

Progress in passive daytime radiative cooling from spectral design to real application

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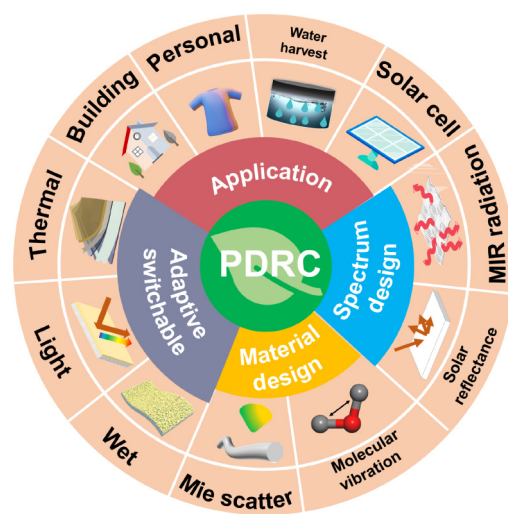
Cite This: *Carbon Future* 2025, 2, 9200033



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ABSTRACT: High-performance cooling technology is increasingly critical due to the rising frequency of extremely hot weather caused by global warming. Passive daytime radiative cooling (PDRC) is an emerging zero-energy-consumption technology that provides sub-ambient cooling under strong solar conditions by emitting heat to the cold outer space (~ 3 K) while minimizing heat gain from solar irradiation. This technology has attracted wide attention and achieved huge progress in the past decade. Recently, extensive efforts have been devoted to constructing high-performance PDRC materials in various fields, such as thermal management of buildings, human comfort, equipment, and dynamic devices. However, there is still a big gap between the laboratory-reported PDRC materials and their practical applications because of their high costs, complex manufacturing processes, insufficient cooling performance, and potential nano- or micro-hazards. In this review, we summarized recent advancements in PDRC technology and focused on the spectral design, cooling mechanisms, and practical applications of PDRC materials. We also discussed the challenges and strategies for bridging the gap between academic research and real-world implementation. We hope that this review will provide more insight into the further development of advanced PDRC technologies.

KEYWORDS: radiative cooling, spectral design, building thermal management, human thermal management, switchable radiative cooling



1 Introduction

Global warming induces frequent scorching weather and emphasizes the vital role of cooling technologies^{1–4}. Intensive heat poses a severe threat to public health, with approximately 350,000 annual deaths attributed to excessive exposure in scorching environments^{5, 6}. The cooling command is crazily increasing not only for human thermal comfort but also in buildings, food storage, cold-chain transportation, cell thermal management, etc.^{7–9}. However, conventional cooling technologies such as air conditioners consume about 10% of the world's electricity supply, contributing severely to the total CO₂ emissions and creating a

vicious cycle^{10, 11}. Therefore, innovative cooling technologies with less energy consumption and low carbon emissions are urgently needed to minimize energy consumption.

Passive daytime radiative cooling (PDRC) is an emerging zero-energy-consumption cooling technology based on thermal radiation transfer between the Earth (~ 300 K) and the cold outer space (~ 3 K) which is a natural cooling sink. It achieves sub-ambient cooling even under strong sunlight conditions by emitting long-wave infrared radiation (LWIR, 2.5–25 μm) into the cold outer space while reflecting incident solar heat^{12, 13}. This heat transfer process must pass through the Earth's atmosphere, but only a narrow region of LWIR, primarily within the 8–13 μm region, is transparent to Earth's heat, which is known as atmospheric transparent window (ATW)^{14, 15}. According to the Stefan–Boltzmann law, the peak thermal radiation of most objects on Earth (at typical temperatures of 30–50 °C) falls within the 8–13 μm ATW¹⁶. Therefore, PDRC offers a sustainable energy-free cooling solution with significant advantages over traditional technologies.

Actually, radiative cooling (RC) is not a novel concept. Dating back to ancient times, around 2000 years ago, Indians and Iranians

Received: October 26, 2024; **Revised:** January 7, 2025

Accepted: January 7, 2025

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<https://doi.org/10.26599/CF.2025.9200033>



harnessed the RC effect to produce ice at night, a process known as nighttime RC^{17, 18}. The evolution of the RC materials is shown in Fig. 1. In the early 1970s, the nighttime RC effect was realized in some polymers due to their intrinsically high LWIR emissivity, including polymethyl methacrylate (PMMA)¹⁹, polyvinyl chloride (PVC)²⁰, and polyphenylene oxide (PPO)²¹, as well as in gases²² and white paintings^{23, 24}. However, when exposed to strong sunlight, these materials failed to provide a cooling effect because the solar heating power (usually over $1000 \text{ W}\cdot\text{m}^{-2}$) far exceeds the net radiative cooling power (usually below $160 \text{ W}\cdot\text{m}^{-2}$)²⁵. For a long time, combining LWIR heat emission with solar reflection to achieve daytime cooling remained a challenge.

Until 2014, Fan's group experimentally demonstrated sub-ambient daytime cooling under strong sunlight (i.e., PDRC) for the first time, using an alternating SiO_2 - HfO_2 multilayer photonic crystal²⁶. Since then, various PDRC structures, such as period photonic crystals^{27, 28}, multilayer structures²⁹, multi-scaled fibers^{30, 31}, metamaterials^{32–34}, porous structures^{35–37}, and random dielectric particles with binders (i.e., polymers)^{38, 39}, have been developed in the past decade. PDRC materials have been promoted into paints^{40–42}, films^{43–45}, woods^{46, 47}, glasses⁴⁸, ceramics⁴⁹, aerogels^{50, 51}, hydrogels⁵², and textiles^{53–55} to adapt to potential applications widely. PDRC's application has also been promoted to diverse scenarios like building thermal management^{60, 61}, human thermal management^{58, 62, 63}, solar cells^{64, 65}, water harvest⁶⁶, and others (ice protection³⁰, plant growth⁶⁷, wound healing⁶⁸, wearable electronics^{69, 70}, etc.).

Several reviews of PDRC have been published in recent years, focusing on materials^{71–74}, structures^{14, 75–78}, fabrications²⁵, spectral designs^{79–81}, real applications^{82, 83}, etc. However, up to date, few reviews focus on the gap between the basic research and practical applications of PDRC technology. In this review, we summarized the recent progress of PDRC materials and their main applications (building cooling, personal thermal management, water harvesting,

solar cell cooling, and dynamic thermal regulation), emphasizing the spectral design principles, material design strategies, and efforts for the practical applications (Fig. 2). In addition, we also briefly discussed the limitations of PDRC materials in practical application and suggested prospects for developing PDRC for future systematic, scalable, and durable goals.

2 Fundamental thermal and photonic concepts

RC is a technology that achieves cooling by emitting thermal radiation, an electromagnetic wave within the infrared (IR) spectrum ($0.76\text{--}100 \mu\text{m}$) traveling at the speed of light ($3 \times 10^8 \text{ m}\cdot\text{s}^{-1}$) and requiring no medium for propagation⁸⁴. According to Planck's radiation law, objects above 0 K emit thermal radiation, with intensity significantly increasing as temperature rises⁸⁵. Through radiative thermal transfer, high-temperature objects can rapidly transfer heat to lower-temperature objects without needing a medium, thus achieving radiant cooling.

This review focuses on thermal radiation transmission between the Earth and outer space. The outer space serves as a near-vacuum super-cold reservoir, with a temperature of approximately $300 \text{ }^\circ\text{C}$ lower than that of the Earth's surface^{86, 87}. The significant temperature difference allows the transfer of large amounts of thermal energy from the Earth to outer space, achieving effective cooling—a process known as radiative sky cooling. Radiant heat can be rapidly transferred into the vastness of outer space through ATWs, rimarily in the $8\text{--}13 \mu\text{m}$ range, at the speed of light^{88, 89}. However, unlike conventional RC processes, when facing the sky, there is not only the ultra-cold outer space but also the sun, a superheat source ($\sim 5500 \text{ }^\circ\text{C}$) which complicates radiative sky cooling in sunny conditions because solar heating often masks the cooling effect^{26, 90}. To achieve sub-ambient PDRC effect under strong sunlight conditions, it is necessary to eliminate the solar heat

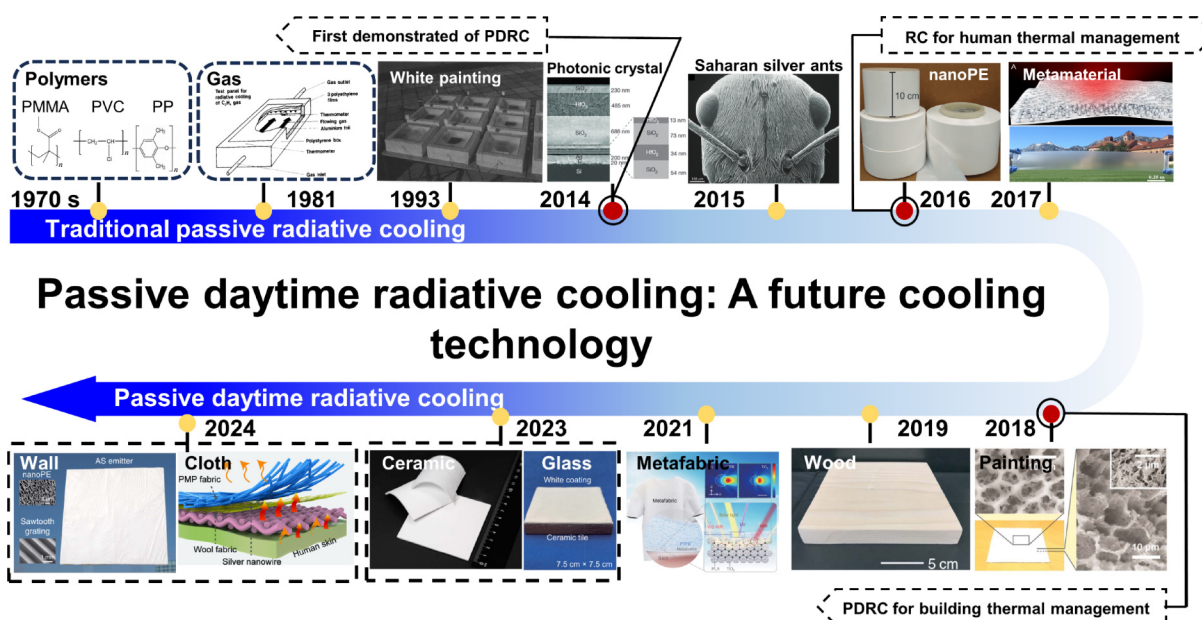


Fig. 1. Overview of the developed process of RC. Reproduced with permission from Refs.^{19–24, 26, 32, 33, 36, 46, 48, 49, 56–59}, © Elsevier Ltd. 1977; © Società Italiana di Fisica 1969; © EDP Sciences 1979; © American Institute of Physics 1981; © American Chemical Society 2001; © Elsevier Ltd. 1993; © Macmillan Publishers Limited 2014; © American Association for the Advancement of Science 2017; © Zeng, S. N. et al. 2021; © Mandal, J. et al. 2018; © Li, T. et al. 2019; © Zhao, X. P. et al. 2023; © Lin, K. X. et al. 2023; © American Association for the Advancement of Science 2015; © American Association for the Advancement of Science 2016; © Wu, R. H. et al. 2024; © Xie, F. et al. 2024.

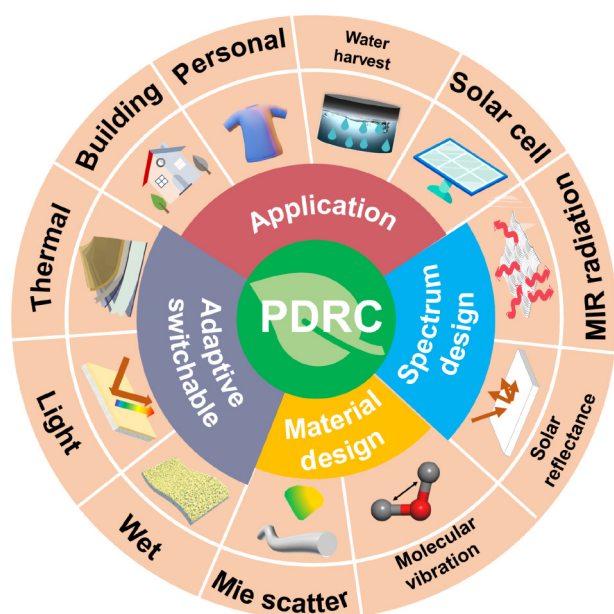


Fig. 2. Schematic of material design principle, spectral design, application, and adaptive switchable in PDRC materials.

load as much as possible (requiring a high solar reflectance, R_{solar}) while transferring heat to outer space. The significant temperature difference enables the PDRC to achieve cooling below ambient temperature (i.e., sub-ambient cooling) even in strong sunlight without using any terrestrial energy, which has attracted considerable attention^{26,91}.

In the past decade, various high-performance PDRC materials have been developed^{26, 32, 33, 36, 46, 48, 49}, employing three primary cooling mechanisms classified based on their spectral response in the LWIR wavelength range: emission cooling mode (Fig. 3a), transmission cooling mode (Fig. 3b), and reflection cooling mode (Fig. 3c).

2.1 Emission cooling mode

These materials have a high LWIR emissivity and a high solar reflectance, enabling cooling by dissipating heat to outer space while eliminating the solar heat load^{26, 32, 36}. Known as thermal emitters, the emission cooling materials or devices include non-selective thermal emitters (with a high emissivity over the entire LWIR spectrum)^{33, 45} and selective thermal emitters (with a high emissivity only over the 8–13 μm ATW waveband)^{12, 26, 92}, primarily used for building and personal thermal management.

2.2 Transmission cooling mode

The transmission type thermal transmitters exhibit a high LWIR transmissivity and a high solar reflectance^{51, 54}. When being used on high-temperature substrates (e.g., human skin)^{57, 93}, they can dissipate the substrate heat to achieve cooling. However, achieving both a high thermal transmissivity and a high solar reflectance is challenging due to the thickness limitation of materials^{33, 87}. Most high-thermal-transmittance PDRC materials, such as nano-sized pure polyethylene (PE), lack sufficient solar reflectance and are unsuitable for sunlight exposure, thus mainly used for indoor personal thermal management^{57, 94}.

2.3 Reflection cooling mode

This mode achieves cooling by reflecting both solar radiation and ambient thermal radiation^{95, 96}. These materials, known as thermal reflectors, possess both a high infrared reflectance and a high solar reflectance, primarily used in non-sky-facing surfaces like building sidewalls^{95, 97}. These surfaces often reach temperatures significantly above human thermal comfort levels, frequently exceeding 30 $^{\circ}\text{C}$ and even surpassing 50 $^{\circ}\text{C}$ under intense sunlight^{59, 98}. This reflective design plays a crucial role in mitigating the urban heat island effect.

Additionally, some PDRC materials with hybrid cooling modes have recently been developed, such as selective emission–reflection cooling mode⁹⁹, selective emission–transmission cooling mode⁹⁴,

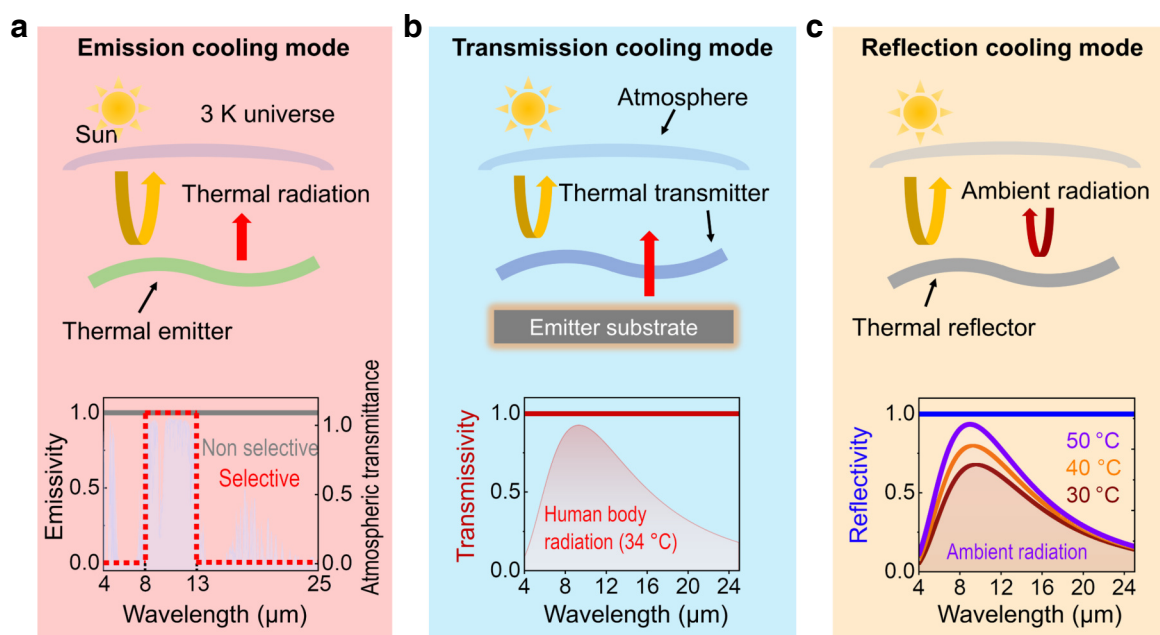


Fig. 3. The cooling mechanism of the PDRC material. a, The emission cooling mode. b, The transmission cooling mode. c, The reflection cooling mode. It is important to note that these three types of PDRC modes are classified based on their spectral response in the LWIR wavelength range.

and visible (VIS) transmission-infrared emission cooling mode⁶⁷, which significantly expand the application range of RC technology and will be discussed in the following sections.

The cooling performance of PDRC materials or systems can be simulated using a simple one-dimensional heat transfer model²⁶. Specifically, the quantitative energy balance equation for the thermal transfer between the Earth and outer space is shown as Eq. (1)

$$P_{\text{net}} = P_{\text{rad}} - P_{\text{atm}} - P_{\text{sun}} - P_{\text{non-rad}} \quad (1)$$

where P_{net} is the net cooling power of PDRC materials or systems, P_{rad} is the emitted thermal radiation from the thermal emitter, P_{atm} is the absorbed thermal radiation from the atmosphere, P_{sun} is the absorbed thermal radiation from sunlight, and $P_{\text{non-rad}}$ is the non-radiative heat transfer by thermal conduction and thermal convection.

