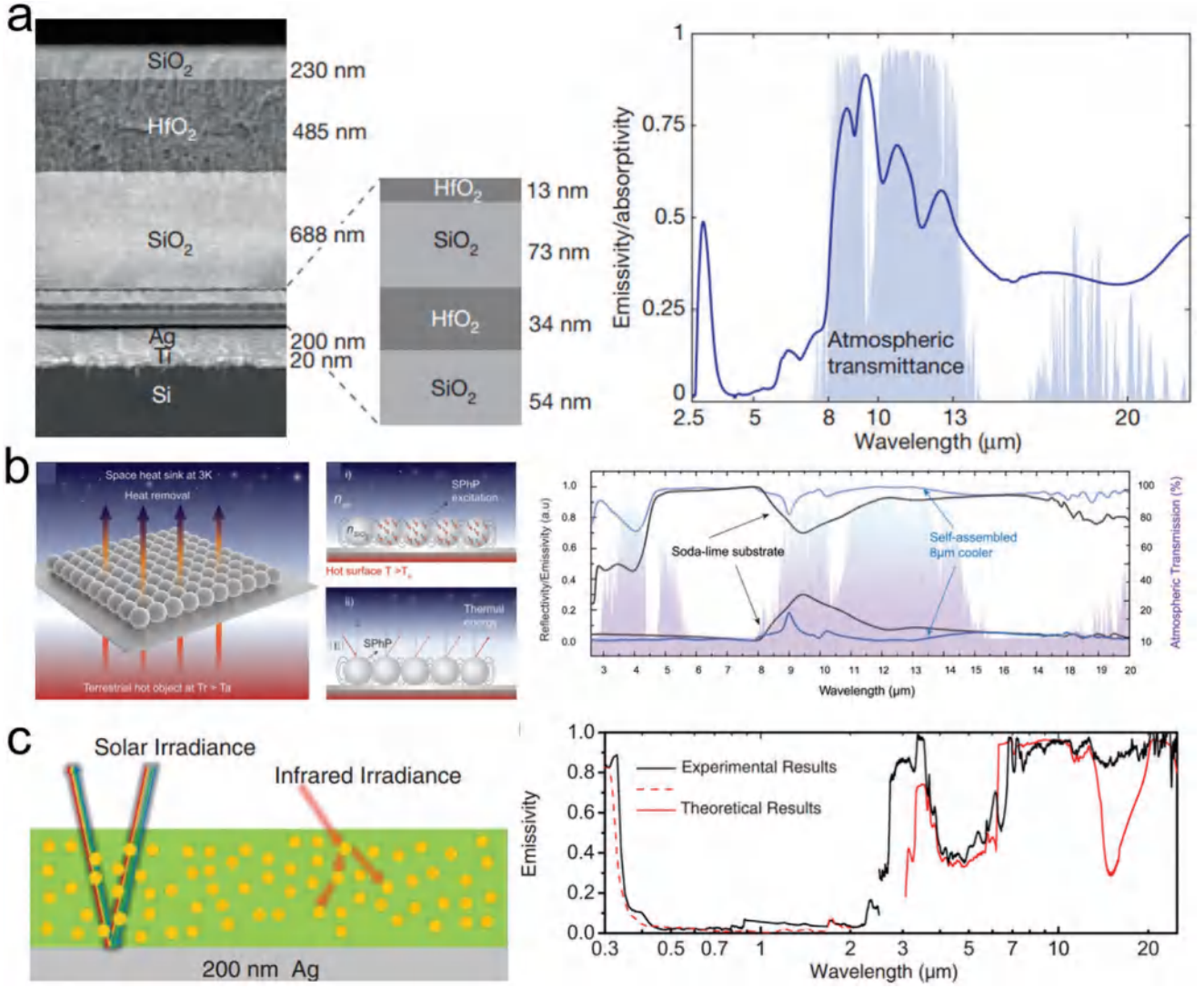

Figure 3. Mid-IR emittance of inorganic dielectric materials. a) Multilayer multilayer photonic design for high MIR emittance. Reproduced with permission.[10] Copyright 2014, Springer Nature. b) Schematic of the high infrared emittance of a self-assembled SiO_2 sphere cooler. Reproduced with permission.[29] Copyright 2019, Wiley-VCH. c) Schematic of a daytime radiative cooler consisting of polymer and inorganic particles. Reproduced with permission.[12] Copyright 2017, AAAS.

performance. It was revealed that cooling materials possess air permeability and thermal-moisture comfortability.

Polymers also have potential for PDRC because of their promising high IR emittance. The IR "fingerprint" of polymers with different functional groups/bonds, such as C–F, C–C, and C–O, overlaps with the atmospheric transmittance window.[37,38] Thus, most polymers can dissipate heat via their high mid-IR emittance. For example, the longwave infrared ray (LWIR) emittances of 200 μm thick polymethyl methacrylate (PMMA) and poly(1,1-difluoroethylene) (PVDF) films are ≈0.95. Accordingly, these materials have been widely used for PDRC purposes (**Figure 4**a).[37] Compared with inorganic dielectric materials, polymers with easy manipulation and low costs are suitable for large-scale manufacturing and various practical applications via different form methods. Various polymer-based PDRC structures, including fibrous films,[39] porous films,[40] and fabrics,[24] have been reported. In addition to these synthetic polymers, natural polymers have also demonstrated their radiative cooling performance. Natural wood has cellulose nanofibers or fiber bundles. The molecular vibration and stretching of cellulose enable strong IR emission, which can dissipate heat in IR radiation. Hu and co-workers[20] exploited cooling wood by employing the processes of complete delignification and densification, which has a high solar reflectance and strong mid-IR emittance. The cooling wood achieved continuous subambient conditions during the day and night (Figure 4b). Similarly, other cellulose-based materials[35,41–48] as efficient IR emitters have been explored for PDRC. Tian et al.[41] designed scalable cellulose-based composites with strong solar reflectance and mid-IR emittance, and a subambient cooling performance of 5 °C under sunlight was achieved. In addition, native silk fibers composed mainly of fibroin are excellent natural materials and are considered to be ideal candidates for textile and biomedical applications. Kim and co-workers[49] found that the intrinsic biomolecules in the IR radiation of silk enable heat to radiate to the cold universe via the transparent atmospheric window

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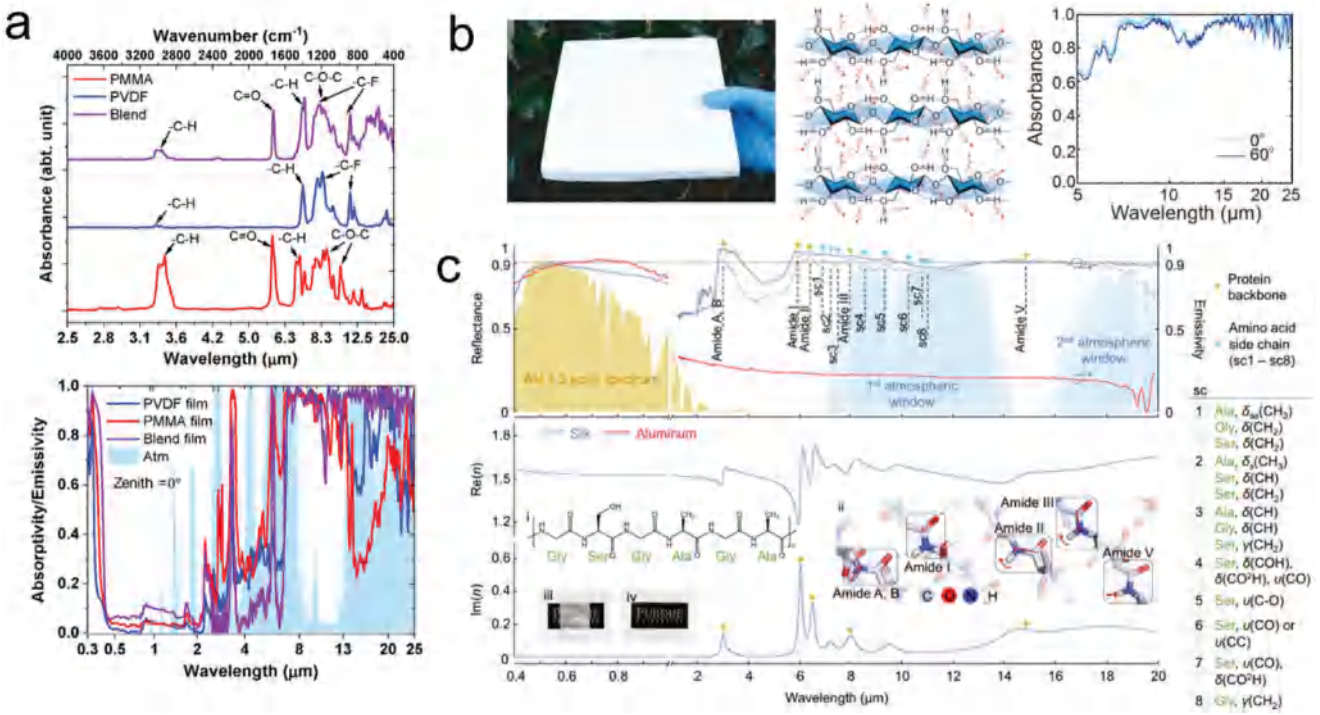

Figure 4. Mid-IR emittance of polymers. a) The infrared spectrum and emissivity of PMMA, PVDF, and their blend show strong emittance in the atmospheric window. Reproduced with permission.[37] Copyright 2021, Elsevier. b) Schematic of infrared emission by molecular vibration of the cellulose functional groups in the cooling wood and the corresponding IR emittance spectrum. Reproduced with permission.[20] Copyright 2019, The Authors, some rights reserved; exclusive licensee American Association for the Advancement of Science.. c) The spectrum of a white silk cocoon with a thickness of ≈400 μm (solid blue lines) and the complex refractive index of a regenerated silk film in the entire visible/NIR/IR region. Reproduced with permission.[49] Copyright 2018, Springer Nature.