The P_{rad} and P_{atm} are described by the Fourier's law³³, which gives Eqs. (2) and (3)

$$P_{\text{rad}} = 2\pi \int_0^{\pi/2} \sin \theta \cos \theta \, d\theta \int_0^{\infty} \epsilon I_{\text{bb}}(T_{\text{sample}}) \, d\lambda \quad (2)$$

$$P_{\text{atm}} = 2\pi \int_0^{\pi/2} \sin \theta \cos \theta \, d\theta \int_0^{\infty} \epsilon_{\text{atm}} I_{\text{bb}}(T_{\text{ambient}}) \, d\lambda \quad (3)$$

where T_{ambient} and T_{sample} are the temperatures of the ambient air and the thermal emitter, respectively. ϵ_{atm} and ϵ are the emittance of the ambient air and the thermal emitter, respectively. λ is wavelength, and $I_{\text{bb}}(T)$ is the blackbody radiation intensity. The $I_{\text{bb}}(T)$ can be calculated from

$$I_{\text{bb}}(T) = \frac{4\pi c^2 \hbar}{\lambda^5} \frac{1}{e^{\frac{2\pi \hbar c}{\lambda k_B T}} - 1} \quad (4)$$

where c , $\hbar$, and k_B are the speed of light ($3 \times 10^8 \text{ m}\cdot\text{s}^{-1}$), the reduced Planck constant ($1.055 \times 10^{-34} \text{ J}\cdot\text{s}$), and Boltzmann constant ($1.381 \times 10^{-23} \text{ J}\cdot\text{K}^{-1}$), respectively. The non-radiative heat transfer is described by the Fourier's law, which gives Eq. (5)

$$P_{\text{non-rad}} = h(T_{\text{ambient}} - T_{\text{sample}}) \quad (5)$$

where h is the non-radiative heat transfer coefficient.

To achieve a PDRC performance, careful design of nano-microstructures and functional group (or chemical bonding) vibrations in PDRC materials is essential (Fig. 4). Specifically, a high solar reflectivity requires selecting materials with high refractive indices and appropriate nano-microstructures^{32, 92}. According to the Mie scattering theory, materials with microstructures (such as pores, fibers, and particles) which have sizes close to the wavelength of sunlight exhibit a high Mie scattering efficiency in the solar waveband, contributing to a high solar reflectivity¹⁰⁰.

Additionally, according to the molecular vibration or plasma resonance theory, resonance-enhanced absorption/emission occurs when chemical bonds in organic or inorganic materials (e.g., molecular bonds in polymers^{92, 101} and free carriers in metal oxides¹⁰²) vibrate at the same frequency as the vibration of incident electromagnetic waves. To achieve a high absorption/emission or transmittance in the LWIR waveband, a targeted design of the material's molecular vibrations/plasma resonance modes within this waveband is necessary.

For an emission cooling mode, functional groups with strong molecular vibrations/plasma resonances in the LWIR waveband, especially within ATW wavebands, should be selected (e.g., C–O, C–Si, C–F, Al–O, Si–O, and Ti–O)⁸¹. Conversely, to achieve a transmission cooling mode, strong molecular vibration absorption in the LWIR waveband should be avoided. For example, PE, which contains only simple C–C and C–H bonds, exhibits a high thermal transmissivity.

Additionally, materials with high thermal reflectance are typical metals (such as aluminum or foil)⁹⁵. Future breakthroughs in PDRC technology will depend on more refined designs of micro-nanostructures and functional groups in RC materials. This advancement requires researchers to utilize new technologies, such as artificial intelligence technology, to develop quantitative and reliable theoretical models and simulation methods.

In the following, we will provide a detailed overview of several typical applications of radiative cooling technology, including building thermal management (which also extends to other terrestrial applications such as vehicle cooling and glacier protection), personal thermal management, and water harvesting.

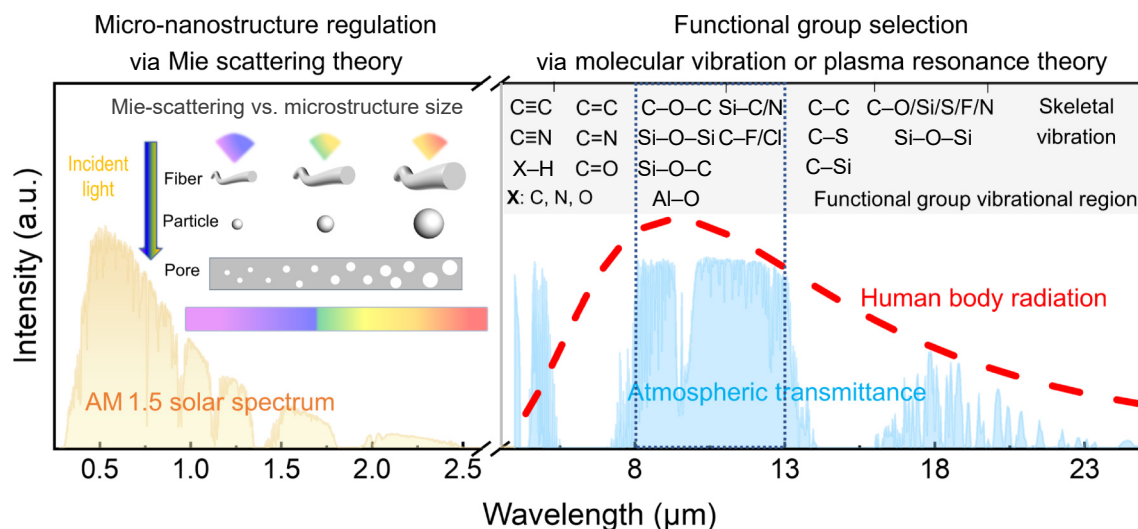


Fig. 4. Design principles of PDRC materials. It mainly included the micro-nanostructure regulation via Mie scattering theory (left) and functional group selection via molecular vibration or plasma resonance theory (right).

3 PDRC materials for building thermal management

Buildings are one of the main applied areas of PDRC materials. This is because buildings consume 30% of the Earth's energy to maintain thermal comfort and play a major role in total CO₂ emissions¹⁰³. For example, in 2020, CO₂ emissions from buildings are ~ 5.08 billion tonnes, accounting for 50.9%/37% of total carbon production in China. Almost half of the energy used in buildings is consumed by heating, ventilation, and air conditioning (HVAC) systems¹⁰⁴. To achieve a net-zero carbon emission, energy-efficient HVAC technology for buildings is necessary. As a zero-energy cooling technology, PDRC is a promising alternative to energy-intensive air conditioning systems and shows a high potential to reduce building energy consumption.

3.1 Spectral design of PDRC building materials

Over the last decade, various PDRC building materials have been developed. Depending on their spectral characteristics, they can be mainly categorized into three groups: emission-type PDRC materials (also known as thermal emitters with emission cooling modes), reflection-type PDRC materials (also known as thermal

reflectors with reflection cooling modes), and visible transmission-type PDRC materials (show selective transmission in visible waveband (0.38–0.76 μm) to achieve both brightness and cooling).

As shown in Fig. 5a, emission-type materials are typically employed in roofs facing the sky to maximize the heat transfer between the buildings and the outer space. For vertical walls (side walls), reflection-type PDRC materials are a better choice to eliminate the absorption of thermal radiation from surrounding buildings and the heated ground, especially in narrow building configurations (Fig. 5b). As for cooling windows or sunrooms, maintaining transparency to visible light is essential to meet the lighting requirements of buildings, albeit this increases the load on HVAC systems. Visible-transmission-type PDRC materials allow visible light to pass through, continuously block near-infrared (NIR) radiation from sunlight, and emit LWIR to outer space to minimize heat buildup, making them ideal cooling candidates (Fig. 5c).

3.1.1 Emission-type PDRC building materials

Emission-type PDRC building materials, also known as thermal emitters, show a high LWIR emissivity and a high solar reflectance (low emissivity and transmissivity in the solar waveband), with the emission cooling mode mentioned above (Fig. 6a)¹⁰⁵. Undoubtedly,

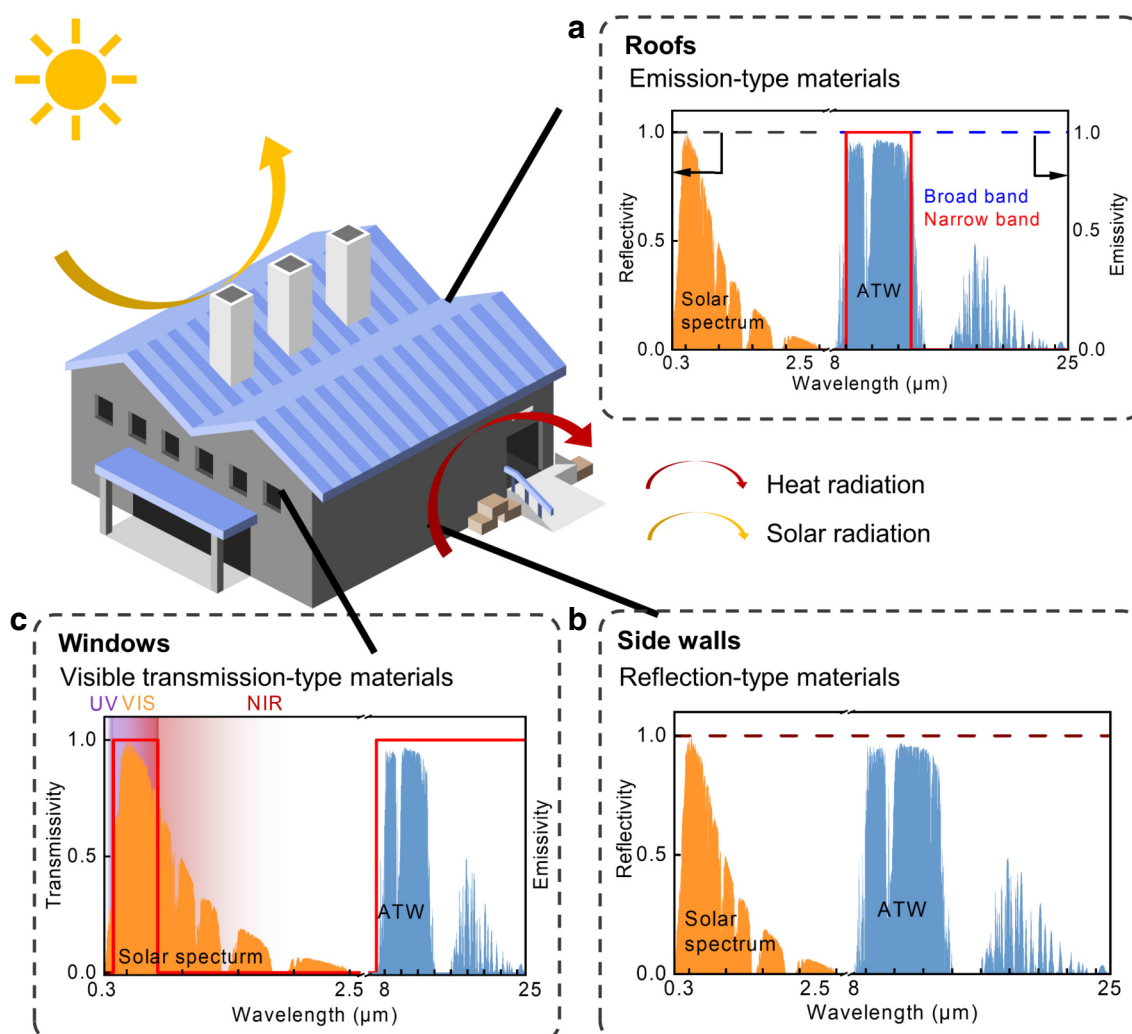


Fig. 5. Schematics of three main types of PDRC materials in building thermal management. a, Emission-type materials for roofs. b, Reflection-type materials for side walls. c, Visible transmission-type materials for windows.

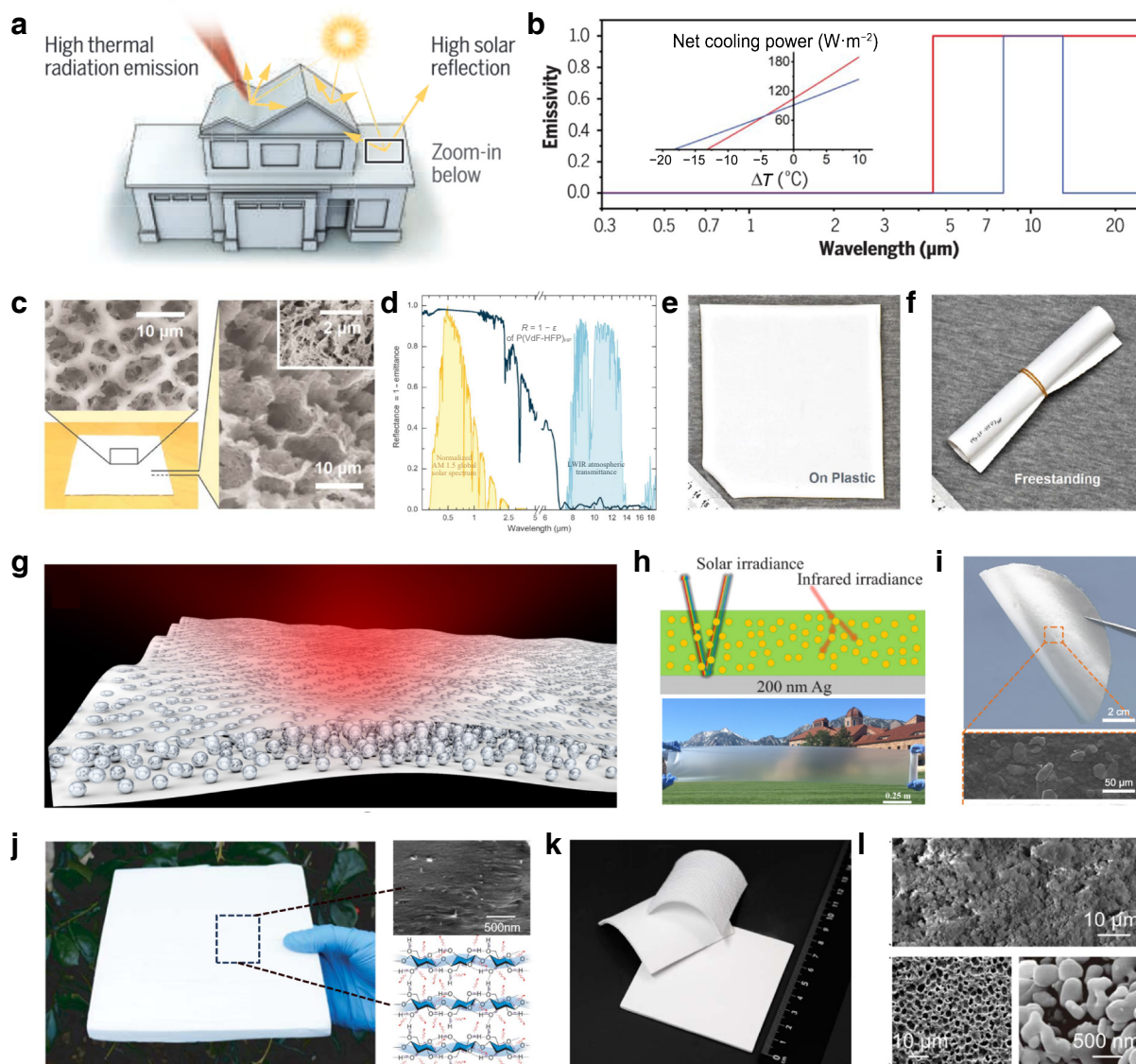


Fig. 6. Non-selective thermal-emission-based PDRC building materials. **a**, Schematic of the requirement for building thermal management. Reproduced with permission from Ref.¹⁰⁵, © Zhao, D. L. et al. 2023. **b**, Ideal spectral curves of non-selective emitters (red) and selective emitters (blue). The inset graph presents the net cooling power in various temperature differences between ambient and emitters. Reproduced with permission from Ref.⁹¹, © Yin, X. B. et al. 2020. **c**, The graph and scanning electron microscopy (SEM) images of porous PVDF-HFP paint. **d**, The total reflectance spectra of PVDF-HFP with normalized ASTM G173 global solar spectrum and the LWIR ATW. **e**, **f**, The paint could be coated in object surfaces like plastic (**e**) or made into freestanding sheets (**f**). Reproduced with permission from Ref.³⁶, © Mandal, J. et al. 2018. **g**, The schematic of random glass-polymer hybrid metamaterial film. **h**, The schematic and graph of the hybrid metamaterial. The backed silver reflected solar light strongly. Reproduced with permission from Ref.³², © American Association for the Advancement of Science 2017. **i**, The graph and SEM image of a lamellar thin film with 50 wt.% core-shell TiO₂-coated mica microplatelets. Reproduced with permission from Ref.¹²², © Xiong, L. H. et al. 2023. **j**, The photo of the cooling wood with SEM image showing the aligned wood channels and the cellulose functional groups. Reproduced with permission from Ref.⁴⁶, © Li, T. et al. 2019. **k**, The image of flat and curved cooling ceramics. **l**, The SEM images of the ceramic with a hierarchically porous structure. Reproduced with permission from Ref.⁴⁹, © Lin, K. X. et al. 2023.

emission-type PDRC materials have been the most extensively studied PDRC materials since the inception of this technology. According to the spectral response in the LWIR waveband, these thermal emitters can be mainly categorized into non-selective thermal emitters (broadband emitters) and selective thermal emitters (narrow band emitters)⁹¹. As shown in Fig. 6b, non-selective thermal emitters exhibit high absorptivity/emissivity across the entire LWIR waveband, while the selective thermal emitters exhibit a high absorptivity/emissivity only in the ATW waveband (typically 8–13 μm)⁹¹.

3.1.1.1 Non-selective thermal emitters

Non-selective thermal emitters are common emission-type PDRC materials, which are mainly used as building surface layers (paints and flexible films) and rigid structural materials (used as building matrices, such as ceramics and cooling wood)¹⁰⁶.