(8–13 μm), as shown in Figure 4c. In addition, Anderson light localization occurs in native silk with nanostructures, resulting in strong reflectivity in the solar visible spectrum. Owing to these intrinsic physical properties, including strong solar reflectance and mid-IR emittance, silk has shown a significant radiative cooling effect during the day and night in the summer.

As previously mentioned, inorganic dielectric materials and polymers with a strong IR emittance have been demonstrated for PDRC. However, the IR emission spectrum of most of these materials covers the entire mid-IR band. Based on Kirchhoff's law, a radiator with a broadband emittance beyond the atmospheric window (8–13 μm) will inevitably absorb heat from atmospheric radiation (**Figure 5**a). The theoretical calculation model reveals that compared with a conventional broadband emitter with high emission beyond the atmospheric transmittance window, a larger temperature drop can be achieved using an ideal selective emitter under the same conditions.[34] Therefore, to achieve high cooling performance, various materials and structures with selective emission bands were proposed with IR radiation spectra dominantly located in the transparent atmospheric window. Selective emitter-prepared silicon nitride thin films and aluminum oxide were reported to achieve highly efficient PDRC.[10,50] Zhu and co-workers[18] first utilized polyethylene oxide (PEO) as a selective thermal emitter for efficient PDRC (Figure 5b). PEO consists of C—O—C and C—OH bonds and endows 78% selective emissivity in the 8–13 μm wavelength range, ensuring efficient cooling performance. This PEO-based nanofiber film showed ≈3 °C cooler at night than a nonselective emitter, and it also presented a 5 °C subambient cooling performance under direct sunlight. Lee and co-workers[30] proposed a ransparent sapphire-substrate-based radiative cooler consisting of selective emitters and achieved mean emissivity up to 90% at 8–13 μm (Figure 5c). Experimental results reveal that this cooler avoids absorbing ambient thermal radiation, resulting in an approximately 10 °C subambient radiative cooling effect compared with the daytime ambient temperature.

3.2. Structure Design for Enhancing Solar Reflectance

PDRC remains a challenge because of continuous and intensive solar irradiation (approximately 1000 W m^{-2} at AM 1.5). Without high solar reflectivity, the thermal emittance of radiators to the cold universe through the transparent atmospheric window cannot offset the heat gain from the sun under direct sunlight. The calculation result shows that an ideal emitter provides a cooling power of ≈140 W m^{-2}. Thus, daytime radiative cooling devices must possess extremely high solar reflectance >0.86. Bijarniya et al.[51] presented a numerical strategy (finite difference time domain) to simulate the optical properties of nanostructured materials in both solar and thermal infrared spectra. The calculation results showed that various nanoparticles and void dispersed polymers could reflect efficiently in the solar spectrum. To date, researchers have designed multilayer coating and engineering surface/integral structures to achieve a high solar reflectance across the entire solar spectrum,

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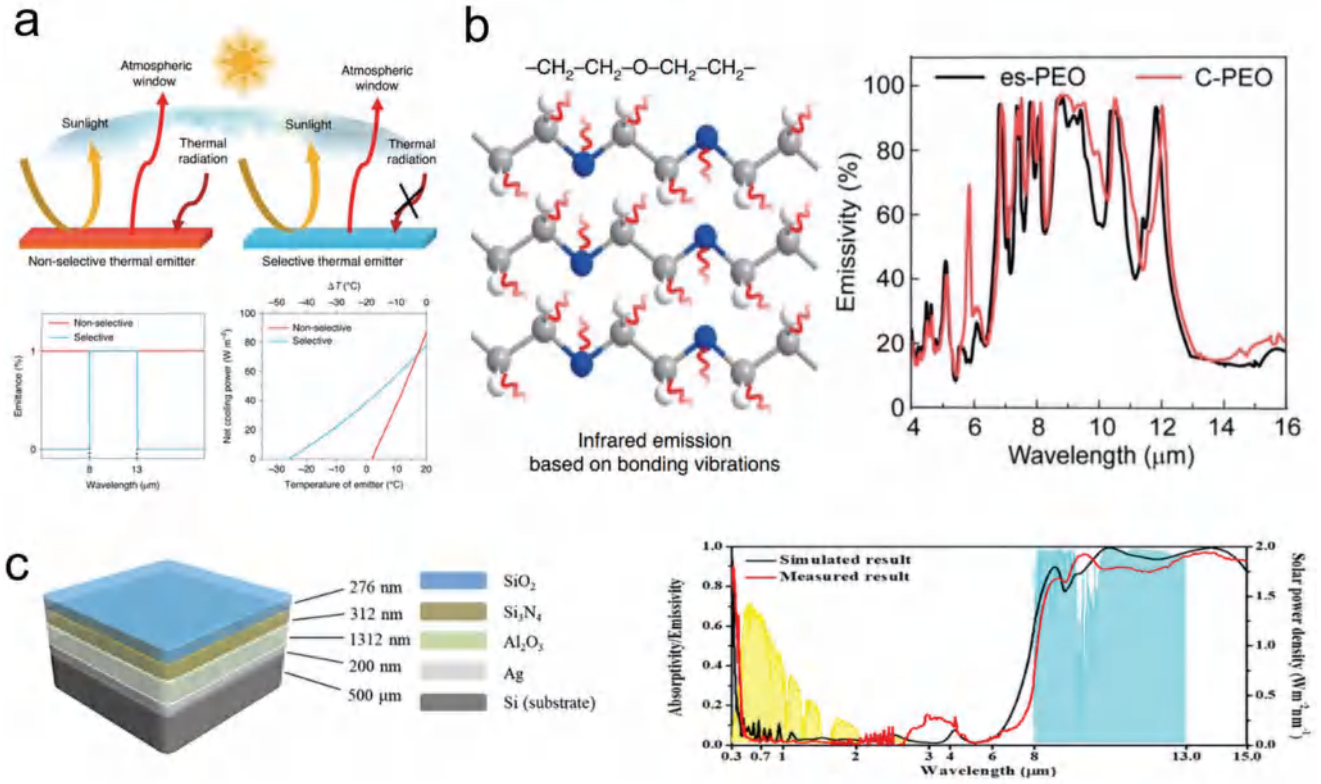

Figure 5. Selective thermal emitter design. a) Schematic and theoretical analysis of a selective thermal emitter in the atmosphere window (8–13 μm). b) Schematic of infrared emission by bond vibrations of the PEO molecular chain and the corresponding selective emittance at wavelengths of 8–13 μm. Reproduced with permission.[18] Copyright 2021, Springer Nature. c) Schematic and spectrum of a multilayer structural cooler based on selective emitters. Reproduced with permission.[30] Copyright 2021, Springer Nature.

including metamaterials, photonic structures, and nanoparticle-doped materials.

Considering the high damping constant and low refractive index of metallic materials, these substances have a high intrinsic potential to be applied in daytime radiative cooling systems. They have been widely used to enhance sunlight reflectance. Multilayer photonic structures,[10] randomly distributed particle structures,[12] and porous polymers[52] can be coated onto a metallic reflector to achieve low absorption across the entire solar spectrum to achieve effective cooling performance under sunlight. The layers above the reflective metal usually have low absorption in the whole solar spectrum and high emission in the mid-IR spectrum or transparent atmospheric window. Specifically, Ag and Al have been extensively investigated and utilized in PDRC applications.[32,52–55] For example, Gan and co-workers[56] designed a simple planar polydimethylsiloxane/metal (aluminum or silver) film structure as a cooler for PDRC, as illustrated in **Figure 6**a. Although its optical absorption in the solar spectrum domain was relatively weak (less than 10%), metallic reflectors coating other materials have achieved effective PDRC performance under sunlight by reflecting sunlight. Metal reflectors are usually fabricated by electron beam evaporation. However, the complicated fabrication, high cost, and inability to scale up limit large-scale PDRC applications. In addition, the instability of these metals in high pollution or high humidity air limits their use for daytime radiative cooling.

Metallic reflector backing has wide applications on the bottom layer of radiative cooling materials to reduce the absorption of solar energy. Furthermore, the photonic structure design of radiators manifests an intriguing and promising route to enhance solar reflectance. In nature, most insects have the intrinsic ability to survive in a hot environment because of their unique body structures.[57–60] For example, Yu and co-workers[61] demonstrated that Saharan silver ants in the African Desert exhibit a conspicuous silvery appearance, which mainly originates from their dense silver hairs with a triangular cross-section (Figure 6b). These hairs can enhance the solar reflectivity of wavelengths within the range from visible to near-IR radiation. Furthermore, insects exhibit strong emissivity characteristics in the mid-IR range, enabling them to dissipate heat to the cold universe via the transparent atmospheric window during the daytime. Inspired by the thermoregulatory effect of N. Gigas, Fan and co-workers designed a radiative cooling film, which consists of a micropyramid-arrayed polymer matrix with random ceramic particles that had high solar reflectivity (≈95%) and IR emissivity (>96%), thereby achieving a cooling effect of 5.1 °C under direct sunlight.[62] In addition, natural silkworm silk has demonstrated prominent PDRC,[49] as the nanofibrils and clusters in a single silk fiber provide strong scattering centers, enhancing the reflectance efficiency. This increased solar reflectivity may be attributed to the high Mie scattering in the macro- and microstructure of these natural insects and materials. The strong reflectivity is combined with the high emissivity of the biomolecules in infrared radiation, and silk radiates heat more than it absorbs for passive cooling.

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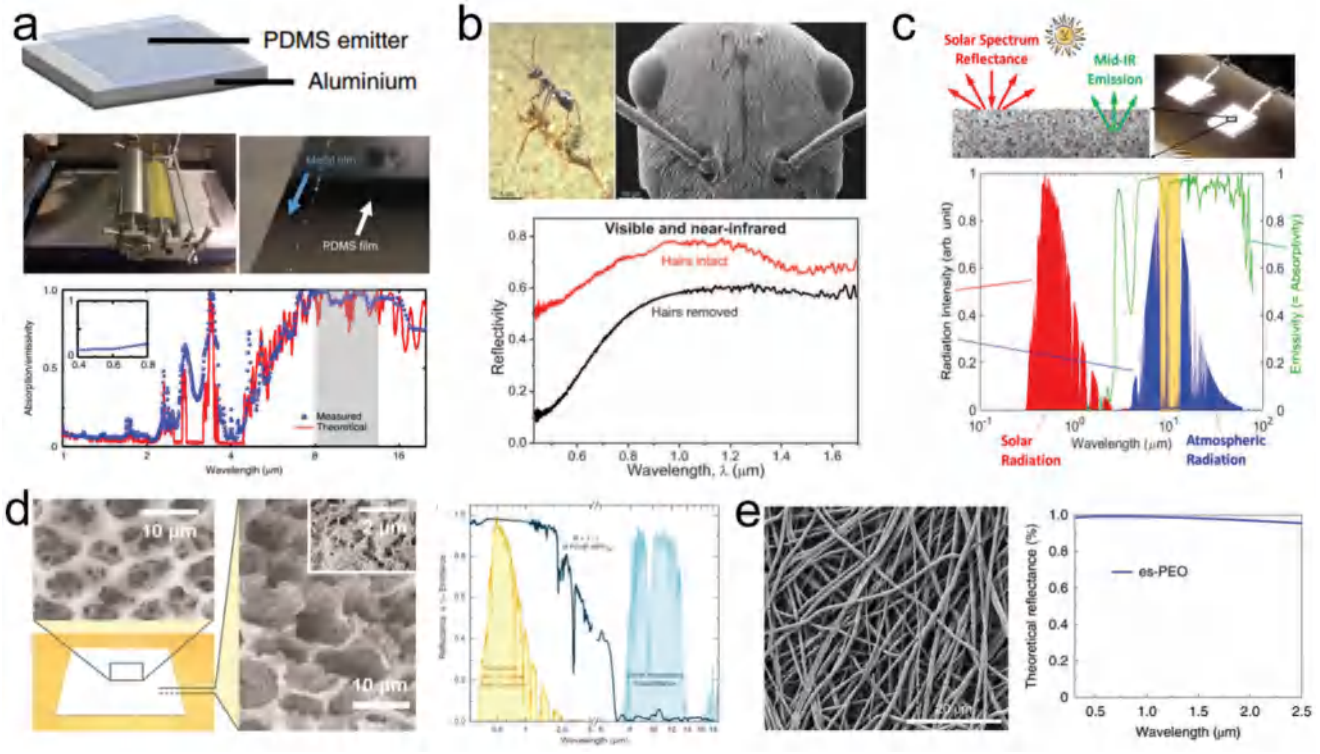

Figure 6. Strategies to enhance sunlight reflectance for PDRC. a) A daytime radiative cooling device consisting of Al film for solar reflectance. Reproduced with permission.[56] Copyright 2019, Springer Nature. b) Natural structure (Saharan silver ants) in the enhancement of solar reflectivity. Reproduced with permission.[61] Copyright 2015, AAAS. c) Designed inorganic dielectric microspheres Reproduced with permission.[66] Copyright 2019, American Chemical Society. d) Porous polymer for enhancing solar reflectance. Reproduced with permission.[11] Copyright 2018, The Authors, some rights reserved; exclusive licensee American Association for the Advancement of Science. e) Polymer-based nanofiber for enhancing solar reflectance. Reproduced with permission.[18] Copyright 2021, Springer Nature.

In addition to natural daytime radiative coolers, the use of Mie scattering in artificial radiative cooling materials is a promising route to enhance solar reflectance. Specifically, the aforementioned dielectric particles, such as titanium dioxide and barium sulfate, play critical roles in the tactical management of optical properties.[63–65] As shown in Figure 6c, Atiganyanun et al. developed white coating paint consisting of randomly arranged SiO_2 microspheres (diameter: ≈0.9 μm)[66] that has high reflectance in entire solar radiation spectra and high emittance in the mid-IR bands. The randomly distributed dielectric particles in polymers also exhibited Mie scattering and were found to enhance solar reflectance for PDRC. For example, Cui and co-workers[13] reported a highly efficient daytime cooling material using zinc oxide (ZnO) nanoparticles and polyethylene (PE). The embedded ZnO nanoparticles in the polyethylene film featured strong scattering resulting with high reflectivity in the visible and near-IR regions.

Another strategy is that air voids in polymers have been employed to provide strong solar reflectance by Mie scattering in fabricating PDRC devices. Yang and co-workers[11] demonstrated that porous poly(vinylidene fluoride-co-hexafluoropropene) coatings with micro- and nanopores formed by phase inversion effectively achieve substrate-independent hemispherical solar reflectances of 0.96 and longwave infrared emittances of 0.97 allow for subambient temperature drops of ≈6 °C and cooling powers of ≈96 W m^{-2} under solar intensities of 890 and 750 W m^{-2} (Figure 6d). Similar work based on hierarchically porous structured PMMA films with micro- and nanopores significantly improved solar reflectance and revealed superior daytime and nighttime passive radiative cooling.[40] Specifically, the cooling performance can achieve subambient cooling of ≈6.0–8.9 °C during midday under solar intensities of 900 W m^{-2}. Note that the solar reflectance of hierarchically structured PMMA (0.95) over the entire solar spectrum is much higher than that of the nanopore PMMA (0.74), micropore PMMA coating (0.23), and pristine PMMA film (0.10).

In addition to the aforementioned strategies, regulating the diameter of widely investigated nanofiber films has demonstrated a promising route to achieve Mie scattering, thereby boosting solar reflectance over the entire solar spectrum. Zhu and co-workers[18] designed a hierarchical PEO nanofiber-based film to prepare a scalable electrostatic spinning process. Owing to light scattering by micro- and nanostructures between nanofibers, the as-obtained PEO nanofiber-based film with a certain fiber diameter has remarkable reflectance (96.3%) of incident solar power at near-normal incidence (Figure 6e). Similarly, other polymer-based nanofiber films have demonstrated efficient cooling performance under sunlight.[39,67,68] Compared to metallic reflectors, polymers show promising potential in low-cost and large-scale applications in various fields. Meanwhile, structural polymers, dielectric particles, and composite materials possess better optical performance over a broad solar spectrum for PDRC.

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3.3. Thermal Management

Daytime cooling performance can be effectively enhanced under sunlight with selective spectral designs (high solar reflectance and strong mid-IR emittance). However, the temperature of the radiative cooler is lower than the ambient temperature in conventional daytime radiative cooling. Heat conduction and convection between the cooler and the ambient result in extra heat gain of the cooler, reducing the cooling performance of the coolers under sunlight. In 2016, Fan and co-workers[69] designed a vacuum chamber to eliminate extra heat gain (**Figure 7**a). An ultralarge temperature reduction of up to 42 °C was achieved below ambient temperature when the cooler was exposed to peak solar irradiance. However, the chamber's high cost and complex processing limit its large-scale application.

To resolve these challenges, Wang and co-workers designed a polyethylene aerogel that possesses both spectral selectivity and thermal insulation (Figure 7b).[19] The as-fabricated polyethylene aerogel provides insulation to prevent heat gain from the environment. Meanwhile, its high solar reflectance and IR transmittance enable daytime radiative cooling. As a result, the aerogel achieved 13 °C below ambient cooling performance around solar noon. Another approach demonstrated that radiative cooler consisting of hierarchically hollow microfibers achieved high passive cooling performance (9 °C subambient) in the summer (Figure 7c),[70] wherein hierarchically hollow microfibers with nanostructures are an efficient light scattering medium and thermal insulator, providing strong solar reflection (94%) and IR thermal emission (0.94). Simultaneously, the hollow microfiber structure with ultralow thermal conductivity (i.e., 0.014 W m^{-1} K^{-1}) restricted heat transfer between the cooler and its surrounding environment.