PDRC paints: Paint is a prominent utilization of PDRC materials in building applications, which shows high application potential due to its scalability and large-area coating ability¹⁰⁷. Existing PDRC paints include various types, such as organic^{108, 109}, inorganic^{110, 111}, and organic-inorganic¹¹² paints. Organic paints

consist of pure polymers and usually reflect solar radiation by multi-scaled porous structures^{108, 113, 114}. In 2018, Mandal et al. reported an organic PDRC coating, namely porous poly(vinylidene fluoride)-co-hexafluoropropene (PVDF-HFP), by a phase-separation method (Fig. 6c)³⁶. It showed a high solar reflectance (0.96) and a high LWIR emissivity of 0.97 due to the strong Mie scattering effect of multi-scaled pore sizes (Fig. 6d). It could be easily composited as paint on the surfaces of objects, such as plastics, copper, and wood (Figs. 6e and 6f). In commercial applications, organic-inorganic paints represent the prevailing choice, typically comprised of dielectric particles and polymers¹¹⁵. Titanium dioxide (TiO₂) stands out as the most prevalent filler in such commercial paints¹¹⁶. However, its strong absorption of ultraviolet (UV) light, attributable to its narrow energy gap (3.2 eV), imposes a theoretical constraint on solar reflectance, limiting it to approximately 0.92^{110, 115}. To achieve effective PDRC effect, researchers attempted to seek alternative light scatters with band gap for avoiding absorbing photons¹¹⁷. For example, Li et al. replaced rutile TiO₂ with calcium carbonate (CaCO₃)¹¹⁸ or BaSO₄ and mixed them with acrylic¹¹⁹, achieving a solar reflectance of 0.955/0.976 and a sub-ambient cooling temperature reduction of 1.7 °C/4.5 °C, respectively.

However, organic and organic-inorganic paints exhibit less robustness when exposed to outdoor environments for long periods, mainly due to polymer aging, which limits their practicality^{48, 120}. To address this issue, inorganic PDRC paints have recently been developed that minimize the use of organic components to meet durability requirements. For example, Yang et al. developed an inorganic PDRC paint incorporating barium sulfate (BaSO₄), nano-silica (SiO₂) particles, and porous geopolymer, which showed both high cooling performance (~ 4.09 °C sub-ambient reduction) and outdoor robustness like high mechanical stability, high-temperature resistance, and waterproof¹²¹.

PDRC films: Various PDRC films have recently been developed as covers for building cooling^{123, 124}. Films exhibit many advantages, such as being substrate-free, being adaptive to curved surfaces, and having mechanical robustness⁷⁵. Zhai et al. developed a glass-polymer hybrid film by embedding random SiO₂ microspheres in transparent polymethyl pentene (TPX), resulting in a high solar reflectance (~ 0.96) and a substantial radiative cooling power (> 100 W·m⁻²) when being combined with an Ag substrate (see Figs. 6g and 6h)³². As for the application of PDRC films in real scenarios, factors such as cost, mechanical robustness, and environmental resistance must be taken into consideration. Xiong et al. used a solvent exchange-reprotonation processing method to fabricate a lamellar thin film integrating aramid nanofibers with core-shell TiO₂-coated mica microplatelets (Fig. 6i), achieving a high solar reflectance of 0.92 and an average sub-ambient temperature drop of ~ 3.35 °C, a high mechanical strength (~ 112 MPa), anti-aging capability, a high-temperature adaption, etc.¹²².

Rigid PDRC matrix: In addition to PDRC paints and films, rigid PDRC structural materials (such as wood, glasses, or ceramics), have also been developed as building matrix materials, which have been shown to be much more weather-resistant than paints and films and therefore have high potential for real-world applications^{48, 125–128}. For example, in 2019, Li et al. developed a wood-based PDRC structural material by delignifying and densifying wood fibers, achieving excellent mechanical properties (high tensile strength of 404.3 MPa) alongside efficient PDRC performance (the average reflectance of 0.96 and cooling power of

63 W·m⁻²) (Fig. 6j)¹²⁹. To further improve the practicality of PDRC building materials, ultra-durable PDRC ceramics based on inorganic components have been developed. Most recently, Lin et al. introduced a hierarchically porous alumina-based PDRC ceramic (Fig. 6k) inspired by the *Cyphochilus* beetle⁴⁹. The ultra-white ceramics showed densely packed outer layers and numerous internal voids, exhibiting a high R_{solar} (0.996) and a high $\epsilon_{8-13\text{ }\mu\text{m}}$ of 0.965. The solid ceramic exhibited excellent color compatibility, weather resistance, and outdoor durability, providing a cooling power of > 130 W·m⁻² at noon. Zhao et al. also created a glass by sintering Al₂O₃ and SiO₂ and achieved a temperature drop of 3.5 °C even in a high-humid environment⁴⁸.

3.1.1.2 Selective thermal emitters

Compared with non-selective thermal emitters, selective thermal emitters have previously been demonstrated to have higher cooling performance due to the exclusion of atmospheric parasitic heat^{130–132}. Recently, various selective thermal emitters have been developed for building cooling, including photonic crystals, polymers, etc.¹³³.

The photonic crystal is an ideal candidate for selective emitters for controlled spectral curves by periodic structures or multilayers^{134, 135}. In 2014, Fan and co-workers reported a selective thermal emitter based on a HfO₂-SiO₂ multilayer photonic crystal that showed a strong selective emittance in ATW and 97% solar reflectance, achieving nearly 5 °C sub-ambient daytime cooling, which is the first experimental demonstration of sub-ambient PDRC (Figs. 7a and 7b)²⁶. Then in 2016, they further demonstrated the cooling potential of selective emitters with a silicon nitride (Si₃N₄)-amorphous silicon (Si)-aluminum (Al) photonic crystal (Fig. 7c), which showed a strongly selective emittance in ATW and achieved an ultra-high sub-ambient cooling (~ 60 °C) in a vacuum system (to minimize parasitic heat loss by convection and conduction) (Fig. 7d)¹³⁶. Despite the remarkable performance of these photonic crystals in achieving selective thermal emitters, their intricate and expensive fabrication limits their practical scalability. In 2022, Lin et al. fabricated an inorganic selective emitter by a solution-process method¹². They constructed a sandwich structure composed of top SiO₂ spheres, the SiO_xN_y layer, and the reflective layer. The narrow band emitter showed a high selective emission in ATW (~ 0.946) with a spectral selectivity of 1.46 while reflecting 96.4% of the sunlight.

In 2021, Li et al. developed a hierarchically designed polyethylene oxide (PEO) nanofiber-based film by a scalable roll-to-roll electrospinning process, which shows high selective emissivity (0.78) in the 8–13 μm ATW waveband and high solar reflectance (0.963) (Fig. 7e)⁹². As a result, the PEO nanofiber-based film achieved ~ 3 °C cooling improvement as compared to that of a non-selective emitter at night, and 5 °C sub-ambient cooling under sunlight.

In addition to the well-known ATW in the 8–13 μm waveband (first ATW), there is also an ATW in the 16–25 μm waveband (second ATW), especially in arid climates. While current research on PDRC materials has primarily focused on the first ATW and ignored the second one, the cooling effect of the second ATW has been overlooked and the cooling potential of PDRC technology has been under-exploited (Fig. 7f). Recently, our group developed a dual-selective thermal emitter consisting of polyformaldehyde (POM) nanofibers, polytetrafluoroethylene (PTFE) microparticles, and Al foil (POM-PTFE-Al) by a roll-to-roll electrospinning

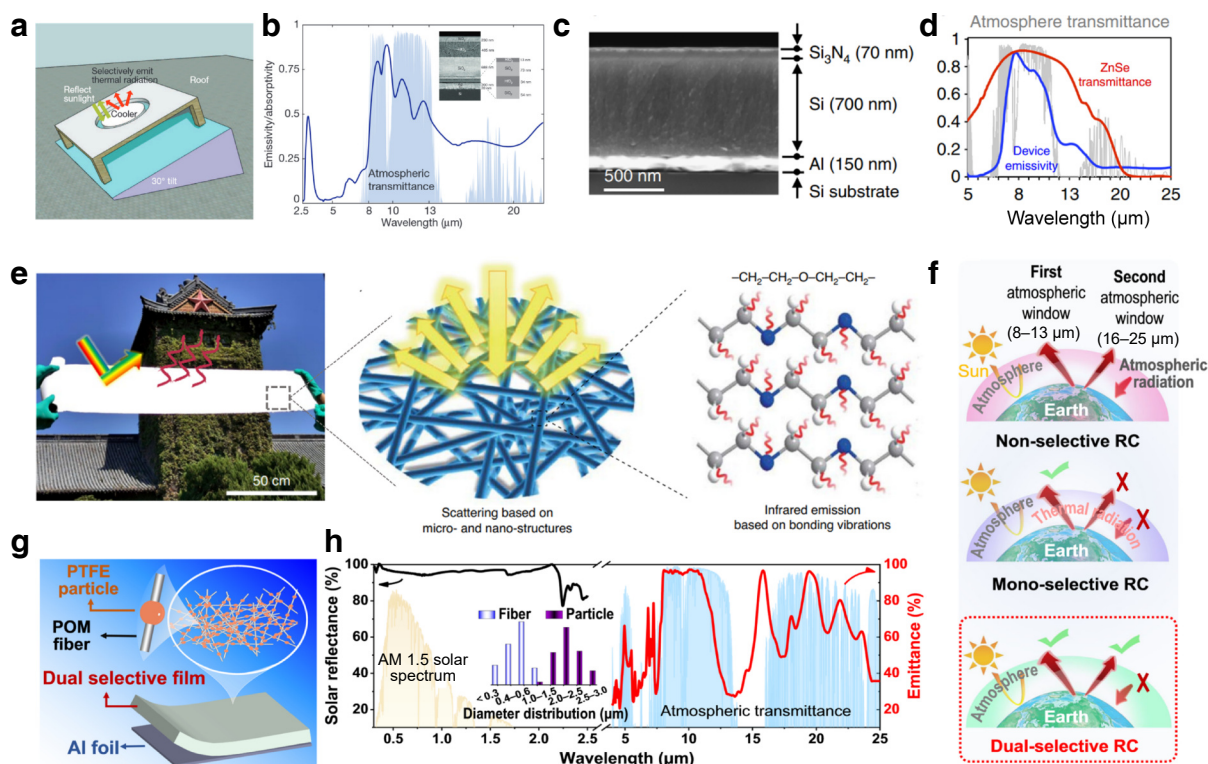


Fig. 7. Selective-thermal-emission-based building materials. **a**, The three-dimensional schematic of radiative emitter and apparatus. **b**, The emissivity of the photonic crystal in LWIR bands. The inset cross-sectional SEM image presents the multilayer structure of the emitter. Reproduced with permission from Ref.²⁶, © Macmillan Publishers Limited 2014. **c**, The cross-sectional SEM image of the selective emitter. **d**, The emissive spectrum of the selective emitter (blue) and transmittance spectrum curve of ZnSe (red) aligned with the ATW. Reproduced with permission from Ref.¹³⁶, © Chen et al. 2016. **e**, The image and emissive and scattering schematics of mono-selective electrostatic spinning-PEO (es-PEO) film produced by a roll-to-roll electrospinning process. Reproduced with permission from Ref.⁹², © Li, D. et al. 2020. **f**, The spectral response of the dual-selective POM-PTFE-Al film. **g**, Schematic of the non-selective (top), mono-selective (middle), and dual-selective (bottom) PDRC materials. **h**, Schematic of Al-based POM-PTFE dual selective film. Reproduced with permission from Ref.⁹⁹, © Wu, X. K. et al. 2024.

process, which showed high selective emissivity in both ATWs (0.832 in 8–13 μm and 0.675 in 16–25 μm , respectively) and high solar reflectance (~ 0.954), as shown in Figs. 7g and 7h⁹⁹. The dual selective characteristics of the dual-selective thermal emitter were due to the molecular vibrations of the C–O–C bonds of POM (mainly in the first ATW) and the C–F bonds of PTFE (mainly in the first ATW), it therefore dissipated heat through both windows at the same time⁹⁹. As a result, thermal measurements in a real desert environment showed superior sub-ambient daytime cooling performance compared to the non-selective and mono-selective thermal emitters ($\geq 3^\circ\text{C}$ cooler).

3.1.2 Reflection-type PDRC building materials

In real scenarios, various heating effects contribute to elevated temperatures in addition to solar heating, such as thermal radiation from surrounding high-temperature objects, which complicates the heat transfer process¹³⁷. For example, in densely built cities, buildings are also heated by surrounding buildings and grounds, mainly through the vertical walls that do not face the sky (heat transfer to outer space is limited or blocked), leading to a gradual accumulation of thermal load (i.e., the hot island effect)^{98, 138}. To cool a building in such scenarios, the vertical wall materials should preferably be highly reflective for both solar and LWIR band (Fig. 8a), i.e., reflection-type PDRC materials (also known as thermal reflectors)¹³⁹. This allows buildings to be cooled by reflecting incoming solar and ambient heat. Besides, the reflection-type

PDRC materials also prevent heat loss from the interior of the building during the cold winter months, resulting in year-round building energy savings, which has been demonstrated by recent literature (Fig. 8b)⁹⁶.

Specifically, Peng et al. devised a reflection-type (low-emissive (low-e)) colorful paint (Fig. 8c), comprising a bottom layer of IR-reflective coating (Al microflakes) and a top layer of IR-transparent color layer (Prussian blue (PB), iron oxide (Fe_2O_3), goethite ($\alpha\text{-FeOOH}$), and zinc oxide (ZnO)). The Al microflakes reflected LWIR thermal radiation, reducing heat gain from sunlight and the surroundings. The LWIR-transparent top layer contributed to vibrant colors. Constructing random patterns with the bilayer low-emissive paint solutions was straightforward (Fig. 8d). The bilayer structure reflected $\sim 80\%$ LWIR radiation, compensating for thermal absorption by polymer binders and porous structure (Fig. 8e). Despite this, the colorful paint maintained a reflectance of 0.65 to 0.75 in the NIR wavelength range (Fig. 8f).

In addition, they also developed a colored low-emissivity film for building envelopes with PE, pigment nanoparticles, and Al foil through a hot press method (Fig. 8g)⁹⁵. Thermal measurements showed that the low-emissivity film mostly reflected heat radiation, resulting in a temperature rise of approximately 3.5°C , lower than that observed with blank or commercial blue paint (Figs. 8h and 8i). In cold environments, the insulating film envelope maintained a steady temperature of 25°C , demonstrating its effectiveness in reducing heat loss through reflective characteristics.

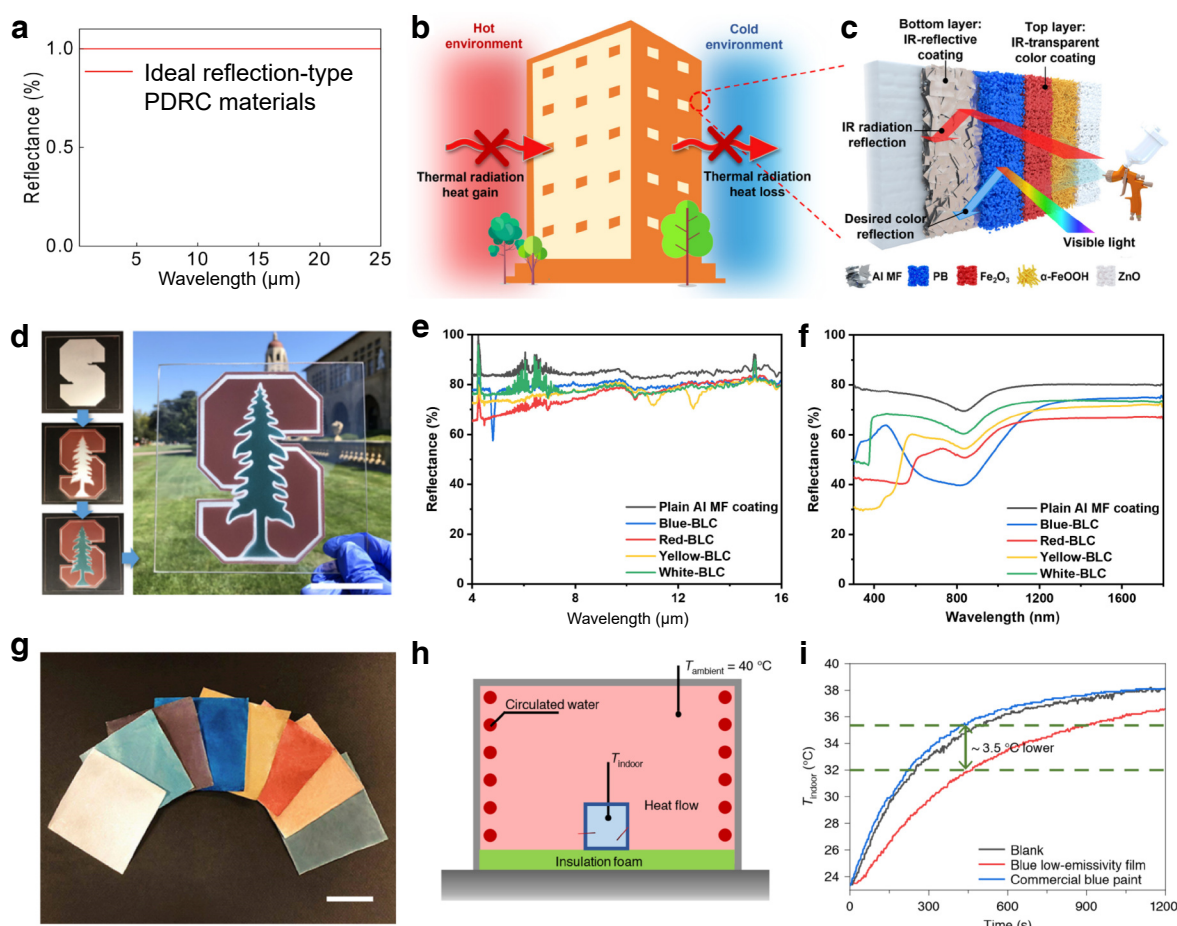


Fig. 8. Reflection-type PDRC building materials. **a**, The ideal spectrum of reflection-type PDRC materials. **b**, The schematic of the working mechanism of reflection-type paint. **c**, The schematic image of the bilayer low-emissivity paints. **d**, A photo of the fabricated process and the final produced Stanford logo by reflection-type paint (scale bar, 5 cm). **e**, **f**, The measured spectrum of colorful paints on the glass substrate in LWIR bands (**e**) and solar irradiation spectra (**f**) for the Al MF coating and bilayer low-e coatings (BLCs) in blue, red, yellow, and white, respectively. Reproduced with permission from Ref.⁹⁶, © Peng, Y. C. et al. 2023. **g**, A photograph of colorful low-emissivity enveloped films. **h**, The schematic illustration of the tested system of reflective envelopes. **i**, The measured temperature curves of buildings with different enveloped materials. Reproduced with permission from Ref.⁹⁵, © Peng, Y. C. et al. 2021.