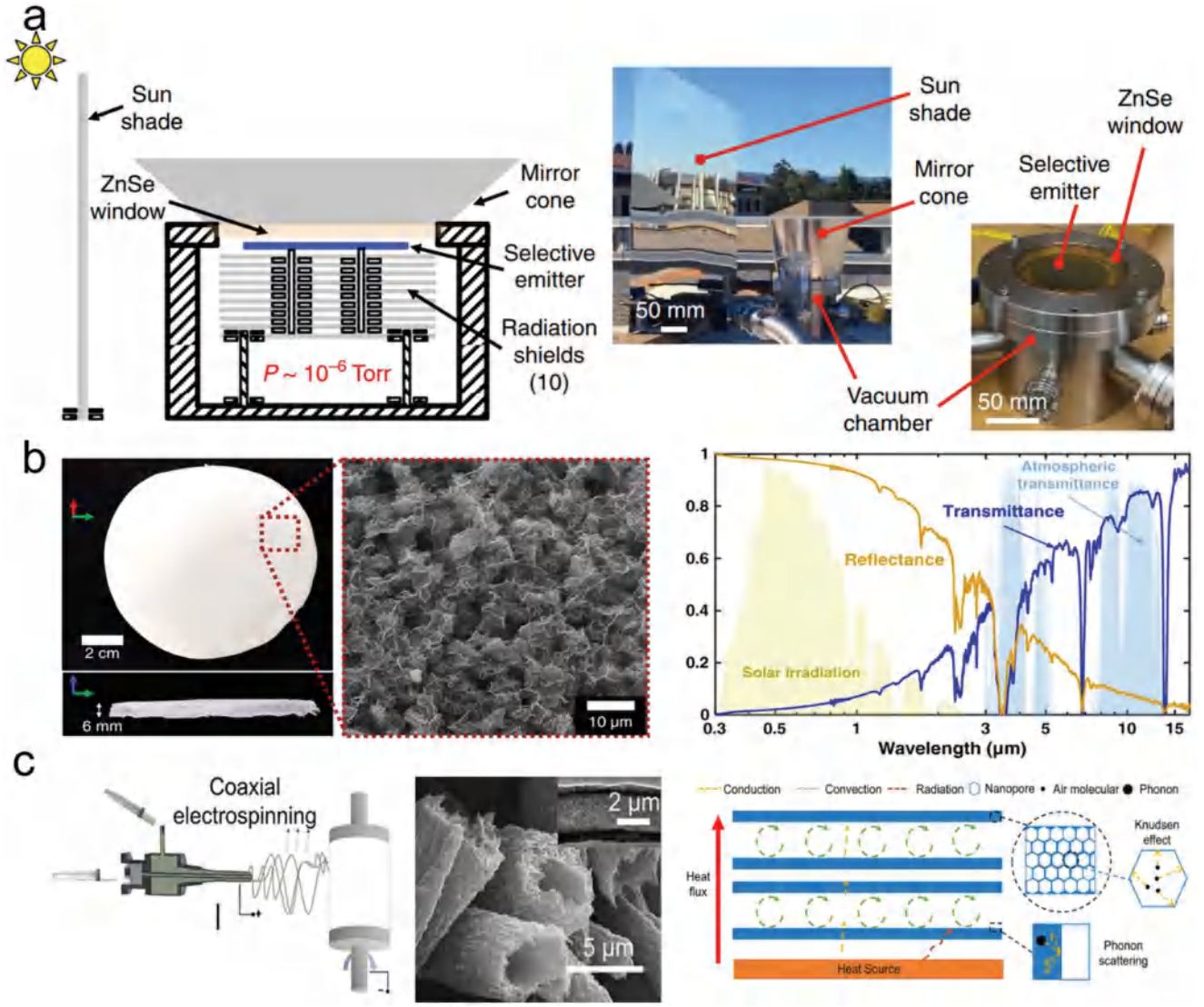

Figure 7. Thermal insulating design for PDRC. a) Schematic and photograph of the experimental vacuum chamber for eliminating the heat exchange between the emitter and the outdoor environment. Reproduced with permission.[69] Copyright 2016, Springer Nature. b) Thermally insulating polyethylene aerogel-based cooler to suppress convection heat transfer and the corresponding optical properties. Reproduced with permission.[19] Copyright 2019, The Authors, some rights reserved; exclusive licensee AAAS. Distributed under a Creative Commons Attribution NonCommercial License 4.0 (CC BY-NC). c) Schematic of hierarchically hollow microfibers reducing environmental heat gain. Reproduced with permission.[70] Copyright 2021, American Chemical Society.

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4. Application of Daytime Radiative Cooling

Daytime radiative cooling is a significant potential direction to alleviate the energy crisis, and its application has attracted considerable interest in recent years. It is predominantly demonstrated for cooling objects, including buildings and photovoltaics (PVs), as well as personal thermal management. Moreover, this technology can harvest energy and freshwater by adjusting the optical and thermal features. This section is intended to highlight the recent developments that exemplify the potential of scalable applications.

4.1. Radiative Cooling for Buildings

Studies show that cooling systems consume 15% of electricity generated globally and account for 10% of global greenhouse gas emissions. Under favorable climate conditions (hot and sunny), the PDRC can supply ≈80% of the cooling load of buildings.[71] In particular, PDRC can be used as both roof and siding material that needs to be cooled.[72–78] As shown in **Figure 8**a, Hu and co-workers proposed cooling wood with continuous subambient cooling during the daytime and night.[20] The total cooling energy-saving patterns were calculated and analyzed using radiation cooling wood as the building material. Figure 8b indicates that ≈35% and 20% energy savings can be achieved in cooling old and new buildings, respectively.

Another PDRC approach is to develop an active system where a coolant is used for cooling. This approach has more applications to regulate the cooling power (Figure 8c,d).[71] Researchers have calculated that implementing fluid cooling panels would save 14.3 MWh of electricity, thereby reducing 21% of the required electricity for air conditioning of buildings. The daily electricity savings over this period vary from 18% to 50%. However, these systems require more external energy (fan or pump) to transfer fluids or air for cooling.

To determine the influence of climate parameters on large-scale PDRC deployment, the global PDRC potential is presented in Figure 8e. It is worth noting that considering regional climate conditions, the PDRC potential is highly location-dependent.[5] Regions with a dry and hot climate tend to have higher radiative cooling power, up to 120 W m^{-2}. By comparison, cold, highly humid, or cloudy regions tend to have much lower radiative cooling potentials. This high cooling potential can significantly improve building thermal management and reduce the need for extra equipment, roof insulation, and solar shading structures.

4.2. Radiative Cooling for Photovoltaic Device

Thermal management is of significant importance for the proper operation of devices. For instance, a high operating temperature reduces the efficiency of PV systems and greatly reduces their lifetime. Heat can increase the temperature of a solar panel by 40 °C above the ambient temperature. An elevated PV panel temperature is detrimental to its energy conversion, in which 0.4–0.5% energy efficiency loss has been reported for every degree of temperature increment.[79] Studies show that the effective spectral range of Si-based solar cells is within 0.3–1.1 μm, while the rest of the incident solar energy

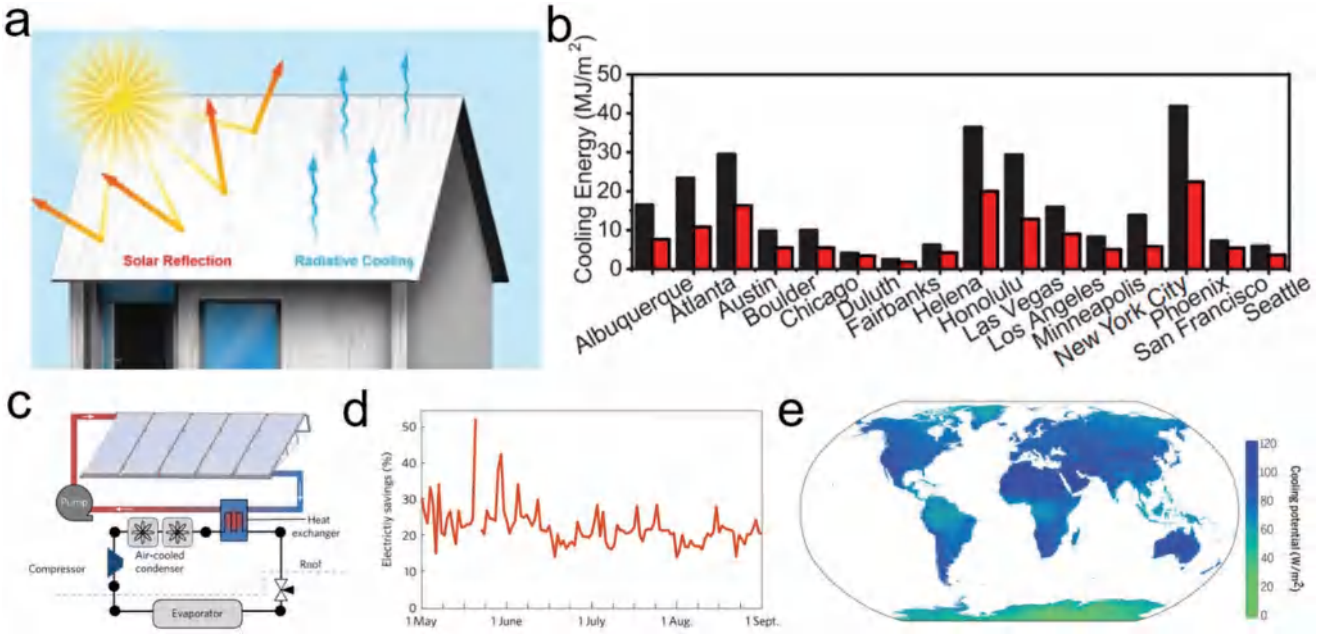

Figure 8. PDRC for building cooling. a) Modeling energy savings by installing cooling wood panels on roofing and external siding of midrise apartment buildings. b) Total cooling energy savings per year among all 16 cities. Reproduced with permission.[20] Copyright 2019, The Authors, some rights reserved; exclusive licensee American Association for the Advancement of Science. c) A panel-cooled cooling system, where the panels address part of the condenser load to lower the overall condenser temperature. d) The average daily cooling load for a two-story office building in Las Vegas, Nevada, USA, from May 1 to September 1 of the Typical Meteorological Year dataset. Reproduced with permission.[71] Copyright 2017, Springer Nature. e) Global radiative cooling potential. Reproduced with permission.[5] Copyright 2020, Springer Nature.