3.1.3 Visible-transparent PDRC building materials

Transparent roofs, walls, and windows offer an effective method for harnessing daylight in buildings and have attracted extensive attention in recent years¹⁴⁰. However, they are hindered by their high energy consumption^{141–143}. For example, conventional silicon-based windows show high solar radiation transmissivity in both the visible and NIR wavebands, resulting in high heat stress in hot weather and thus more energy required to operate HVAC systems to maintain a comfortable environment^{144–146}.

Recently, various visible-transparent PDRC materials have been developed to reduce the energy consumption of buildings, which enable the passage of visible light while blocking UV and NIR light, and also emitting LWIR radiation to dissipate heat and harness natural light simultaneously^{147, 148}. This spectral design is beneficial for both light and thermal comfort, which is important for human beings^{143, 149}. In 2020, Zhou et al. developed a visible-transparent PDRC window based on a bilayer structure of highly NIR reflective ITO glasses as substrate and saturated polydimethylsiloxane (PDMS) (high LWIR emissivity) as a top layer (Fig. 9a)¹⁴⁰. The 80-mm-thick PDMS absorbed sunlight slightly (~ 0.004), and had a high solar transmissivity (0.94) and a high emissivity at 8–13 μm

(~ 0.9) (Fig. 9b). As a result, compared with conventional window materials, the visible-transparent PDRC window showed a cooling of 7 °C and a max reduction in energy consumption of approximately 12% ($\sim 68 \text{ MJ}\cdot\text{m}^{-2}$) (Fig. 9c). Wen et al. carried out a supramolecular co-assembly strategy to construct a Bolas-shaped polyethylene glycol peptide (BPP) and silk fibroin film, which integrated high stress (27.8 MPa), toughness ($3.64 \text{ MJ}\cdot\text{m}^{-3}$), transparency (0.89), and LWIR emissivity (0.905) together¹⁵⁰.

In addition to windows in buildings, visible-transparent PDRC materials have been used in greenhouses to manage heat stress and promote plant growth. Zou et al. designed a visibly transparent PDRC multilayer film (transparent radiative cooling (T-RC) film) based on Ag (high NIR reflectance), PVDF (high emissivity in ATW), and polyethylene terephthalate (PET) for the greenhouse (Figs. 9d and 9e)⁶⁷. The T-RC film provided sufficient photosynthetically active radiation (PAR, the effective band for plant growth, 400–700 nm) transparency (0.689) for plant growth in summer, reducing room temperatures by up to 18.6 °C compared to commercial counterparts (polyolefin (PO) film). Additionally, it improved crop quality by decreasing heat accumulation and reducing the proline effect of plants. In 2024, Li

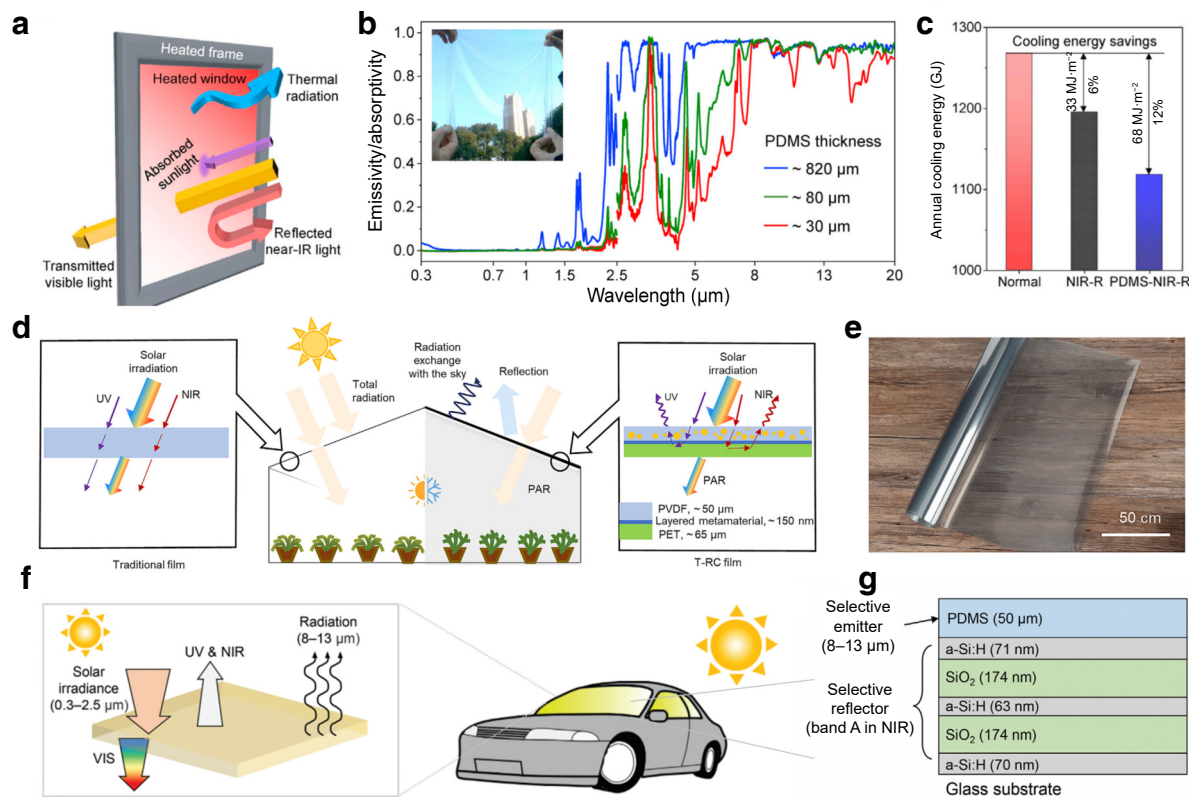


Fig. 9. Visible-transparent PDRC building materials. **a**, The schematic of the cooling mechanism of PDRC windows. **b**, The spectral response of the transparent PDMS film with different thicknesses. The inset graph shows a PDMS film. **c**, Annual energy consumption of cooling with normal windows, windows with NIR reflector, and windows with PDMS and a NIR reflector. Reproduced with permission from Ref.¹⁴⁰, © Zhou, Z. G. et al. 2020. **d**, Schematics of traditional greenhouse film and T-RC film, respectively. **e**, A photo of the T-RC film. Reproduced with permission from Ref.⁶⁷, © Zou, H. et al. 2023. **f**, The schematic illustration of the spectral response of ideal transparent PDRC materials. **g**, Schematic of the structures of designed transparent PDRC materials. Reproduced with permission from Ref.¹⁵⁴, © Wiley-VCH GmbH 2021.

et al. reported a photonic-engineered sandwiched film for active photosynthesis of plants made of PDMS, a phonic crystal substrate, and an antifogging polyacrylamide (PAM) layer¹⁵¹. They refined the visible light band according to the growth of plants (0.4–0.5 and 0.6–0.7 μm) and designed photonic structures to achieve selection of transmissivity. The film could cool down air temperature by 1.9–4.6 °C, prevent water evaporation from the soil by 2.1%–31.9%, and improve the accumulation of plant biomass yield to 20%–370%.

Moreover, visible-transparent PDRC materials also find interesting applications in car cooling in hot weather, as car interiors absorb solar heat radiation, leading to heat accumulation and unexpected energy waste in cooling (Fig. 9f)^{152, 153}. In 2021, Kim et al. developed a visible-transparent car window film based on a five-layer photonic crystal, consisting of hydrogenated amorphous silicon (a-Si:H) and alternatively stacked SiO₂ with a PDMS top layer, and a glass substrate (Fig. 9g)¹⁵⁴. This film maintained a high visible transmissivity (0.87), enabling a temperature reduction of 14.4 °C, meeting both optical and cooling requirements. Recently, Lee et al. integrated a triboelectric nanogenerator (TENG) with a radiative cooler (TeRC) and created a highly transparent window for sustainable and all-weather powerful cooling¹⁵⁵. The integrator consisted of top TENG electrodes and bottom reflector and emitters for PDRC, which could generate electric power from water droplets (248.28 W·m⁻²) while keeping 80% transparency of visible light and demonstrating potential in energy-saving worldwide.

As a passive cooling technology, PDRC undoubtedly plays a vital role in alleviating extra energy consumption. Its wide application and continuous integration with other fields, depending on spectral design in multiple wavelength bands (including UV, VIS, NIR, and ATW/LWIR), are encouraging. PDRC materials are expected to be utilized wherever cooling is essential.

3.2 Applications of PDRC building materials

In addition to the superior cooling performance, PDRC materials also show many metrics required for real-world applications in buildings, including heat stability, color aesthetics, and long-term stability. Researchers developed various tactics to alter materials to comply with user directions to advance PDRC materials in practical applications.

3.2.1 Self-clean and long-term durability

In real-world applications, PDRC materials face rigorous natural environments, such as UV exposure, rain, and dust exposure, which pose threats including polymer aging, reduced mechanical robustness, and surface pollution, as shown in Fig. 10a¹⁵⁶. In this section, we reviewed the outdoor tests that PDRC building materials must undergo, recommending that researchers consult ASTM standard D7897-18 weather test methods (*Practice for Laboratory Soiling and Weathering of Roofing Materials to Simulate Effects of Natural Exposure on Solar Reflectance and Thermal Emittance*) to ensure materials meet unified standards for comparison¹⁵⁷.

3.2.1.1 UV defense

UV defense is an important characteristic of anti-aging PDRC materials, particularly for organic polymer-based materials vulnerable to UV degradation. UV radiation, with wavelengths from 290 to 400 nm, can break the chemical bonds and initiate a photooxidation reaction, leading to polymer aging, yellowing, and mechanical strength reduction¹⁵⁸. The use of UV absorbers is a universal method of mitigating UV aging, albeit at the expense of partial R_{solar} . For example, Yao et al. developed a spider-silk-inspired core-shell nanofiber comprising PEO with $\text{K}_2\text{Ti}_6\text{O}_{13}$ (PT) nanofiber dopants¹⁵⁹. The PTs could absorb high-energy UV radiation, converting it into negligible heat, thus safeguarding polymers from aging. After a 1.5 h of UV exposure at a 500 W mercury lamp, the PT@PEO films retained their tensile strength and flexibility, whereas pure PEO films fractured under external tensile force (Fig. 10b).

3.2.1.2 Self-cleaning

Furthermore, self-cleaning ability is essential for maintaining the stability and longevity of PDRC materials¹⁶⁰. In outdoor environments, surface pollution such as dust, water, soot, and particulate organic matter is inevitable¹⁶¹. Surface contamination diminishes solar reflectance and net cooling power¹⁶². To address the issues, in 2023, Zhao et al. developed a highly resilient PDRC glass by mixing Al_2O_3 and SiO_2 and then sintering it to create a homogeneous white coating that tightly adhered to the paints and substrates (Fig. 10c)⁴⁸. The characteristics of glass provided numerous advantages, including high emissivity (via Fröhlich resonances), self-clean ability, UV defense, and waterproofing. The surface could be easily restored to its original condition even after exposure to highly liquid contaminants (Fig. 10d). Similarly, Song et al. adopted a strategy to minimize polymers and formulated an anti-aging cooling paint (AACP) using rutile TiO_2 as the primary filler, augmented with a superhydrophobic perfluorooctyltrichlorosilane (PFOTS) coating¹⁰⁰. This coating endowed the TiO_2 with exceptional self-cleaning ability, while the absence of organic polymers mitigated concerns regarding aging. Following the ASTM D7897-18 standard weather test, the paint kept high solar reflectance (~ 0.93) after long-time UV exposure and simulated rain compared to commercial paint (Fig. 10e).

3.2.2 Aesthetic requirement

Typical PDRC materials are white or silver to maximize solar reflectivity (or minimize heat load from sunlight)¹⁶³. However, in real applications, aesthetic architectural properties are also desired. Researchers have explored various methods to strike a balance between color and cooling performance. Three primary methods for achieving colorization include: (i) adding a colored top layer⁹⁹, (ii) structural colorization¹⁶⁴, and (iii) mixing photoluminescence dyes¹⁶⁵.

One common method involves adding a colorful top layer with high NIR transmittance onto scattered bottom layers¹⁶⁶. When considering top-layer materials, transparency for NIR light and color durability are essential requirements. Chen et al. applied colorful thin top layers onto P(VdF-HFP) substrates (Fig. 11a)¹⁶⁷. The delicate bilayer structure declined optical paths in pigment to minimize the absorption of NIR for a high NIR reflectivity. As shown in Fig. 11b, the bilayer color paint exhibited nearly identical optical characteristics in the visible waveband but a higher NIR reflectivity (as shown in infrared images). Even with a dark layer, the sample absorbed the most visible light but reflected $\sim 63\%$ NIR radiation, followed by the TiO_2 -based bilayers (Fig. 11c).

Alternatively, Wu et al. recently colorized a PDRC film (POM-PTFE-Al) by applying cheap and commercially available colored PE films as top layers (Figs. 11d and 11e)⁹⁹. This simple design allows the PDRC samples to be well colored while maintaining high NIR reflectivity ($> 94\%$), contributing to a sub-ambient cooling even in strong sunlight (Fig. 11f).

Structural colorization employs period nanostructures to achieve selective reflection and absorption, another color PDRC strategy¹⁶⁸. Li et al. achieved the same pink color with different stacked layers¹⁶⁹. The “cold” photonic crystal comprised seven alternated layers including silicon (Si) and silicon dioxide (SiO_2) with a top layer of titanium dioxide (TiO_2) (Fig. 11g). Conversely, the “hot” crystal consisted of three layers of metal-insulator-metal (MIM) and alternated SiO_2 with TiO_2 (Fig. 11h). These structures exhibited that different structures brought different spectra and abilities to absorb heat (Fig. 11i). In 2022, Zhu et al. created a structural colored film using naturally derived cellulose nanocrystals (CNCs)¹⁷⁰. The film's birefringent CNC nano-rods formed a periodic helicoidal structure, reflecting visible light strongly and selectively. When coated on a highly scattered porous ethylcellulose (EC) base layer, the bilayer structure simultaneously achieved combination and sunlight reflection (Fig. 11j).

The use of traditional dyes for colorful PDRC inevitably fails to achieve sub-ambient cooling due to the absorption of solar heat in the visible range¹³³. Recently, researchers have turned to photoluminescence dyes that efficiently convert the absorbed photons into re-emitted light, minimizing the solar thermal effect and showing high potential for sub-ambient cooling. Wang et al. developed a colored PDRC emitter comprising top photoluminescent perovskite quantum dots dyes (CsPbX_3) as the top layer and a film consisting of cellulose acetate (CA) nanofibers as substrate (Fig. 11k)¹⁷¹. The photoluminescent colorant absorbed radiation in specific wavebands and re-emitted them, while the CA substrate strongly reflected sunlight and radiated thermal load. As a result, the color cooler achieved a sub-ambient cooling of 5.4–2.2 °C under sunlight (peak solar irradiance $> 740 \text{ W m}^{-2}$).

3.2.3 Heat transfer characteristics and thermal stability

In real environments, there are three ways of thermal transfer, namely conduction, convection, and thermal radiation¹⁷². These factors determine the thermal performance of a thermal material or system. However, most current PDRC research only focuses on thermal radiation and convection and ignores thermal conduction, resulting in limited practical cooling performance¹⁷³. The thermal conductivity of PDRC materials influences the heat transfer rate from hot sources to cold sources¹⁷⁴. In building applications, when the indoor temperature is higher than the outdoor temperature, PDRC materials with high thermal conductivity are required to promote heat dissipation from inside to outside to achieve cooling (Fig. 12a). When the opposite is true, cooling is achieved by using low thermal conductivity materials (i.e., thermal insulating materials) to block the entry of heat from the outside (Fig. 12b)¹¹⁷.