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converts to heat, thereby reducing the conversion efficiency of the solar cells. Thus, effective and versatile PV panel cooling is important for effective and long-term power generation. In contrast to radiative cooling, the operating temperature of solar cells is usually higher than the ambient temperature. Accordingly, it is not required to suppress nonradiative heat transfer. Meanwhile, it should be indicated that Si-based solar cells have a relatively high emittance (up to 85%) in the LWIR transmission window, which may be attributed to covered glass containing 70% to 80% silica. Except the emissivity spectrum of silica shows two large dips near 10 and 20 µm. These dips correspond to the phonon-polariton resonances of silica.[80]

As shown in **Figure 9**a,b, Li et al. designed a photonic cooler made of 1D photonic films for cooling solar cells in a solar panel scheme that can strongly radiate heat through its thermal emission while also significantly reflecting the solar spectrum in the sub-bandgap and ultraviolet regimes.[81] The performed experiments in this regard showed that this scheme could reduce the temperature of Si-based cells by 5.7 °C. However, the high capital costs and immature technology of photonic structures are other challenges of this scheme in commercialization. Another approach is to design a thin-layer PDRC coating to radiate heat through thermal emission for solar cells (Figure 9c).[21] The performed experiments show that a temperature drop up to 36 °C can be achieved using concentrated PV, which increases the open-circuit voltage of GaSb cells by 27% and significantly increases the lifetime of the cell by 4 to 15 times. Many other approaches also apply a PDRC coating to remove excess waste heat from solar cells.[21,80,82] The main advantage of this approach is its low cost and scalability.

4.3. Radiative Cooling for Electricity Generation

Considering the characteristics of the PDRC coating to maintain a surface below the ambient temperature, the temperature difference can be converted into usable electricity using a thermoelectric (TE) generator. A thermoelectric generator is a solid-state device that converts heat flux (temperature differences) directly into electrical energy through the electromotive force that develops across two points of an electrically conducting material when there is a temperature difference between them. Accordingly, this technology has a high potential to generate electricity. As shown in **Figure 10**a, a commercial TE generator was experimentally combined with a radiative cooling coating at night to generate a power of 25 mW m^{-2}, which can be used to light a dark space.[22]

Figure 10b indicates that another choice is to generate thermoelectric power continuously throughout the day using radiative cooling to generate temperature difference.[83] In this

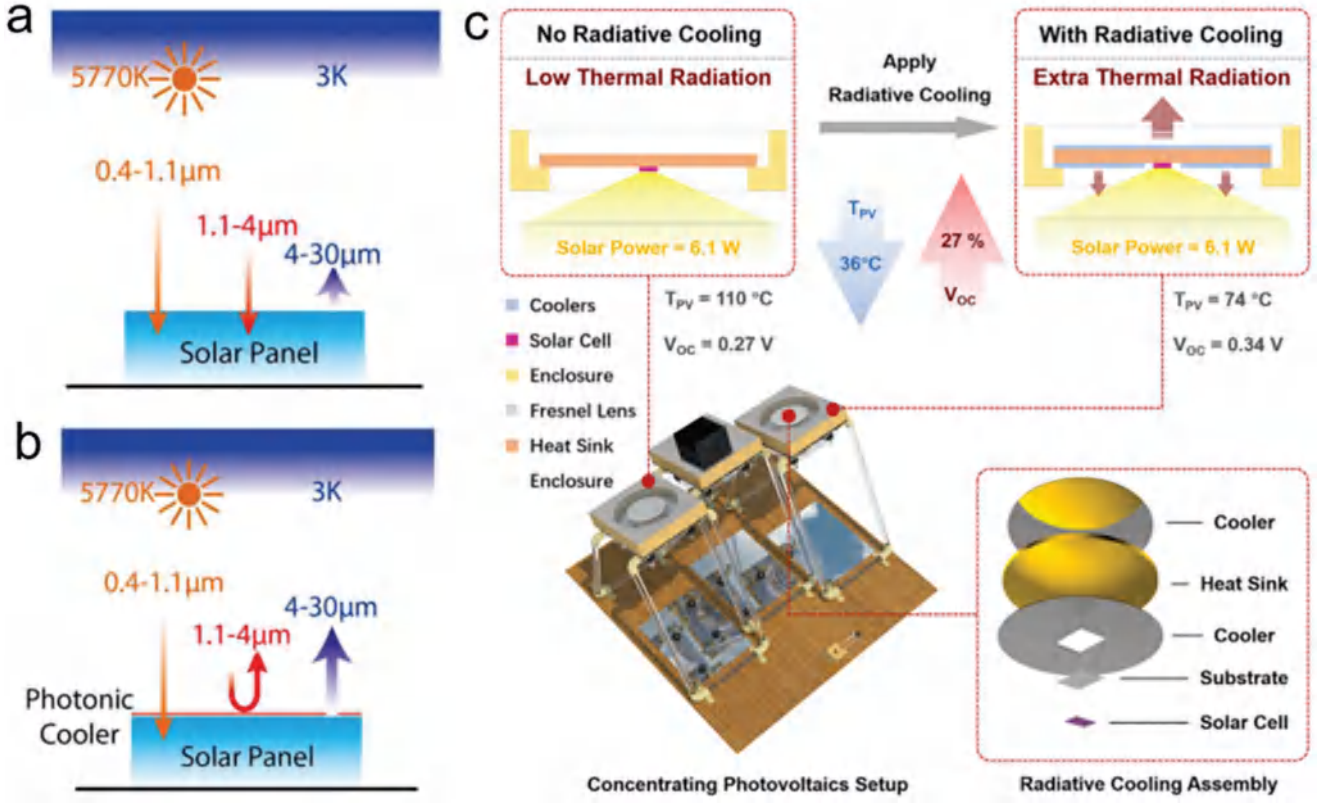

Figure 9. PDRC for photovoltaic cooling. a) Schematic of the solar absorption and thermal radiation properties of existing solar panels. b) With a photonic cooler coated on top of the solar panel, the radiative cooling can be enhanced, and the sub-bandgap solar radiation can be strongly reflected. Reproduced with permission.[81] Copyright 2017, American Chemical Society. c) A concentrating photovoltaics setup with (without) radiative cooling and the assembly of radiative cooling. Reproduced with permission.[21] Copyright 2020, Cell.

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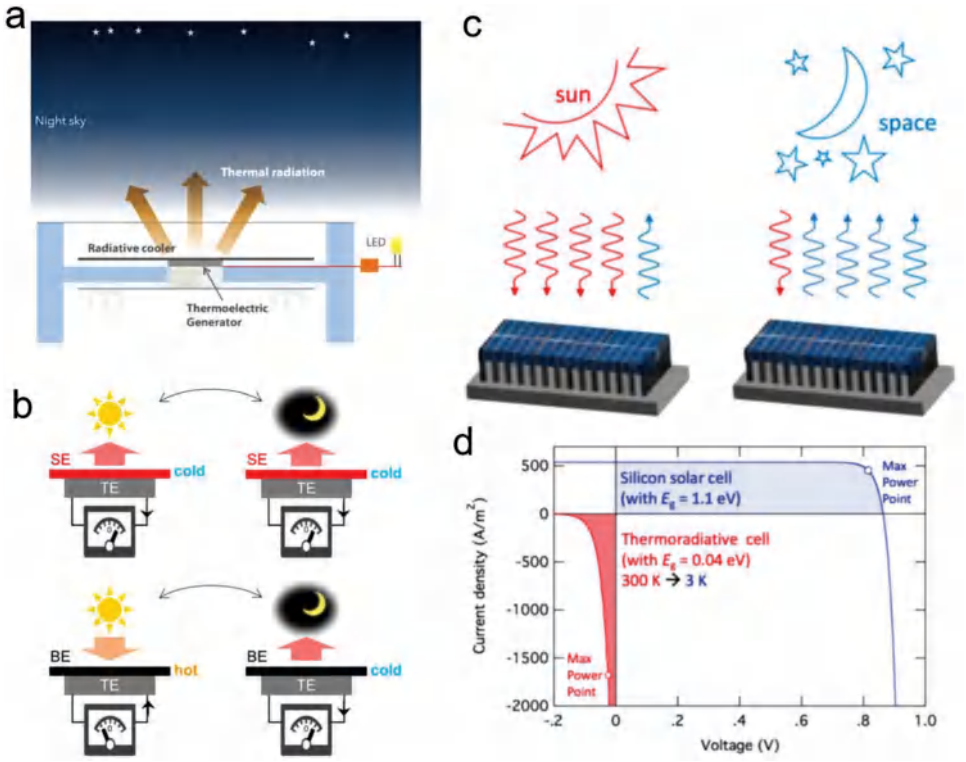

Figure 10. Radiative cooling for electricity generation. a) Schematic of the low-cost nighttime thermoelectric generator device and its key components. Reproduced with permission.[22] Copyright 2019, Cell. b) Conceptual drawings of thermoelectric (TE) devices have a wavelength selective emitter (SE) and a broadband emitter (BE) on the top. Reproduced with permission.[83] Copyright 2020, AIP Publishing. c) Photovoltaic cells are illuminated by solar irradiation during the day and night. Absorbed photons create electron–hole pairs across the semiconductor bandgap and establish a working voltage, *V*. d) *I*–*V* characteristics of a photovoltaic (quadrant 1) and an ideal thermoradiative (quadrant 3) cell with bandgaps of 1.1 and 0.04 eV, respectively; both show power generation. For the thermoradiative cell, a negative voltage and negative current generate positive power across an external load. Reproduced with permission.[84] Copyright 2020, American Chemical Society.

scheme, the emitter has a selective MIR emissivity that its surface kept cooler due to radiative cooling than the bottom side of the thermoelectric module, which is placed below the selective emitter. Therefore, the device can generate thermoelectric voltage during the day and night without dropping to zero. The device can be used as a power supply for sensors and monitors when placed outdoors.