In hot seasons, outdoor temperatures tend to be higher than indoor temperatures, so building materials are often thermally insulated¹⁷⁵. Insulated PDRC materials cool buildings by both thermal radiation and conduction, contributing to improved cooling performance¹⁷⁶. Zhong et al. developed a thermal insulating film composed of PVDF and poly(vinyl alcohol) (PVA) using a coaxial electro-spinning process (Fig. 12c)¹⁷⁷. The insulated film comprised hollow core-shell microfibers with nanopores smaller than the mean free path of air molecules, achieving an ultralow thermal

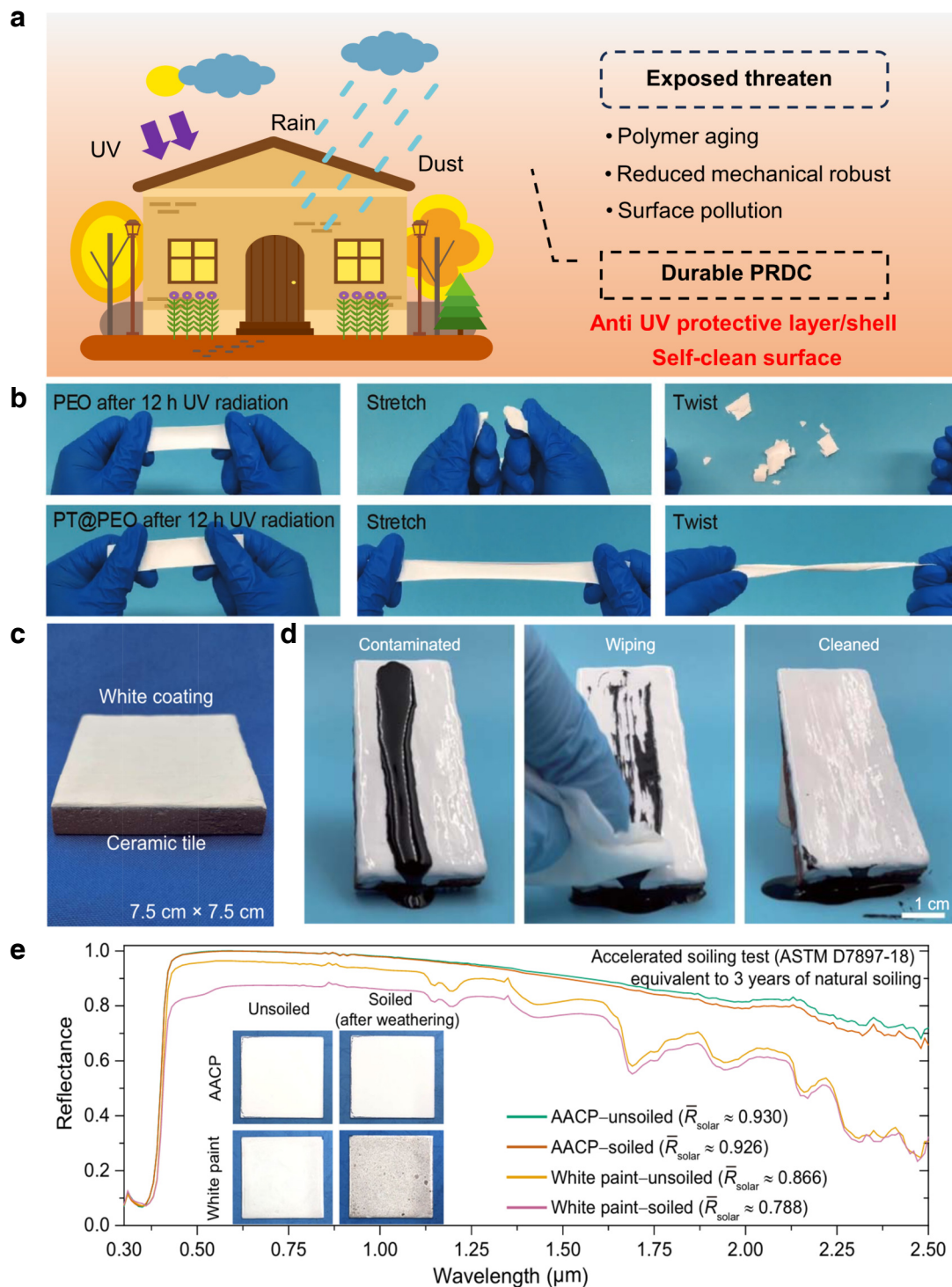


Fig. 10. Self-clean and long-term durability for building materials. **a**, The schematic of the requirement of exposed PDRC materials. **b**, Photos of PEO and PT@PEO after UV irradiation exposure. Reproduced with permission from Ref.¹⁵⁹, © Wiley -VCH GmbH 2022. **c**, The photo of radiative cooling ceramic tile. **d**, The contamination and wiped process of cooling ceramics with a transparent protective layer. Reproduced with permission from Ref.⁴⁸, © Zhao, X. P. et al. 2023. **e**, The reflective spectra of AACP paint and white paint before and after the soiled process based on ASTM D7897-18 standard, equivalent to 3 years of natural soiling. Reproduced with permission from Ref.¹⁰⁰, © Song, J. N. et al. 2021.

conductivity ($0.014 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$), even lower than that of air ($0.026 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$), as shown in Fig. 12d. The insulated film's thermal and radiative cooling properties enabled it to achieve sub-ambient cooling of 9°C below the ambient air under a hot summer climate.

In colder environments, PDRC materials should facilitate rapid heat flux transfer to cool down efficiently¹⁷⁹. Tian et al. fabricated ultralong hydroxyapatite (HAP) fibers into an insulated film using a solvothermal process and successive baking method (Fig. 12e)¹⁷⁸. The resulting film exhibited a high thermal conductivity of

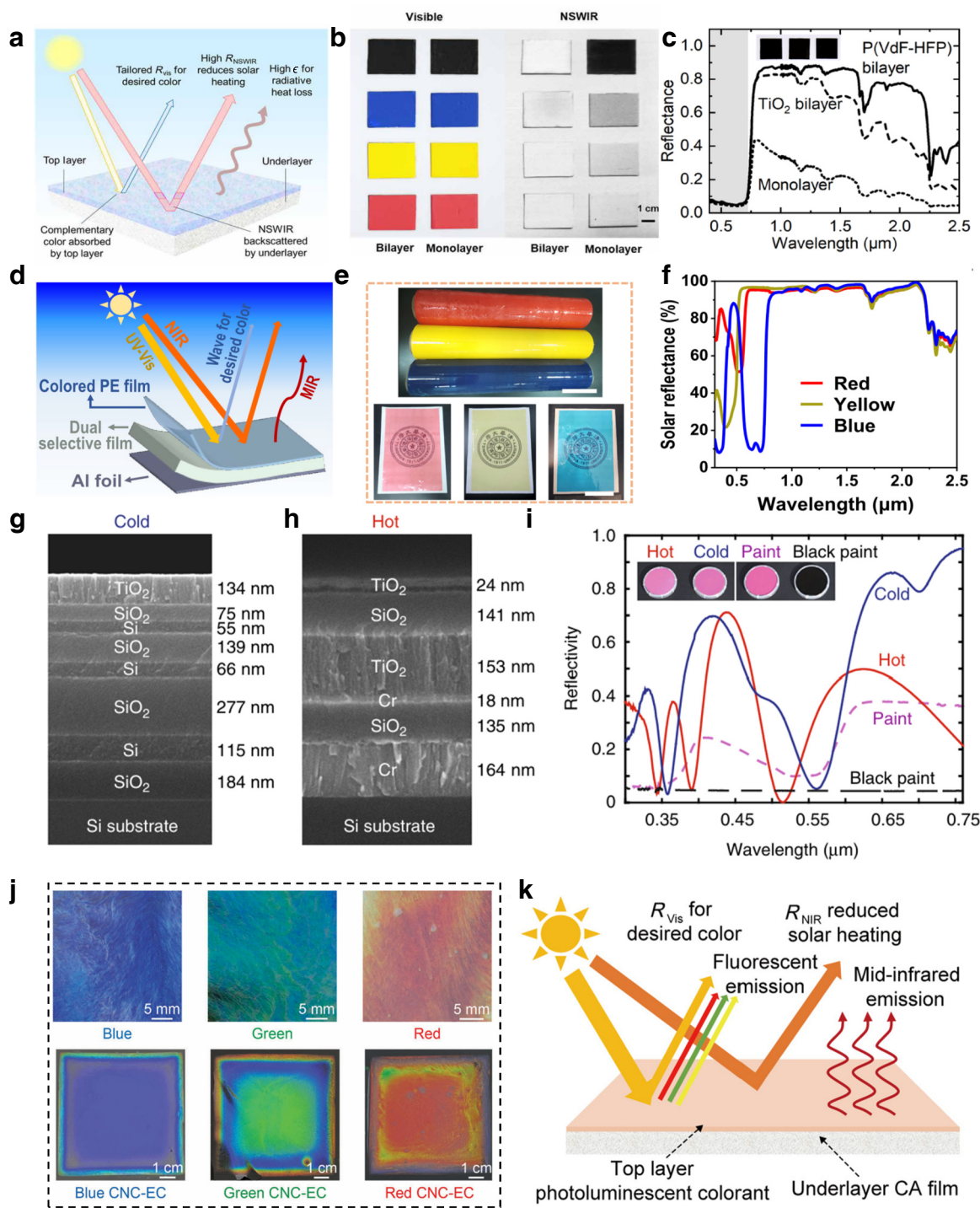


Fig. 11. Colored PDRC materials for aesthetic command in buildings. **a**, Schematic of bilayer design with a top colored layer and bottom high NIR reflective layer. **b**, The photograph of four pairs of bilayer P(VdF-HFP) paint and mono-paint in visible (left) and near-to-short wavelength infrared (NSWIR) (right) photographs, respectively. **c**, The reflective spectra of black bilayer P(VdF-HFP) paint in visible and NIR bands. Reproduced with permission from Ref.¹⁶⁷, © Chen, Y. J. et al. 2020. **d**, Schematic of colored dual-selective emitters with top PE film. **e**, Photographs of commercial colorful PE films (scale bars = 10 (upper) and 5 cm (lower)). **f**, The reflective spectra of colored dual-selective emitters with red, yellow, and blue colors, respectively. Reproduced with permission from Ref.³⁹, © Wu, X. K. et al. 2024. **g, h**, The cross-sectional SEM images of photonic crystal structures with "hot" (g) and "cold" (h) modes. **i**, The visible spectral response of "hot" (red curve), "cold" (blue curve) photonic structures, pink paint (purple dash), and black paint (black dash), respectively. Reproduced with permission from Ref.¹⁶⁹, © Li, W. et al. 2018. **j**, Photos of blue, green, and red CNC films (upper) and red CNC films (lower). Reproduced with permission from Ref.¹⁷⁰, © Wiley-VCH GmbH 2022. **k**, Schematic of photoluminescent colorant compensate mechanism with CA films. Reproduced with permission from Ref.¹⁷¹, © Science China Press 2022.

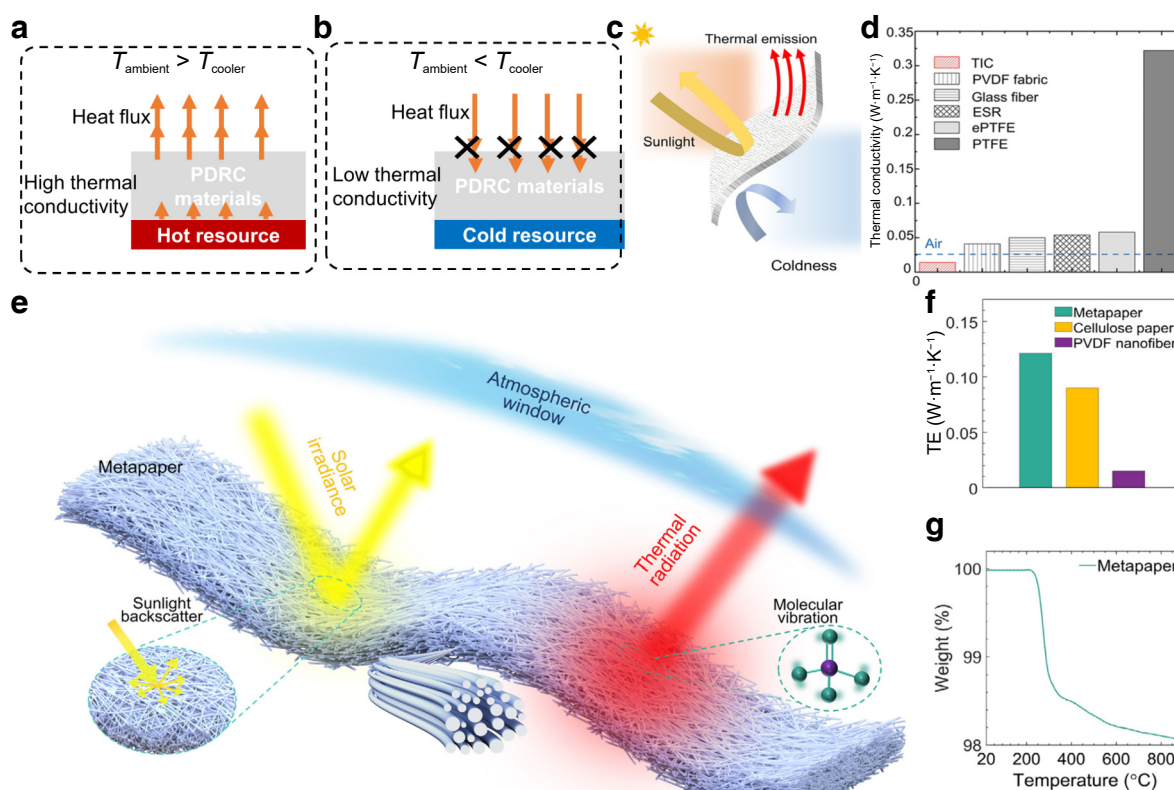


Fig. 12. Heat transfer characteristics and thermal stability. **a, b**, Schematics of heat transfer command for the hot resource (a) and cold resource (b). **c**, Schematic of the cooling mechanism of the insulated PDRC film. **d**, Thermal conductivity of insulated film (thermal insulating cooler (TIC)) and controlled samples. Reproduced with permission from Ref.¹⁷⁷, © American Chemical Society 2021. **e**, Schematic of structure and radiative cooling mechanism of metapaper. **f**, Thermal conductivity of metapaper with controlled samples. **g**, Thermogravimetric (TG) curves of the metapaper. Reproduced with permission from Ref.¹⁷⁸, © Elsevier Ltd. 2022.

$0.12 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$, higher than cellulose paper and PVDF film (Fig. 12f), owing to the superior thermal dissipation capability of inorganic HAP. Additionally, the film demonstrated thermal stability exceeding 900°C thanks to the stability of HAP fibers (Fig. 12g). Under sunlight exposure, the film achieved a sub-ambient temperature drop of $\sim 5.1^{\circ}\text{C}$ and generated a cooling power of $104 \text{ W}\cdot\text{m}^{-2}$. Furthermore, its inorganic composition rendered the film fire-resistant compared to wood. Even after being ignited by a blue torch for 15 s, the film retained its initial stage while the wood was destroyed, underscoring its safety for building applications.

4 PDRC materials for personal thermal management

Human body thermal management is a hot issue for frequent extremely high-temperature weather¹⁸⁰. Hot stress threatens human lives, especially for low-income people and underprivileged groups like young children, pregnant women, and the elders over 65 years old. For people who work outdoors, continuous exposure to hot waves induces many diseases and even deaths^{180, 181}. However, there is still a lack of efficient cooling technology to construct a heat shield for human bodies. Since PDRC technology was developed, researchers combined RC with textiles for long-term and high-performance cooling based on strong thermal radiation¹⁸².

4.1 Spectral design of PDRC textiles

Frequent high-temperature weather caused by global warming makes people need to cool down the surrounding sub-environment¹⁸³. However, the use of air conditioning will further

aggravate the trend of global warming. There is also a lack of an effective and feasible way to cool down the human body outdoors. These greatly limit human activities in high-temperature conditions. Therefore, research on personal thermal management is extremely important. Unlike building thermal management, the goal of personal thermal management is to heat or cool only the human body and its surroundings without wasting excess energy on heating or cooling the entire building. Since the thermal mass of the human body is much smaller than that of the entire building, this approach should lead to higher energy efficiency (thermal radiation is the main way the human body dissipates heat, accounting for 40%–60% of the total heat dissipation)^{184, 185}.

Incorporating cooling and zero-energy consumption properties into widely used textiles through PDRC technology is expected to provide human comfort in high-temperature indoor and outdoor environments while significantly reducing the use of traditional energy-consuming equipment such as air conditioners. This helps achieve net zero carbon and sustainability, demonstrating its huge application potential in personal thermal management.

In the past decade, various PDRC textiles have been developed for cooling the human body. Based on their cooling mechanisms, these textiles can be broadly classified into three groups: transmission-type PDRC textiles designed for indoor human body cooling (with high transparency to human heat, see Fig. 13a)^{53, 57, 93}, emission-type PDRC textiles tailored for outdoor human body cooling (with a high absorptivity/emissivity for human heat, see Fig. 13b)^{33, 186–188}, and hybrid-type PDRC textiles intended for all-weather human body cooling (with high absorptivity/emissivity in

the ATW waveband and high transmission in the remaining LWIR wavebands, see Fig. 13c)⁹⁴.

4.1.1 Transmission-type PDRC textiles

At a normal skin temperature of 34 °C, the human body emits infrared radiation within the range of 7–14 μm , which conveniently aligns with the atmospheric transparency window (8–13 μm)¹⁸⁹. When clothing fabrics are constructed from materials that are transparent to infrared radiation, they can harness the body's inherent infrared emission to facilitate the exchange of thermal energy between the body and the outer layers of the atmosphere, including the cosmic space. During hot summers, such infrared-transparent fabrics can effectively achieve PDRC¹⁹⁰. However, conventional cotton fabrics currently lack the property of infrared transparency. Additionally, infrared-transparent fabrics should also possess characteristics such as breathability and moisture-wicking functionality.

To fully harness the advantages of human skin as an infrared emitter for achieving cooling effects, Hsu et al. developed a nanoporous PE (nanoPE) material, characterized by nanoscale pores ranging from 50 to 1000 nm, rendering PE with an opaque property to the human eye while maintaining a high transmittance in the infrared region (Figs. 14a and 14b)⁵⁷. Furthermore, for industrial-scale production and convenience in wearing, Peng et al. extruded nanoPE fibers using an industrial approach for textile manufacturing (Fig. 14c)⁹³. Fabrics containing these fibers exhibited remarkable RC effects and demonstrated both knitted and woven radiation-cooling textiles. Individuals wearing nanoPE fabric experienced an increase in the set-point by 2.3 °C while maintaining thermal comfort equivalent to those wearing cotton clothes. Current radiation-cooling textiles are limited to white coloration, necessitating a broader range of colors for everyday wear. Building upon this, Cai et al. utilized inorganic nanoparticles such as Prussian blue, iron oxide, and silicon as coloring agents to produce colored mid-infrared (MIR) transparent radiative cooling

textiles (Fig. 14d)⁵³. Even with the addition of various colors, compared to cotton, these radiative cooling textiles passively cooled human skin by 1.6–1.8 °C.

It is crucial to manage the heat from outdoor sunlight to address the issue of human infrared thermal radiation control within the mid-infrared spectrum and maximize the effectiveness of RC. Solar radiation spectrum primarily encompasses ultraviolet, visible, and near-infrared bands. The combined heat from the visible and near-infrared bands accounts for approximately 0.934 of solar irradiance. Therefore, blocking the heat from these bands can effectively mitigate most of the solar heat. Developing a textile capable of reflecting visible and near-infrared light significantly while maintaining transparency to human infrared radiation can achieve more efficient cooling. Cai et al. proposed a novel spectral-selective nanocomposite textile, employing nanoPE embedded with zinc oxide nanoparticles (ZnO-PE), for outdoor radiative cooling (Fig. 14e)⁵⁴. By reflecting over 90% of solar irradiance and selectively transmitting human body heat radiation, this textile can prevent overheating by 5–13 °C compared to ordinary textiles like cotton under peak sunlight conditions. The authors also demonstrated the feasibility of manufacturing ZnO-PE fibers, which can be knitted/woven into practical textiles, enhancing durability. However, further improvements are needed in the wearability of nanoPE. Here, Hu et al. proposed a bilayer anisotropic wettability nanoPE (BAW-nanoPE) which could efficiently combine RC with sweat evaporation with or without perspiration (Fig. 14f)¹⁹¹. By modifying the surface of nanoPE, the material exhibited excellent RC capability (approximately 2.6 °C lower than cotton) and outstanding wearability. This demonstrates the greater potential for the application of nanoPE textiles.

In order to simultaneously achieve high reflectance in the visible and near-infrared spectra and high transmittance in the mid-infrared spectrum for RC applications, while avoiding the use of composite inorganic oxides, Liu et al. developed shish-kebab superstructure thin films¹⁹². These films exhibit high infrared

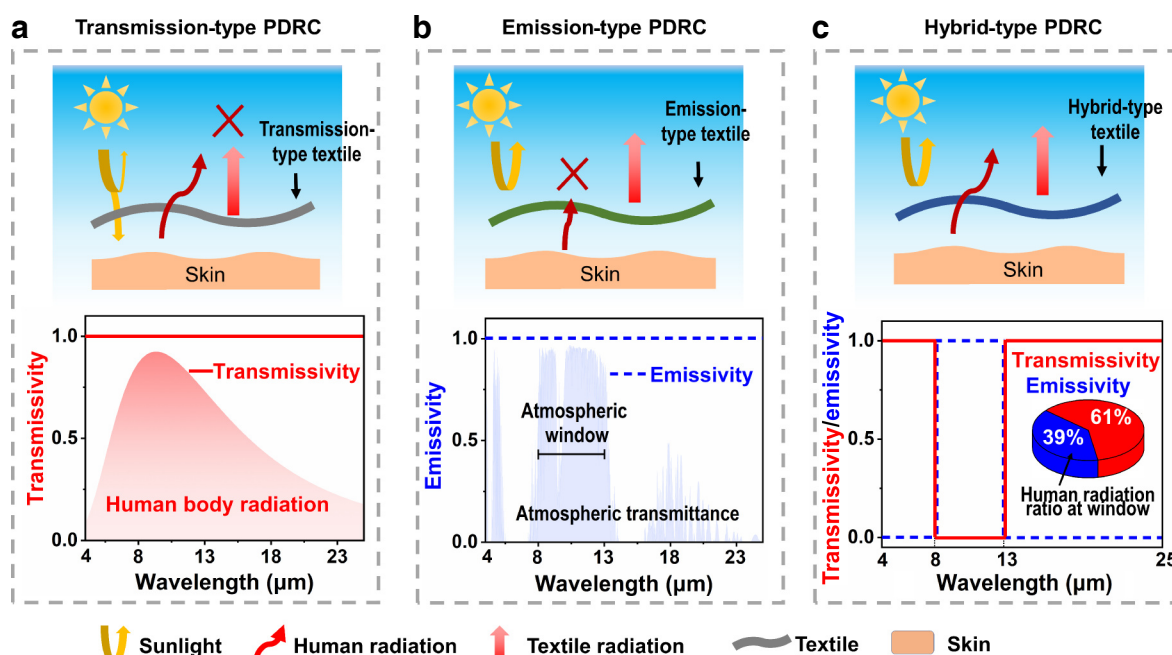


Fig. 13. Main types of PDRC textile materials. a, Transmission-type PDRC textile materials. b, Emission-type PDRC textile materials. c, Selective emission–transmission-type PDRC textile materials.

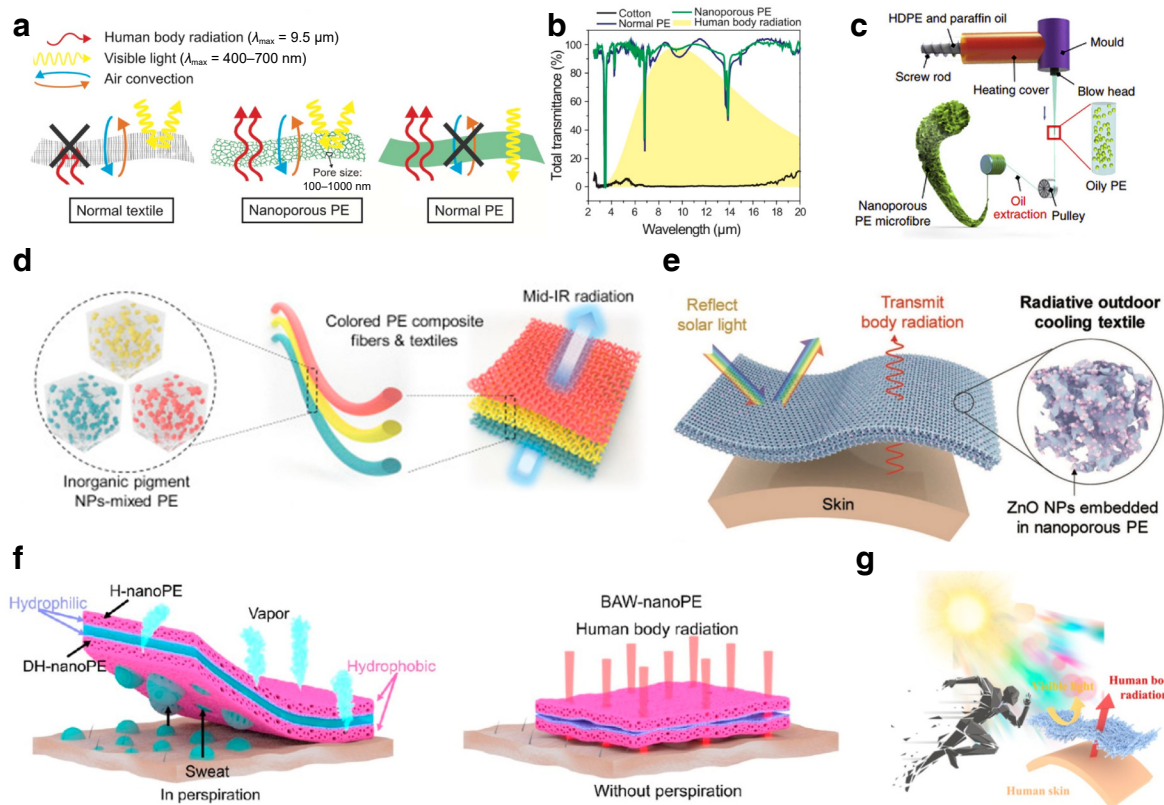


Fig. 14. The transmission-type PDRC textiles. a, Schematics of comparison between nanoPE, normal PE, and cotton. Only nanoPE satisfies IR transparency, visible light opacity, and air convection simultaneously. b, Measured total Fourier transform infrared (FTIR) transmittance of nanoPE, normal PE, and cotton. Reproduced with permission from Ref.³⁷, © American Association for the Advancement of Science 2016. c, A schematic diagram of the manufacturing process for the nanoPE microfibre. Reproduced with permission from Ref.⁹³, © Macmillan Publishers Limited, part of Springer Nature 2018. d, Design schematic for the coloration of RC textiles, which is made by mixing IR-transparent inorganic pigment nanoparticles with PE. The mixed composites can then be extruded into continuous fibers for knitting into interlaced textiles via large-scale industrial processes. Reproduced with permission from Ref.⁵³, © Elsevier Inc. 2019. e, Schematic of the ZnO nanoparticle-embedded nanoPE textile. Its spectrum was designed to be transparent for the human body's thermal radiation and reflective of sunlight. Reproduced with permission from Ref.⁵⁴, © WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim 2018. f, Schematic diagrams of BAW-nanoPE. Reproduced with permission from Ref.¹⁹¹, © American Chemical Society 2022. g, Schematic of shish-kebab superstructure films. Reproduced with permission from Ref.¹⁹², © American Chemical Society 2023.

transmittance (0.87) and improved solar reflectance (0.83) (see Fig. 14g). By employing a skewer-like nanostructure design, the polyethylene material achieved solar reflectance. The outdoor and indoor testing of the shish-kebab thin film conducted in the study revealed temperature reductions of 2.5 and 2.6 °C, respectively, compared to conventional textiles.

4.1.2 Emission-type PDRC textiles

Utilizing materials with high transmittance in the mid-infrared spectrum, such as nanostructured polyethylene, maximizes the efficacy of human skin's high emissivity¹⁹⁵. However, when the thickness of the fabric exceeds 150 μm , it no longer maintains sufficient transmittance in the mid-infrared region⁹⁴. The comfort of a fabric is to some extent directly proportional to its thickness; in other words, maintaining the mid-infrared transmittance of PE fabric contradicts its commercial comfortability. In contrast, mid-infrared emissive textiles do not encounter such constraints. When the material is opaque to mid-infrared and possesses high emissivity characteristics, the fabric acts as an infrared emitter, enabling radiative cooling.

The performance of mid-infrared emissive textiles is independent of human skin's emissivity, thus relaxing the restrictions imposed by thickness. Consequently, there is an urgent need to manufacture fabrics that exhibit high reflectance in the

visible and near-infrared spectra while maintaining high emissivity in the mid-infrared spectrum^{196, 197}. Zeng et al. designed a multi-layer metafabric composed of composite microfibers, with each layer consisting of titanium dioxide-poly(lactic acid) (TiO₂-PLA) laminated with PTFE (Fig. 15a)³³. This meta-fabric exhibited a high LWIR emissivity (0.945) while maintaining a high reflectivity (0.924) in the solar spectrum, indicating an excellent RC performance (Fig. 15b). Compared with traditional cotton fabrics, the human body covered with meta-fabric could lower by approximately 4.8 °C. Additionally, its hydrophobic surface demonstrated an outstanding waterproof property. The woven structure enabled it to easily adapt to complex deformations (bending, stretching, and twisting) to achieve multifunctional compatibility. Except for artificial fabrics, many natural fabrics inherently possess high solar reflectivity and emissivity in the LWIR spectrum, such as silk, which can be modified to achieve the desired effect of excellent radiative cooling. Zhu et al. utilized a reagent-assisted dip-coating method to attach Al₂O₃ particles to natural silk and formed nanoengineered silk. The band gap Al₂O₃ particles compensate UV absorption by protein silk, thus increasing the UV reflectance from 0.70 to 0.85 and developing the overall solar spectrum reflectance from 0.86 to 0.95 (Fig. 15c)¹⁸⁶. While maintaining the wearability and durability of silk, it resulted in a temperature reduction of approximately 3.5 °C.

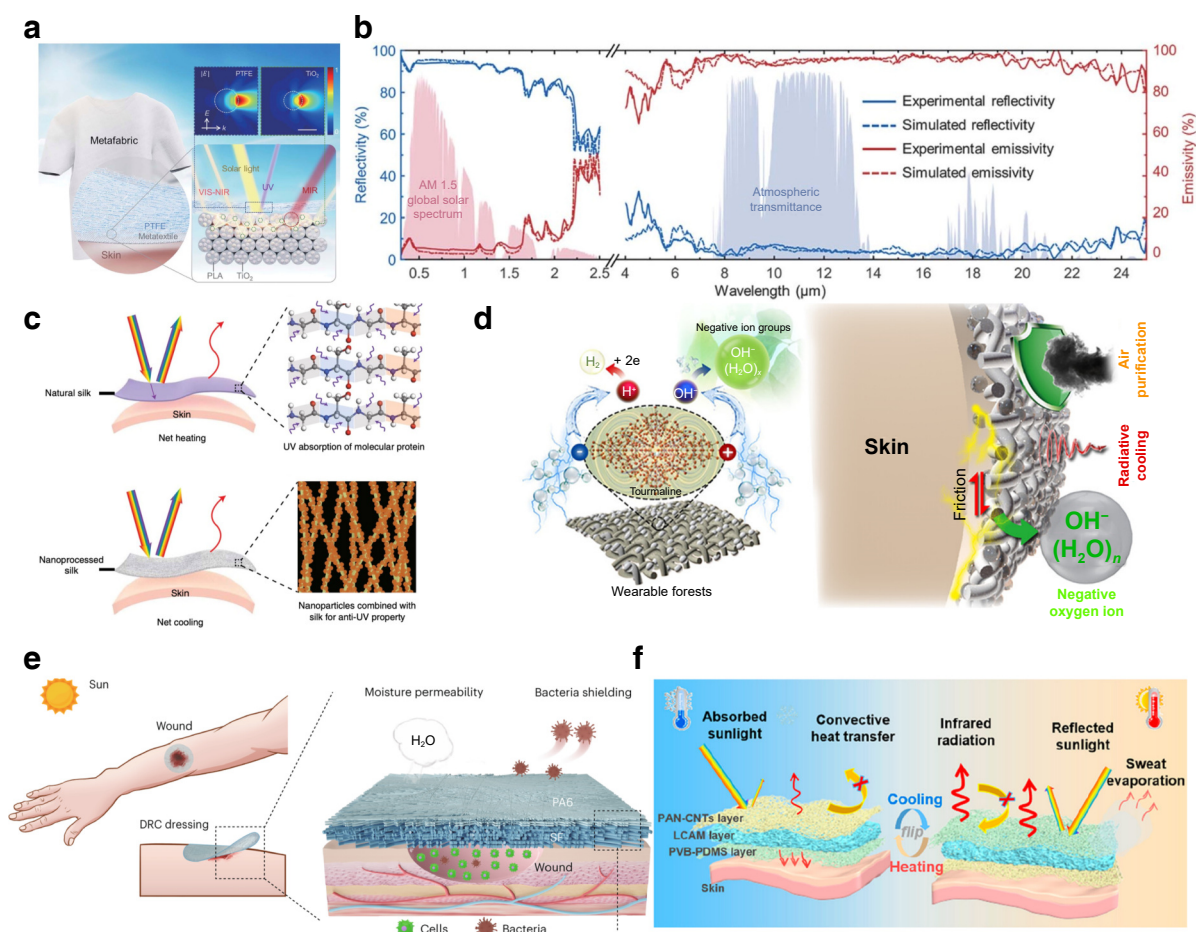


Fig. 15. Emission-type PDRC textile materials. **a**, Schematic of a metal fabric for daytime radiative cooling. **b**, Measured reflectivity and emissivity spectra of the metafabric (0.3 to 25 μm). Reproduced with permission from Ref.³³, © Zeng, S. N. et al. 2021. **c**, Schematic of the net heating performance of natural silk and nano-processed silk. Reproduced with permission from Ref.¹⁸⁶, © Zhu, B. et al. 2021. **d**, Schematic showing the wearable forest-like textile releasing negative ion groups. Reproduced with permission from Ref.¹⁹³, © American Chemical Society 2023. **e**, Schematic figure of the radiative cooling dressings for accelerating wound healing. Reproduced with permission from Ref.⁶⁸, © Zhang, Q. et al. 2024. **f**, Schematic of HNF textile. Reproduced with permission from Ref.¹⁹⁴, © American Chemical Society 2023.

To enhance the solar reflectance of fabrics, it is also possible to regulate the micro-nanostructure of organic fibers except for adding inorganic pigments. Chen et al. proposed a “wearable forest-like textile” based on helical lignocellulose-alanine composite fibers, which exhibited mechanical strength superior to cellulose-based fibers and natural microfibers, as well as excellent PDRC performance (Fig. 15d)¹⁹³. Compared with traditional textiles, it was cooler approximately 8.2 °C. The surface of textiles generated negative oxygen ions from vaporized sweat by an electric field caused by tourmaline’s spontaneous polarization effect, where the concentration was even higher than in a natural forest. Zhang et al. developed a daytime radiative cooling dressing based on a bilayer of polyamide silk fibroin molecules, which can reduce the thermal load on skin wounds under sunlight exposure (Fig. 15e)⁶⁸. The combination of mid-infrared transparent polyamide and biocompatible silk fibroin exhibited a high-infrared emissivity (~ 0.94) and a sunlight reflectivity (~ 0.96), achieving temperatures approximately 7 °C lower than ambient temperature under direct sunlight. Xia et al. successfully manufactured cooling patches by combining biodegradable silk fibroin with boron nitride nanosheets^{68, 198} and high thermal dissipation ability (inner surface 27.58 $\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ and outer surface 1.77 $\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$), achieving significant simulated skin temperature reductions of approximately

2.5 and 8.2 °C under outdoor and indoor conditions, respectively. The membrane demonstrated excellent biocompatibility which can be recycled and reused for at least three months.

Through nanostructural design, PDRC fabrics can exhibit both cooling and insulation effects in extreme environments of high temperatures and cold. Gu et al. designed a hierarchically nanofiber (HNF) textile consisting of an RC layer (PDMS), an intermediate thermal barrier layer (porous lignocellulose aerogel film), and a radiative heating layer (polyacrylonitrile (PAN) with added carbon nanotubes (CNTs)) (Fig. 15f)¹⁹⁴. In hot environments, the temperature of HNF textiles can be reduced by 7.2 °C compared to white cotton, while in cold environments, they are 12.2 °C warmer than black cotton.

4.1.3 Selective emission–transmission-type PDRC textile materials

The discussion above focuses on two types of PDRC textiles: those primarily used for indoor environments, referred to as transmissive textiles, and those typically employed outdoors, termed emissive textiles. The selective emission–transmission-type PDRC textiles are a kind of textiles capable of exhibiting excellent cooling performance both indoors and outdoors when worn on the human body. In such a scenario, enabling emissive textiles to achieve the same cooling performance indoors as transmissive PDRC textiles

becomes crucial. The key is to find a heat transfer pathway that allows heat to effectively dissipate indoors. Traditional emissive textiles, due to their high absorption (i.e., high emissivity) across the entire mid-infrared spectrum, cannot effectively dissipate heat indoors without exchanging heat with the cosmic space¹⁹⁹. Similarly, they face challenges in overcast outdoor conditions^{200–202}. Therefore, there is a need to design PDRC textiles capable of supporting high cooling performance in various outdoor (including sunny and cloudy conditions) and indoor environments. This can be achieved by precisely adjusting materials across multiple spectral bands (including atmospheric windows, non-mid-infrared, and solar bands), leveraging the advantages of both emissive and transmissive operation modes (see Fig. 16a).

Wu et al. designed a polyoxymethylene (POM) nanotextile that incorporates a hybrid heat dissipation mechanism between emissive and transmissive modes, enabling the human body to cool unaffected by environmental (indoor and outdoor) conditions (Fig. 16b)⁹⁴. According to Mie scattering theory, Wu et al. designed the POM nanofiber structure. The POM textile exhibited a selective

emissivity of 0.757 in the 8–13 μm band (with a high selectivity of 1.67, the ratio of average emissivity in the 8–13 μm band to that in the 4–25 μm band) and a solar reflectivity of 0.946 in the 0.3–2.5 μm band (Fig. 16c). Compared with typical transmissive, emissive, and commercial cotton textiles, the POM textile demonstrated significantly enhanced radiative human body cooling performance. Field tests had shown that our POM textile-based health hazard protective clothing outperformed similar commercial products in cooling performance under sunny outdoor conditions (cooling by 5.4 $^{\circ}\text{C}$), overcast outdoor conditions (cooling by 1.3 $^{\circ}\text{C}$), and indoor environments (approximately 1.0 $^{\circ}\text{C}$) (Fig. 16d). Additionally, the POM textile exhibited good breathability, high tensile strength, and excellent performance under high humidity conditions.