Finally, Deppe et al. proposed an alternative PV concept that uses the earth as a heat source and the night sky as a heat sink to produce electricity after sunset. The proposed scheme is called the "nighttime PV cell," which employs thermoradiative PVs and concepts from the field of radiative cooling.[84] They studied thermoradiative PVs, limitations of this concept, advanced radiative cooling techniques, scalability, and integrability of the nighttime PV concept (Figure 10c).

4.4. Radiative Cooling for Water Harvesting

Freshwater scarcity has become one of the most serious global challenges we face today, as advancements in human civilization have led to substantial consumption and contamination of freshwater. Radiative cooling coatings can be applied to harvest water from the atmosphere without the need for input energy.[85] Through radiative cooling, the emitters can reach temperatures below the dew point and thus condense the water vapor from the atmosphere.[86] Considering the huge amount of water vapor in the atmosphere, this passive technology has a high potential to harvest freshwater.[87–89]

Combined with traditional passive cooling via convection and conduction, daytime radiative cooling can substantially increase the performance of passive vapor condensation (**Figure 11**a,b).[90] Yu and co-workers developed daytime radiative condensers that continue to operate 24 h a day. These daytime radiative condensers can produce water from vapor under direct sunlight without active consumption of energy, which can be used for passive water extraction and purification technologies. Haechler et al.[23] integrated radiative shielding and cooling and designed a system to dissipate the latent heat released during condensation to outer space. Accordingly, a passive superhydrophobic condensate harvester was designed (Figure 11c–e). Moreover, a solar shield was designed to facilitate atmospheric radiative heat transfer and harvest atmospheric freshwater during the daytime. The significant cooling power enhancement enables dew mass fluxes of up to 50 g m^{-2} h^{-1}, which is close to the ultimate capabilities of these systems. Although remarkable achievements have been obtained so far, further investigations are still required to achieve the higher water production of passive water harvesting from air.

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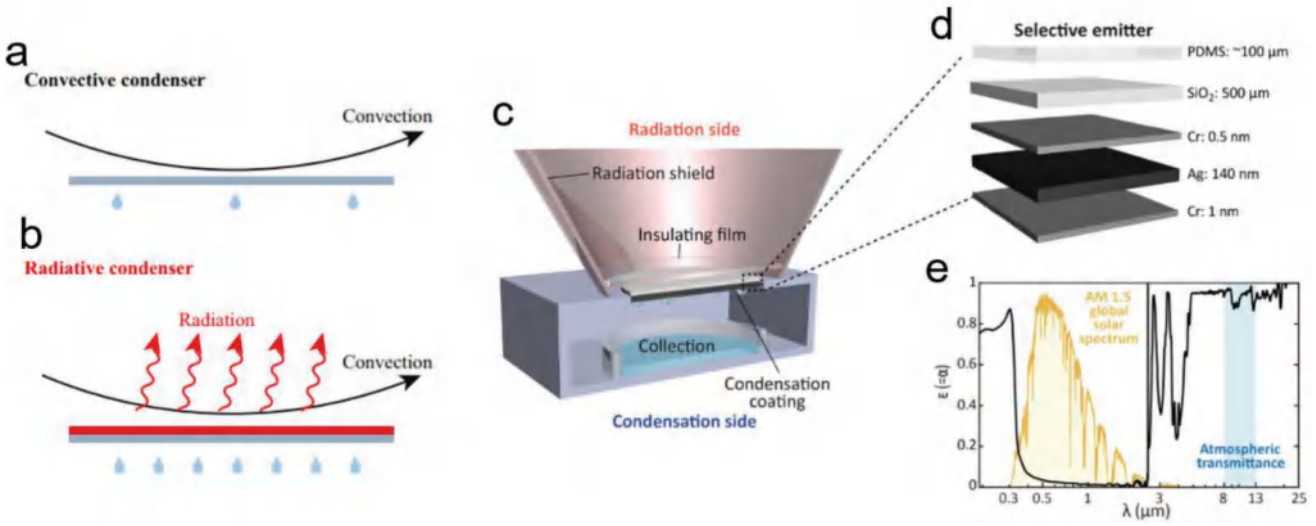

Figure 11. Radiative cooling for water harvesting from air. a) Schematic of a convective condenser and radiative condenser. b) The convective condenser dissipates heat through only convection, while the radiative condenser dissipates heat through both convection and radiation. Reproduced with permission.[90] Copyright 2021, National Academy of Sciences. c) Principle with separated radiation and condensation side. The radiation shield—optimized by accounting for the surrounding radiative environment—allows one to substantially improve the dew harvesting potential of the system and can be applied for any selective emitter. d) Structure of selective emitter. It consists of PDMS and silver coated on a transparent glass substrate (chromium is used for oxidation protection and adhesion). e) Measured spectral absorptivity/emissivity of the selective emitter. Reproduced with permission.[23] Copyright 2019, The Authors, some rights reserved; exclusive licensee AAAS. Distributed under a Creative Commons Attribution NonCommercial License 4.0 (CC BY-NC).

4.5. Radiative Cooling for Personal Thermal Management

Combining passive radiative cooling structures with personal thermal management technologies can effectively defend humans against the intensification of global climate change.[91–94] To date, significant research has been conducted on mid-IR-transparent radiative cooling textiles.[95–97] For example, Cui and co-workers demonstrated the large-scale extrusion of uniform and continuous nanoporous polyethylene microfibers[98] and a ZnO-PE nanocomposite textile.[13] They found that this textile can decrease the temperature of human skin by 2.3 °C, and simulated skin was found to avoid overheating by 5–13 °C. (**Figure 12**a,b). Tao and co-workers[24] developed a large-scale woven metafabric with a hierarchical-morphology pattern of randomly dispersed scatterers that can provide high emissivity (94.5%) in the transparent atmospheric window and reflectivity (92.4%) in the solar spectrum. Considering scalable industrial textile manufacturing routes, metafabrics show excellent mechanical strength, waterproofness, and breathability for commercial clothing while maintaining efficient radiative cooling ability. Practical tests showed that a human body covered with metafabric could be cooled by ≈4.8 °C compared with commercial cotton fabric (Figure 12c).

In practice, temperature varies spatiotemporally with weather conditions. The traditional approach is to either add or remove clothes or constantly adjust the thermostat. However, additional clothes are not always accessible, and changing the thermostat settings frequently is a waste of energy. Therefore, the practical solution is to control the heat transfer of textiles, enabling them to be dynamically adjusted between heating and cooling states.[99] To date, Janus fabrics that can achieve optional localized heating and cooling within the same textile have been reported for body thermoregulation. Hsu et al.[100] demonstrated a Janus textile that can perform both passive radiative heating and cooling without extra energy input by adding a bilayer emitter embedded inside an IR transparent nanoporous PE layer (Figure 12d). They observed that the asymmetrical characteristics of both emissivities could result in two different heat transfer coefficients, allowing it to heat when the low-emissivity layer is facing outside and cool when the high-emissivity layer is facing outside. The obtained results show that the thermal comfort zone of the textile increases to 6.5 °C compared with conventional cloths. Furthermore, a simulation suggests that a 14.7 °C comfort zone expansion can be achieved for dual-mode textiles with large emissivity contrasts. Moreover, since the thickness and morphology of the bilayer emitter are engineered, the air and water vapor permeabilities of the Janus textile are similar to those of conventional textiles. Zhu et al.[101] demonstrated the nanoprocessing of silk through a molecular bonding design and scalable coupling reagent-assisted dip-coating method, can achieve a subambient daytime radiative cooling (Figure 12e). Nanoprocessed silk can achieve a temperature of ≈3.5 °C below ambient conditions in the daytime, and when covering simulated skin, it can achieve a reduction in skin temperature of ≈8 °C under sunlight, with similar comfort and wearability to natural silks. Xu et al.[102] proposed a textile by coating triacetate-cellulose bimorph fibers with a thin layer of carbon nanotubes (Figure 12f), achieving more than 35% IR radiation tuning as the relative humidity of the underlying skin changed. Experiments and modeling demonstrate that this dynamic IR tuning mainly originates from the distance-dependent electromagnetic coupling between neighboring coated fibers in the textile yarns.

5. Outlook

Despite the amazing achievements made in the past several years in PDRC, substantial challenges remain for the broad application of daytime passive cooling technologies. The