4.2 Real applications for PDRC human thermal management materials

When being applied in real-world scenarios, PDRC textiles still encounter a gap between conception and large-scale application. A

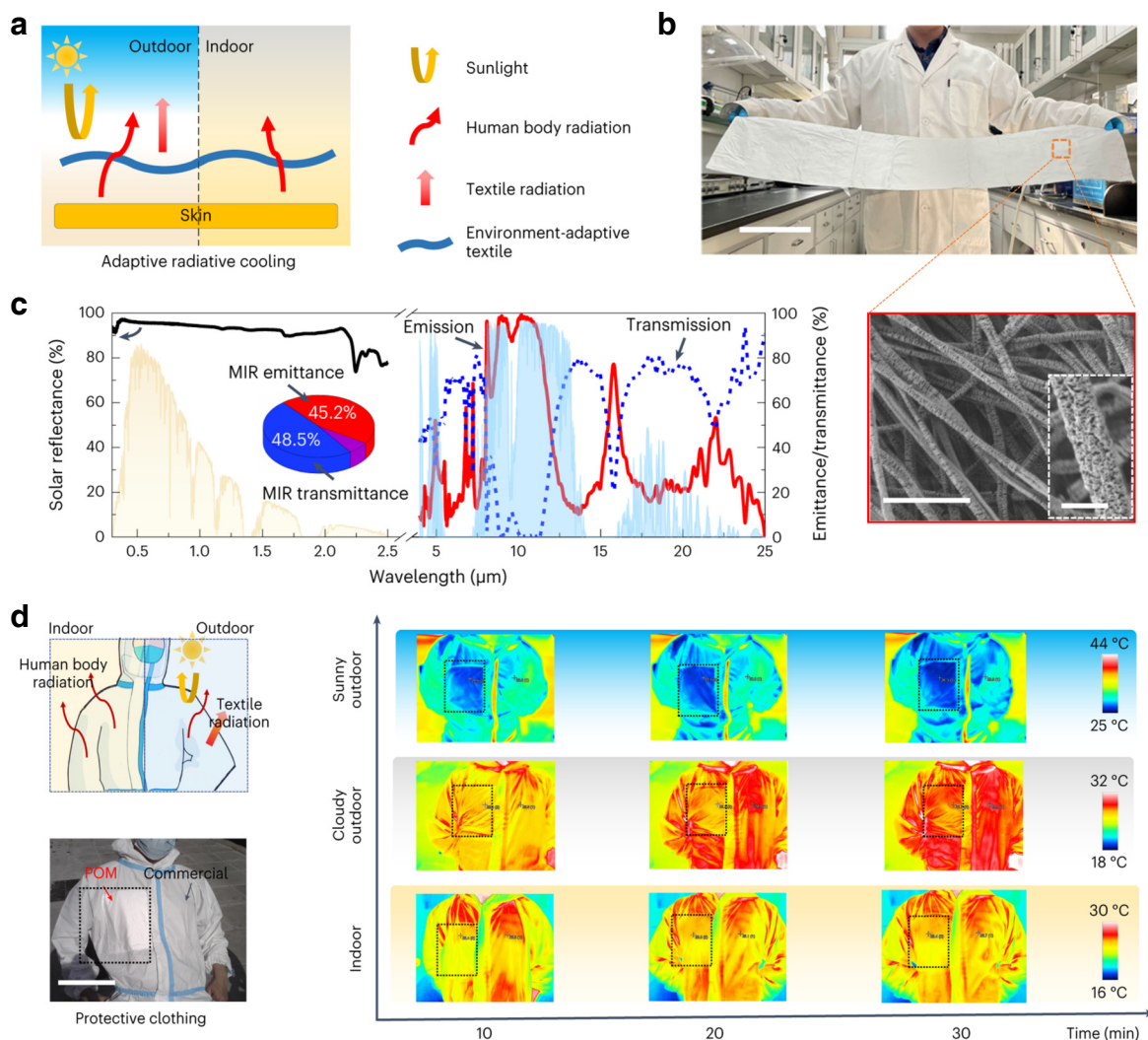


Fig. 16. Selective emission-transmission-type PDRC textile materials. **a**, Schematic of the textile design that featured adaptive human body radiative cooling. **b**, Photograph of the synthesized POM textile. **c**, Spectral response of a ~260- μm -thick POM textile in the 0.3–25 μm wavelength range, including solar reflectance (black line), MIR emissance (red line), and MIR transmittance (blue line). **d**, Infrared images of the person wearing the protective clothing in sunny outdoor (16 May, 2022), cloudy outdoor (17 May, 2022), and indoor (17 May, 2022) environments in Beijing, China (40°0'33" N, 116°20'0.6" E). Reproduced with permission from Ref.⁹⁴, © Wu, X. K. et al. 2023.

rigorous rule was set up for fabrics, including wearability, breathability, fragility, mechanical strength, hydrophilicity, water-vapor permeation, etc. A PDRC textile should take wearable comfort, practicality, and durability into serious consideration for personal thermal management comprehensively²⁰³.

4.2.1 Fabric material evaluation index

In addition to spectral testing and outdoor experiments to evaluate the PDRC performance of fabrics, quantitative analysis of fabric performance is essential for PDRC textiles to be industrially produced and applied in commercial clothing.

In 2016, Hsu et al. first developed polydopamine (PDA)-nanoPE-mesh (Fig. 17a) and evaluated its performance as a fabric using four indicators: water vapor permeability, air flow rate, core absorption distance, and tensile strength, with commercial cotton fabric as the standard (Figs. 17b–17e)⁵⁷. Subsequently, almost all research studies have adopted this evaluation standard, measuring whether the produced fabric meets the standard through these four main indicators. Zeng et al. designed a multi-layered super fabric with an upper layer for water transport and a lower layer for hydrophilicity (Fig. 17f)³³. Therefore, they developed a special device filled with water in the upper layer and air in the lower layer, evaluating the fabric's high air permeability even under waterproof conditions through the direction of bubbles, which facilitated heat exchange

(Fig. 17g). In addition to adopting the four indicators, Wu et al. also added an assessment of the fabric's resistance to moisture by evaluating the change in contact angle over time for different types of radiative cooling fabrics (Fig. 17h)⁹⁴. Furthermore, evaluation criteria for radiative cooling fabrics include washability, resistance to intense ultraviolet radiation, outdoor exposure stability, and high abrasion resistance (Figs. 17i–17l).

4.2.2 Industrialization and application of PDRC textiles

The industrialization and application of PDRC textiles have made significant progress, enabling large-scale production and integration into people's daily lives, thereby providing convenience for humanity (Fig. 18a)³³. Additionally, depending on the materials used, PDRC textiles can exhibit various special functionalities, expanding their application scope. The multi-layered nanofiber (HNF) textiles designed by Gu et al. possessed outstanding self-cleaning capabilities on the RC surface due to the ultra-hydrophobicity ($> 163^\circ$) of the poly(vinyl butyral) (PVB)-PDMS side. Additionally, these textiles exhibit directional sweat dispersion capabilities (Fig. 18b)¹⁹⁴. Upon contact with the hydrophobic PAN-CNT surface, sweat is rapidly absorbed by the hydrophilic lignocellulose aerogel membrane (LCAM) layer (in approximately 4.2 s), indicating excellent directional sweat functionality. This

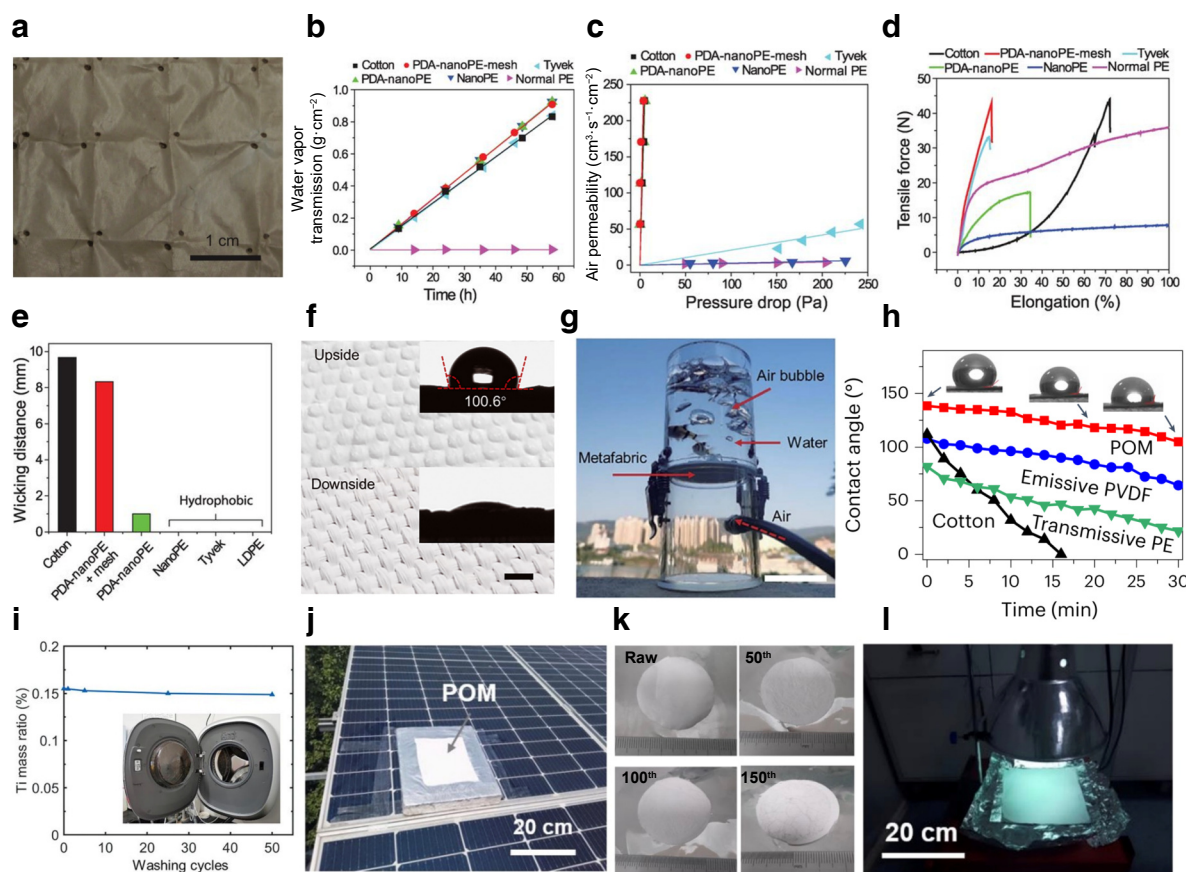


Fig. 17. The standard index of wearable PDRC textiles. a, Photo of PDA-nanoPE-mesh. b, The water vapor transmission rate test shows how human perspiration can be transmitted through the textile. c, The air permeability test examines the air flow rate through the textile at certain pressure drops. d, Wicking distance shows the ability to transport perspiration for quick evaporation. e, The tensile strength test demonstrates that PDA-nanoPE-mesh has the same ultimate tensile strength as that of cotton. Reproduced with permission from Ref.⁵⁷, © American Association for the Advancement of Science 2016. f, Morphologies of the upper and lower surfaces of the metafabric. Scale bar, 1 mm. g, Demonstration of the waterproofness and breathability of the metafabric. Scale bar, 5 cm. Reproduced with permission from Ref.³³, © Zeng, S. N. et al. 2021. h, Water contact angle versus time. i, Washability. j, Outdoor exposure stability. k, High abrasion resistance. l, Resistance to intense ultraviolet radiation. Reproduced with permission from Ref.⁹⁴, © Wu, X. K. et al. 2023.

enables rapid evaporation of sweat and prevents sticky and overheated sensations (Fig. 18c). Furthermore, Dong et al. developed a fabric with an electromagnetic interference (EMI) shielding function (Fig. 18d)²⁰⁴. The white thermoplastic polyurethane (TPU)/PDMS side and the black silver nanowire (AgNW)/MXene side enable PDRC and heating of the fabric, respectively. The cooling side exhibits high LWIR emissivity (97.5%) and solar reflectance (90%), thereby reducing skin temperature by approximately 4.9 °C. The heating side with a high solar absorption rate (86.6%) and photothermal effect increases skin temperature by approximately 5 °C. The EMI shielding

performance of this fabric is achieved through AgNW/Ti₃C₂T_x MXene network, showing a stretchable EMI shielding performance of over 40 dB.

Moreover, the color variety of PDRC textiles can be expanded. Research by Cai et al. demonstrated that using inorganic oxide pigments allowed for the production of textiles in nearly all colors while maintaining radiative cooling efficiency (Fig. 18e)⁵³. The “wearable forest-like textile” capable of generating approximately 18,625 negative ions per cubic centimeter was introduced by Chen et al. (Fig. 18f)¹⁹³. This textile exhibits effective particle purification properties. Moreover, the negative ion environment has the

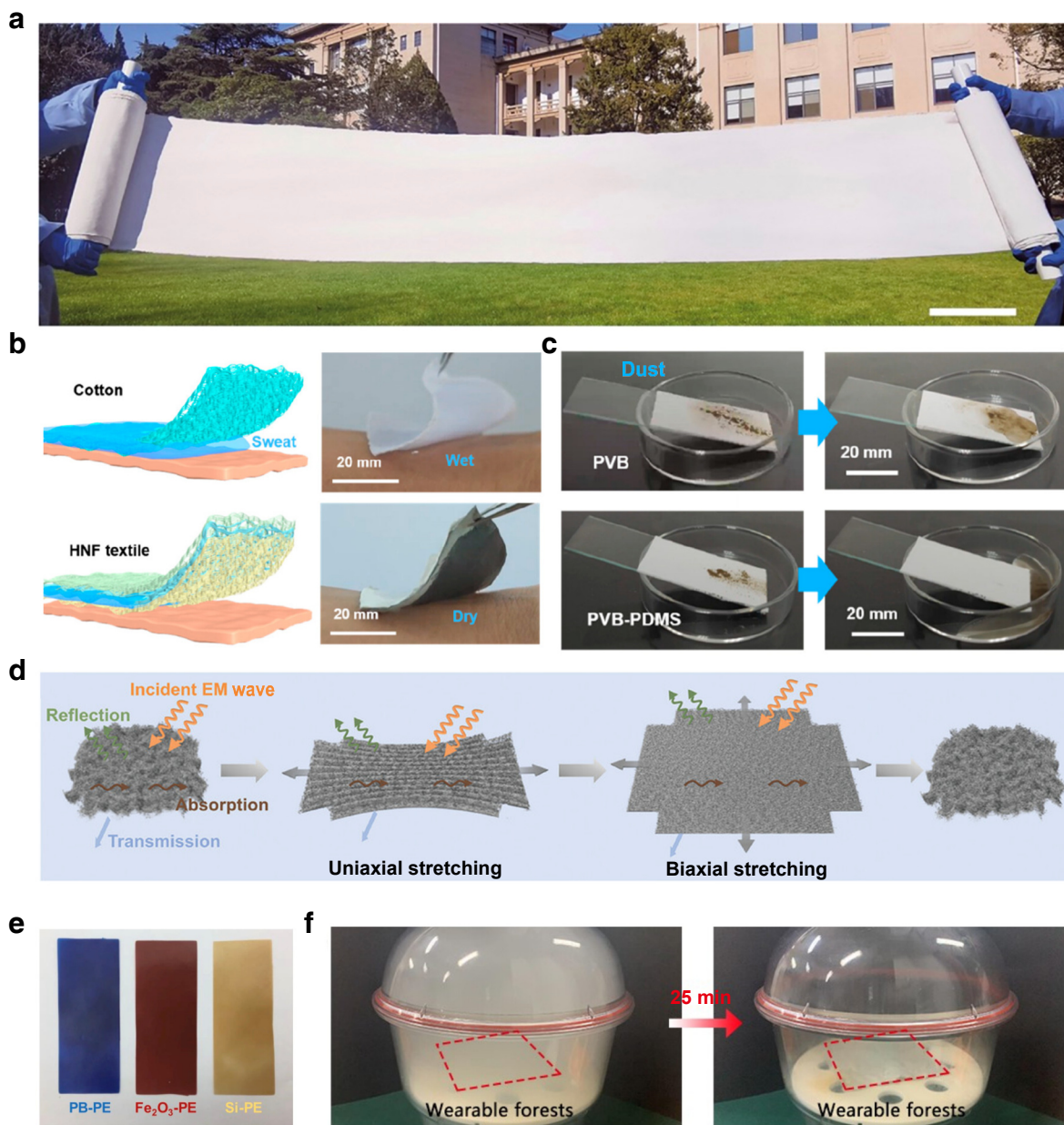


Fig. 18. Industrialization and application of PDRC fabrics. **a**, Fabrication process of the metafabric. Reproduced with permission from Ref.³³, © Zeng, S. N. et al. 2021. **b**, Schematics and on-skin sweat absorbance of cotton (up) and the HNF textile (down). Antigravity directional perspiration. **c**, Self-cleaning test of PVB and the PVB-PDMS with dust as a pollutant. Reproduced with permission from Ref.¹⁹⁴, © American Chemical Society 2023. **d**, Mechanism schematics of the stability of EMI shielding properties during stretching of A625M625 fabric. Reproduced with permission from Ref.²⁰⁴, © Wiley-VCH GmbH 2023. **e**, Photograph of the pigment nanoparticle-mixed polyethylene composite films. Reproduced with permission from Ref.⁵³, © Elsevier Inc. 2019. **f**, Demonstration of the smog-removing performance of the wearable forest-like textile. Reproduced with permission from Ref.¹⁹³, © American Chemical Society 2023.

potential to neutralize free radicals, thereby offering promising effects in delaying fruit decay and suggesting benefits for aging prevention. This textile holds promise for enhancing human health.

In conclusion, in these researches on PDRC textiles, the process for industrial-scale production of such fabrics has been demonstrated, along with various functional studies. These studies have significantly expanded the application scenarios of PDRC textiles in human life, enhancing the possibility of PDRC textiles entering industrial production processes and becoming part of real-life applications. It also demonstrates the potential commercial value of PDRC textiles.