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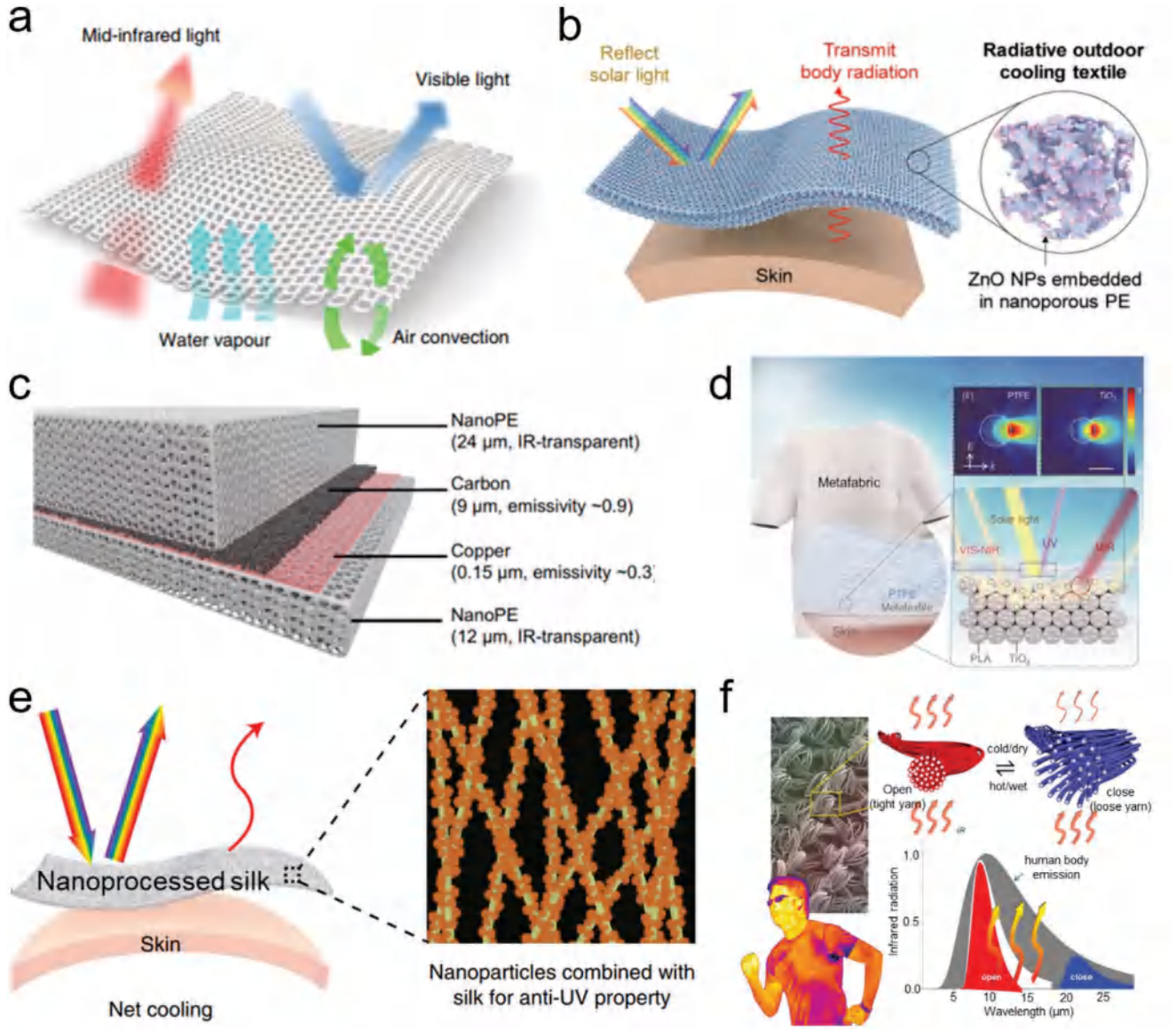

Figure 12. PDRC for personal thermal management. a) A schematic diagram of the nano-PE fabric. The nano-PE fabric exhibits high MIR transparency, visible opacity, and good wearability. Reproduced with permission.[98] Copyright 2018, Springer Nature. b) Schematic of the ZnO nanoparticle–embedded nanoporous PE textile designed for outdoor radiative cooling by reflecting sunlight and transmitting human body thermal radiation. Reproduced with permission.[13] Copyright 2017, Wiley-VCH. c) Schematic of a metafabric for daytime radiative cooling. The blue, green, and red dashed boxes highlight the three-level hierarchical structure responding to the UV, vis–NIR, and MIR bands, respectively. The insets show the calculated scattering fields of 300 and 550 nm light by a 500 nm PTFE particle and a 400 nm TiO_2 particle, respectively. Scale bar: 400 nm. Reproduced with permission.[24] Copyright 2021, The Authors, some rights reserved; exclusive licensee American Association for the Advancement of Science. d) Schematic of the layered structure of the dual-mode textile. Reproduced with permission.[100] Copyright 2017, The Authors, some rights reserved; exclusive licensee AAAS. Distributed under a Creative Commons Attribution NonCommercial License 4.0 (CC BY-NC). e) Schematic of nanoprocessed silk with subambient daytime radiative cooling performance. Reproduced with permission.[101] Copyright 2021, Springer Nature. f) Design principles of an IR gating textile. This design allows this new adaptive IR gating mechanism to synergistically occur with conventional heat exchange channels, including convection and evaporation (not shown), to maximize personal cooling (when hot and sweating) and heating (when cold and dry). Reproduced with permission.[102] Copyright 2019, The Authors, some rights reserved; exclusive licensee American Association for the Advancement of Science..

following are some of the major challenges, which require further comprehensive research efforts.

1) Colorful radiative cooling materials: For daytime radiative cooling, a material should have a high solar reflectance to minimize heat caused by solar irradiation. Although white radiative coolers usually present visual discomfort by specular reflection, light absorption in the visible spectrum is inevitable for colored coolers, which results in a reduced cooling performance under sunlight.[103] To simultaneously have a pleasant color and achieve efficient cooling performance, various color strategies that mitigate the solar absorption of colored PDRC

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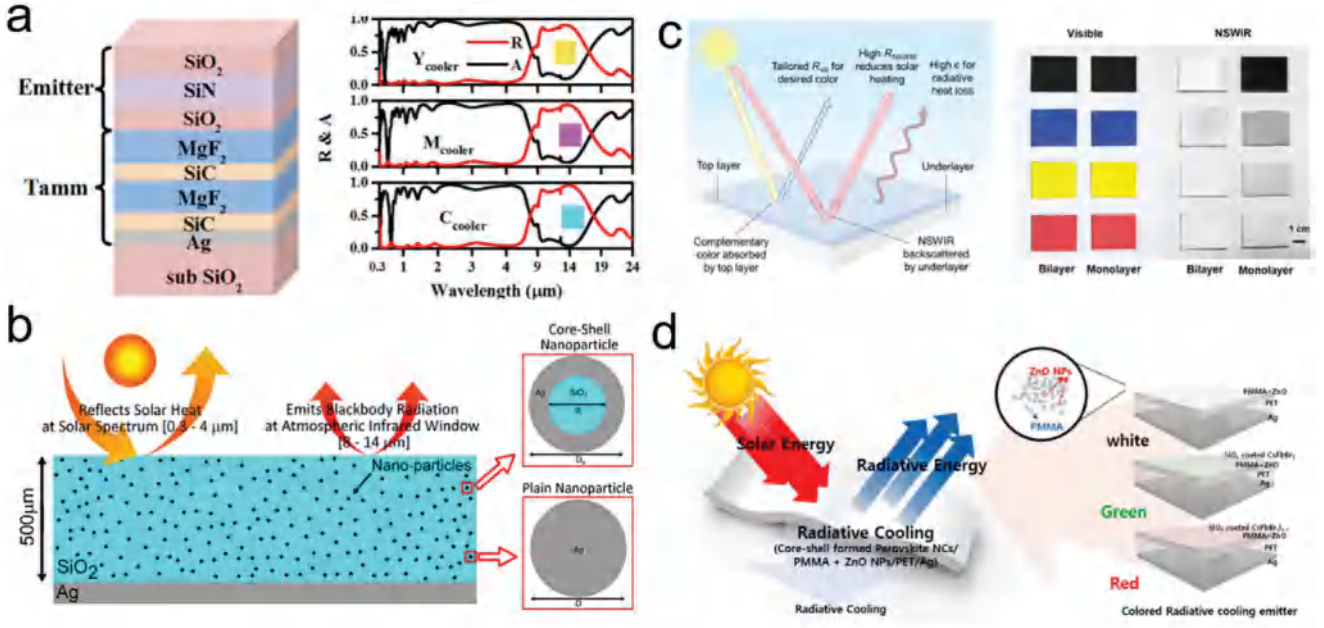

Figure 13. Colored daytime radiative cooling devices. a) Structure diagram and spectrum of the colored PDRC based on the multilayer design. Reproduced with permission.[104] Copyright 2019, ACS. b) Design of colored radiative cooler with the color of the plasmonic nanoparticles. Reproduced with permission.[107] Copyright 2020, ACS. c) Schematic illustrating the optical properties of the paintable bilayer design and photographs of the colored pairs of bilayer and monolayer coatings. Reproduced with permission.[109] Copyright 2021, The Authors, some rights reserved; exclusive licensee AAAS. Distributed under a Creative Commons Attribution NonCommercial License 4.0 (CC BY-NC). d) Schematic of a colored daytime radiative cooling device with perovskite nanocrystals. Reproduced with permission.[110] Copyright 2021, Elsevier.

coatings have been designed. Multilayer photonic structural designs have been introduced to incorporate color-displaying functions into daytime radiative coolers (**Figure 13**a).[104–106] However, these multilayer structures may be difficult to manufacture because of their high complexity. Some researchers utilize nanoparticles to achieve color-preserved daytime radiative coolers.[107,108] A colored radiative cooler embedded with plasmonic Ag@SiO_2 core–shell nanoparticles by soft self-assembly demonstrated narrowband absorption in the visible spectrum and displayed different colors that can be applied to daytime radiative coolers (Figure 13b).[107] Yang and co-workers utilized a paintable bilayer coating to design a colorful radiative cooler, achieving both color and efficient radiative cooling under sunlight (Figure 13c).[109] Specifically, the top layer of the cooler selectively absorbs the visible range to present the unique color, while the underlayer has a high reflectivity in the near-to-short wavelength IR range to reduce solar heating. In addition, colored daytime radiative coolers composed of perovskite nanocrystals reported by Lee and co-workers have exhibited superior daytime cooling performance under sunlight compared with those with colored paint.[110,111] Figure 13d shows that the perovskite nanocrystals exhibited narrowband selective absorption in the visible spectrum. Furthermore, the daytime cooling performance was enhanced because of the light-photon conversion of perovskite. The absorbed solar energy of perovskite is mainly dissipated via photons or heat. Although the recently reported daytime radiative coolers can achieve color, their high cost and low cooling performance limit their large-scale usage and application.

2) Switchable cooling and heating: Although the natural environment temperature changes dynamically depending on time and season, its effect has rarely been studied in previous works. When the environmental temperature is below a critical value, cooling is no longer desired. For example, cooling is not desirable during nighttime in desert areas, as it increases energy consumption for thermal comfort. Thus, developing a dynamic switchable radiative cooler that cools to dissipate heat in a hot environment while preventing overcooling in a cold environment is highly desirable. To date, the proposed dynamic switchable radiative coolers can be divided into two categories: passive and active. Incorporating phase change materials has been considered a promising route for passive dynamic switchable radiative coolers without energy input. Vanadium dioxide (VO_2) with a phase transition (68 °C) can transition from an insulator to metal and has thus been used in dynamic switchable radiative cooling.[112–116] Fan and co-workers proposed a multilayer photonic cooler that incorporates VO_2 for adaptive radiative cooling (**Figure 14**a).[112] Attributed to the transition temperature of VO_2, the emission spectra in the atmospheric window continuously vary with the environmental temperature. This cooler presented efficient radiative cooling performance when the temperature was higher than the transition temperature of VO_2. Moreover, radiative cooling was automatically stopped when the temperature was lower than the transition temperature. Compared with passive systems, cooling can be altered using additional energy input in active systems. One method is to manage the spectrum of the cooler from solar to thermal wavelengths based on reversible wetting with common liquids, such as water and alcohol.[117] Wetting weakens the scattering strength of porous polymers, resulting in a "reflective-to-transparent" transition. For instance,

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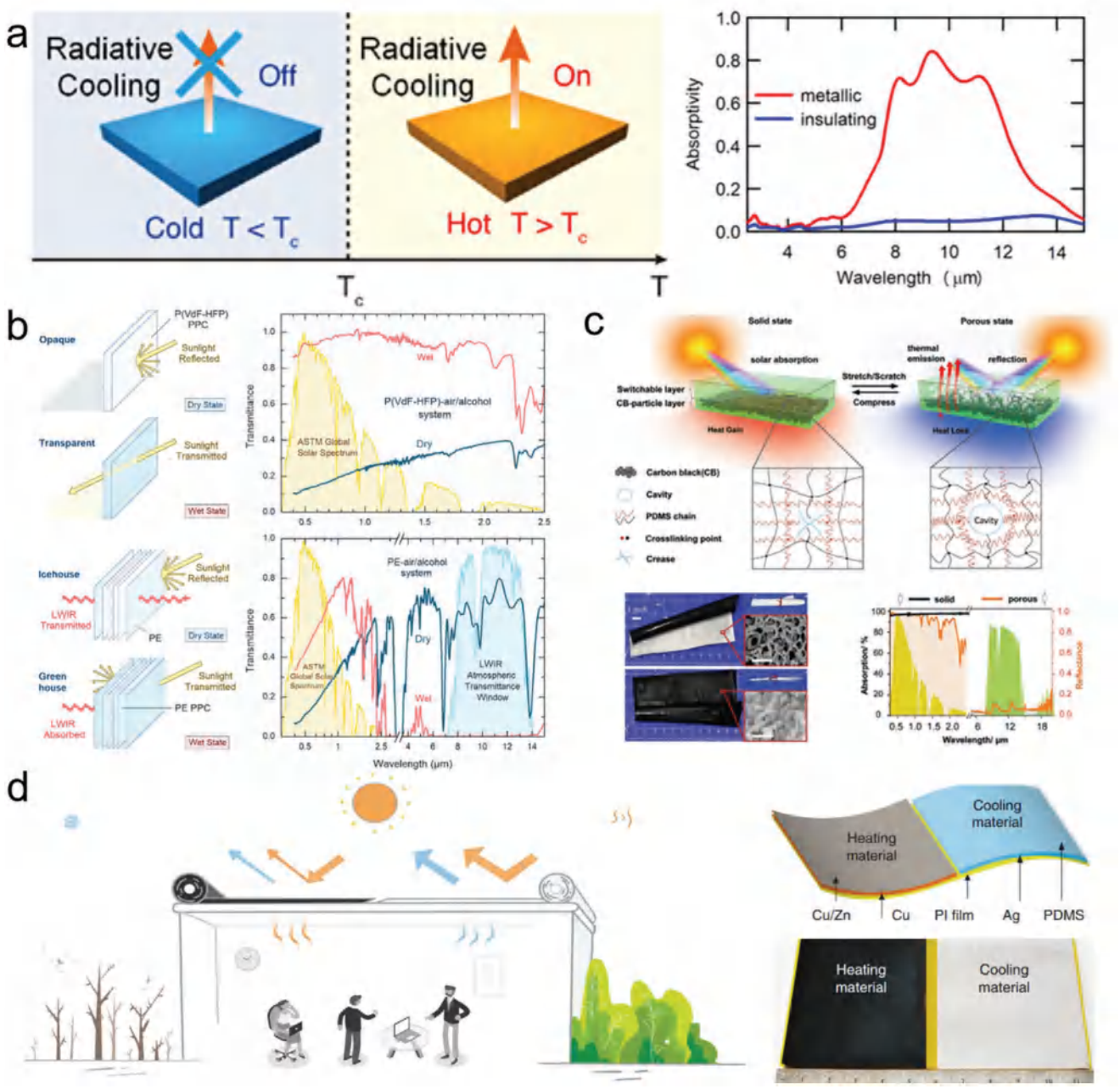

Figure 14. Dynamic switchable PDRC designs. a) Schematic of a self-adaptive radiative cooling device depending on temperature. Reproduced with permission.[112] Copyright 2018, Optica Publishing Group. b) Schematics and spectra of optically switchable porous polymers based on wetting with commercial liquids. Reproduced with permission.[117] Copyright 2019, Cell. c) Schematic illustrating a switchable device for cooling and heating and the corresponding photograph and spectrum. Reproduced with permission.[118] Copyright 2020, Wiley-VCH. d) Schematic and photograph of a device with daytime radiative cooling and solar heating. Reproduced with permission.[121] Copyright 2020, Springer Nature.

white poly(vinylidene fluoride-co-hexafluoropropene) PPCs become transparent when wet, causing large transmittance changes in the solar (0.74) and visible (0.80) wavelengths (Figure 14b). After wetting, the porous polyethylene cooler shows high transparency in the solar wavelength but ultralow IR transparency in the atmospheric window. As a result, switchable subambient cooling of 3.2 °C and above-ambient heating of 21.4 °C can be obtained by changing between wetting and drying. Mechanical force has also been reported to alter the optical properties of a cooler.[118–120] For instance, Zhao et al. proposed dynamic cavitation of PDMS based on stretchability, enabling it to reversibly and continuously change from a high porous state to a transparent solid-state (Figure 14c).[118] The corresponding solar reflectivity is 93% in the porous state and almost zero in the transparent solid. Hence, switchable cavitation by stretching can produce a subambient temperature in a hot environment and an over the ambient temperature in a cold environment under sunlight. Li et al. demonstrated a dual-mode device with electrostatically controlled thermal contact conductance that

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utilizes two infinite radiative heat sources and a cold source for daytime radiative cooling and solar heating.[121] Figure 14d illustrates that the dual-mode device includes a solar absorber (Cu–Zn) for subambient heating and a PDRC coating (PDMS-Ag) for subambient cooling. This dynamic switching can save, on average, 19.2% of the current building heating and cooling energy used in the United States.

3) Wide practical applicability and stability of the PDRC: Climate is a critical factor affecting the cooling performance of the PDRC. Clouds and high humidity weaken the transparent atmosphere window, resulting in reduced cooling performance. Therefore, the PDRC is not suitable for high humidity and coastal zone cities. In addition, the long-term stability of daytime radiative cooling materials has not received substantial attention. Cooling materials must have sufficient optical, physical, and chemical stability as they are entirely exposed to the environment. For polymer-based coolers, high ultraviolet (UV) irradiation accelerates the corrosion of cooling materials under outdoor conditions, which damages their cooling performance. Therefore, the anti-UV aging of materials is still a fundamental challenge inherent in all polymer-based PDRC practices and must be further studied. Moreover, dirt deposition on the surface of cooling systems decreases their reflectance in the solar wavelength, which is vital to the cooling performance. Thus, to avoid manual washing, developing a self-cleaning cooling system is required. To further improve cooling performance, more effort should be devoted to original innovations and thermal understanding, aiming to break current theoretical values. For example, a thermal insulation design that eliminates heating from the environment is important for further investigation. The high cost of cooling materials also limits some large-scale applications. Hence, the cost of the coolers and their scalability are essential considerations for practical applications and require additional research.

6. Conclusion

As an emerging technology, radiative cooling utilizes the outer space as a renewable and stable energy source to dissipate heat. Therefore, it is a promising platform for mitigating current global issues, including the urban heat island effect. This review summarizes the recent development of PDRCs and their different usages in building cooling, PV cooling, and clothing. Moreover, the criteria for efficient cooling under sunlight in terms of broad solar reflectance in solar wavelengths and thermal emissions in different atmospheric windows are discussed. Various strategies to improve PDRC cooling performance, such as material modifications, macro- and nanostructure designs, thermal engineering, and material constituents, have been summarized as a reference to obtain high cooling performance. Overall, significant development has been witnessed in the past several years regarding PDRC. In the coming years, it is necessary to solve the above challenges to meet the practical applications and expand the scope of PDRC. We believe that the broad application of highly efficient PDRCs is an essential enabler for the transformation toward an energy-efficient and sustainable society, and it is now on its way.

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Conflict of Interest

The authors declare no conflict of interest.

Keywords

applications, daytime radiative cooling, solar reflectance, structure design, thermal emittance

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