5 PDRC materials for water harvesting

Freshwater storage has emerged as one of the most pressing global challenges due to global warming and water source pollution^{25, 205}. Moisture evaporated from oceans, rivers, lakes, and other bodies forms the Earth's water system, which is evaluated to hold 13,000 trillion liters of water, representing 10% of the world's total freshwater reserve^{206, 207}. Hence, effective utilization of atmospheric water sources with minimal energy consumption is therefore crucial²⁰⁸. Achieving water harvesting hinges on reducing the surface and internal temperature of materials to the dew point to promote condensation^{209, 210}. Consequently, the development of high-performance PDRC materials, which can lower the temperature without any energy consumption, has attracted significant research interest²¹¹.

Researchers initially used heat dissipation in the LWIR regions and high solar transmission to achieve solar-powered seawater desalination, producing freshwater (Fig. 19a)²¹². However, oceanic water is scarce in many regions, necessitating the exploration of alternative water sources and innovative water harvesting techniques.

Recently, PDRC materials have been developed to capture atmospheric moisture during the daytime, a significant advancement for water-scarce areas¹⁷³. These materials, as shown in Fig. 19b, are designed to exhibit high solar reflectivity and high emissivity in LWIR regions, enabling them to achieve sub-ambient temperatures and condense moisture²¹². In 2021, Poulidakos et al. designed a system capable of round-the-clock atmospheric water harvesting, combining radiative shielding and cooling with a fully passive condensate harvester⁶⁶. This system provided relatively high solar reflectivity for daytime cooling and a multi-layer structure for selective IR emission to dissipate condensation to outer space (Figs. 19d–19f), resulting in a high water-harvesting storage speed of 28.6 g·h⁻¹. However, it's worth noting that broadband IR emitters alone are insufficient. In 2020, Bao et al. proposed a durable enhanced specular reflector-metal (DESR-M) with a simple hydrophilic PTFE coating²¹¹, achieving a selective emissivity of 84.0% in the 8–13 μm waveband and an 88.1% improvement in dew yield compared to a single PTFE coating.

Researchers have also found that the microstructure and hydrophilicity of PDRC materials are crucial for improving the efficiency of water harvesting²¹⁸. For instance, in 2022, Li et al. designed a cellulose network with a high-aspect-ratio for water adsorption, finding that high hydrophobicity of PDRC materials was more beneficial for water capture and storage (Fig. 19c)²¹³. This design achieved a water uptake of 1.29 kg·kg⁻¹ during the night due to the high PDRC performance of the cellulose sample.

Additionally, many other polymer-based PDRC materials have recently shown to have great potential for water harvesting, such as polystyrene films and cellulose acetate²¹⁹.

Great efforts have also been made to alleviate water scarcity in arid regions, which greatly increased the application potential of PDRC materials. In 2022, Wang et al. achieved significant condensation even under low humidity conditions. As shown in Figs. 19g–19k, they achieved an excellent water harvesting capacity of 2.62 g·g⁻¹ even in arid conditions by utilizing devices constructed by a super-hydrophilic inside matrix loaded with deliquescent sorbents, superhydrophobic, elastic fibrous skin, and water leakage prevention²¹⁴. This delicate design could simultaneously achieve radiative cooling, heterogeneous wettability, and elasticity-induced adaptivity, thus realizing water harvesting under arid conditions. Moreover, Ahamd et al. designed a vertical double-sided architecture for the water-harvesting, which could effectively enhance the local power density and thus increase the water collection in both humid and arid regions²¹⁵.

6 PDRC materials for photovoltaic (PV) cooling

PV systems can convert solar energy directly into electricity in a clean way, making them one of the most promising clean solutions to the world's energy problems^{222, 223}. However, the efficiency of these commercial PVs (~ 25%) is limited by the ultrahigh work temperatures of PV panels (beyond 40 °C) due to their high solar absorption (above 0.9). As the temperature of the solar cells increased, their photo-electric conversion efficiency decreased by approximately 0.4–0.5 %·°C⁻¹^{224, 225}. Therefore, the cooling of solar cells is of great significance in improving PV performance and thus contributing to the alleviation of the energy crisis.

In recent years, integrating PDRC materials with PV systems has been proven to be an efficient and sustainable strategy that can significantly reduce PV temperatures by promoting heat dissipation in LWIR regions, particularly in the ATW waveband (8–13 μm), thereby increasing energy efficiency and lifespan (Figs. 20a–20c)^{64, 226}. For instance, in 2015, Zhu et al. first proposed the concept of RC for solar cells and predicted a temperature drop of 18.3 °C using a periodic silica cooler with high transparency in solar the region and high emissivity in the LWIR region (Figs. 20d–20g)²¹⁶. Pei et al. introduced a full-spectrum strategy to enhance the PDRC performance of solar cells by integrating a spectral-selective LWIR cooler of grating silica to selectively block sub-bandgap photons, achieving a temperature drop of 7.1 °C and a photoelectric conversion efficiency increase of 38 mV of open-circuit voltage⁶⁵. The full-spectrum strategy was also used in photovoltaic–thermoelectric hybrid systems, which proved superior to the conventional hybrid system, not only in terms of higher efficiency (39.4%) but also in its ability to operate continuously for 24 h²²⁷.

In addition, more sophisticated multi-band spectral designs have recently been shown to better utilize the PDRC to further improve the performance of PVs. For instance, in 2017, Fan et al. designed a photonic cooler of ethylene-vinyl acetate joint interlayers that radiated heat through LWIR radiation emission while reflecting the solar spectrum in the sub-bandgap (1100–4000 nm) and the ultraviolet regimes (Figs. 20h–20j)²¹⁷. As a result, they achieved a significant reduction in PV temperature of over 5.7 °C and a photoelectric conversion efficiency increase, demonstrating the high

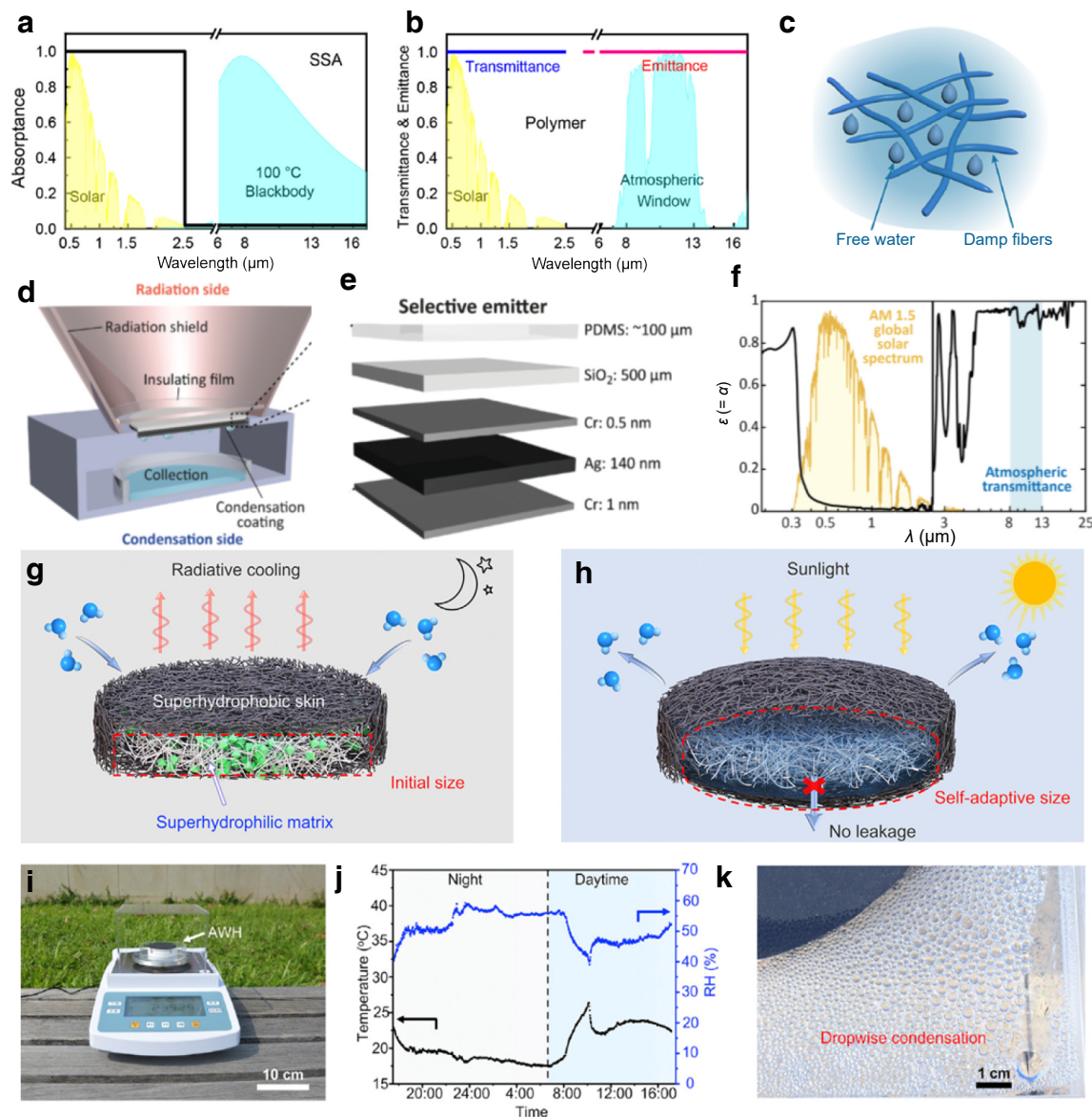


Fig. 19. PDRC materials for water harvesting. **a**, Typical spectral design of PDRC materials for water harvesting. Reproduced with permission from Ref.²¹², © American Chemical Society 2022. **b**, Schematic illustration for the optical response of PDRC materials with water harvesting. Reproduced with permission from Ref.²¹³, © American Chemical Society 2022. **c**, Schematic illustration of the water harvesting networks. Reproduced with permission from Ref.²¹³, © American Chemical Society 2022. **d**, Schematic illustration of a water harvesting device via radiative cooling. **e**, Construction of selective radiative emitters. **f**, Spectra response of the selective emitter. Reproduced with permission from Ref.⁶⁶, © Haechler, I. et al. 2021. **g**, **h**, Schematic illustration of the bio-inspired heterogeneous wetting water harvesting device for atmospheric water harvesting. **i**, The result of outdoor experiments. **j**, Schematic illustration for the double-sided design. **k**, Digital photos of the condensate. Reproduced with permission from Ref.²¹⁴, © Wang, Y. et al. 2022.

cooling performance of this design. Moreover, Lee et al. developed a light-trapping solar cell with a radiative cooler, further studying the relationship between the coolers with various types of solar cells. They achieved a temperature reduction of ~ 6 °C, compared with a conventional glass-mounted cooler with solar cells²²⁸. These results highlight the immense potential of PDRC in the field of solar energy conversions.

7 Self-adaptive radiative cooling materials

The above-discussed PDRC materials with a single cooling function can certainly reduce energy consumption in hot summers. However, their spectral responses are static and hard to modulate, but they can cause overcooling and increase heating energy

consumption in winter or during cold nights^{36, 46, 61, 220, 229–231}. To adapt to complex hot and cold environments encountered in real life, researchers have recently developed a series of radiative thermal regulation materials with dynamic cooling and heating/warming functions (i.e., self-adaptive radiative cooling materials). These self-adaptive materials represent a significant advancement in enhancing the practicality and sustainability of PDRC systems, especially in areas with four distinct seasons or large differences in daytime and nighttime temperatures.

Self-adaptive radiative cooling materials, categorized based on stimuli such as thermal, photon, and water^{152, 232}, offer passive modulation triggered by humidity, heating, and temperature changes. Irrespective of the above stimuli, current self-adaptive materials are designed to allow dynamic modulation of spectral

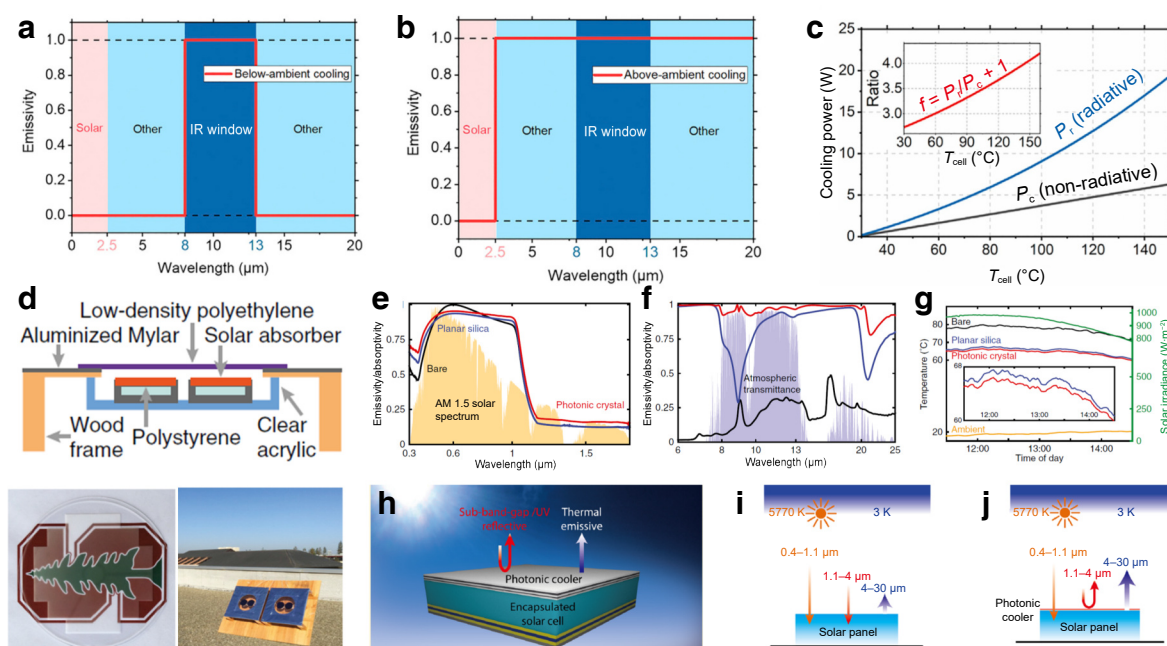


Fig. 20. PDRC materials for photovoltaic cooling. **a, b**, Spectral design of the radiative cooling materials for solar cells, including below-ambient cooling (**a**) and above-ambient cooling (**b**). **c**, Simulation result of cooling performance via radiative cooling technology. Reproduced with permission from Ref.⁶⁴, © Elsevier Inc. 2020. **d**, Schematic illustration of test equipment and digital photos of samples. **e**, Spectral performance in solar regions of solar cells with radiative coolers. **f**, Spectral performance in LWIR regions of solar cells with radiative coolers. **g**, Cooling performance of the solar cells with radiative cooling. Reproduced with permission from Ref.²¹⁶, © National Academy of Sciences 2015. **h**, Schematic illustration of the solar cell radiative cooling with the design in solar regions. **i, j**, Schematic illustration of the specific spectral design. Reproduced with permission from Ref.²¹⁷, © American Chemical Society 2017.

response in the solar and/or LWIR bands (e.g., solar reflectance, solar transmittance, and infrared emissivity). This allows them to maximize cooling performance in hot environments and shielding in cold environments, providing insulation and even heating²³³. For instance, in 2021, Wu et al. developed a temperature-adaptive radiative coating incorporating W-VO₂ as building roofs (**Fig. 21a**), enabling LWIR emissivity between 0.90 and 0.22 (**Figs. 21b** and **21c**). As a result, the W-VO₂ roof showed a great energy-saving potential of 2.64 GJ·year⁻¹ based on a roof area of 118 m². During the same period, Long et al. proposed a W-VO₂-based self-adaptive smart window that enabled LWIR emissivity between 0.61 and 0.21, while maintaining visible transparency and NIR modulation (**Figs. 21d** and **21e**)¹⁴⁵. This design ensured optimal indoor brightness throughout the year while adapting to varying environmental conditions for effective thermal management for energy saving up to 324.6 MJ·m⁻², compared with low-emission windows. In addition, Yan et al. developed a bilayer self-adaptive colored coating consisting of thermochromic dyes and PDMS on a super-white PTFE film, achieving a net cooling power of up to 70 W·m⁻² in a hot outdoor environment (with an ambient temperature of 50 °C) and heating power of 330 W·m⁻² under a cold condition with an ambient temperature of -10 °C (**Fig. 21f**)²²¹. They also validated that the self-adaptive coating could save 5%–44% of energy consumption in different climates, compared with commercial white and black coatings (**Figs. 21g** and **21h**). Moreover, the thermo-driven mechano-change radiative cooling materials were also reported for the excellent MIR emissivity modulation. For instance, Wang et al. reported a self-adaptive fiber via changing its loose structure under varying thermal conditions. This dynamic fiber could modulate its emissivity by 0.35 in infrared regions to adapt to demanding environments and had great potential for practical application¹⁹⁶.

In addition to thermal stimulus-driven dynamic radiative materials, humidity-driven self-adaptive materials have also been widely investigated for their environmental sensitivity and energy-saving properties⁵². Initially, most of these materials focused on a solvent with a high refractive index, which can change the color of radiative coolers from white to opaque, using substances like organic polymers^{52, 234, 235}. As technology progressed, researchers developed new approaches to simultaneously modulate solar and thermal irradiation through structure reconstruction triggered by interaction with water. In 2019, Yang et al. presented a porous polymer coating based on PVdF-HFP, where solar transmittance reversibly changes by 0.74 with liquid wetting²³⁶. This coating served as a platform for optical management across from solar to LWIR wavebands, achieving modulation values of 0.74 and 0.64 in the solar and LWIR regions, respectively. Given humidity variations are small in some regions, the development of humidity-temperature-co-driven dynamic radiative materials can be effectively used in a wider range of areas. Despite these advancements, challenges such as complex synthesis processes, durability issues, and performance limitations remain, hindering the scale-up and practical application of self-adaptive radiative cooling materials. Future research efforts must focus on addressing these challenges to unlock the potential of these materials for their real-world applications.

8 Conclusions and outlook

In this review, we summarized novel progress in PDRC materials from the perspective of spectral design and practical command. PDRC materials can be primarily categorized into emission-type, transmission-type, reflection-type, and hybrid (or selective)-type based on their spectral response in the LWIR wavelength range, and into visible-opaque-type and visible-transmission-type based

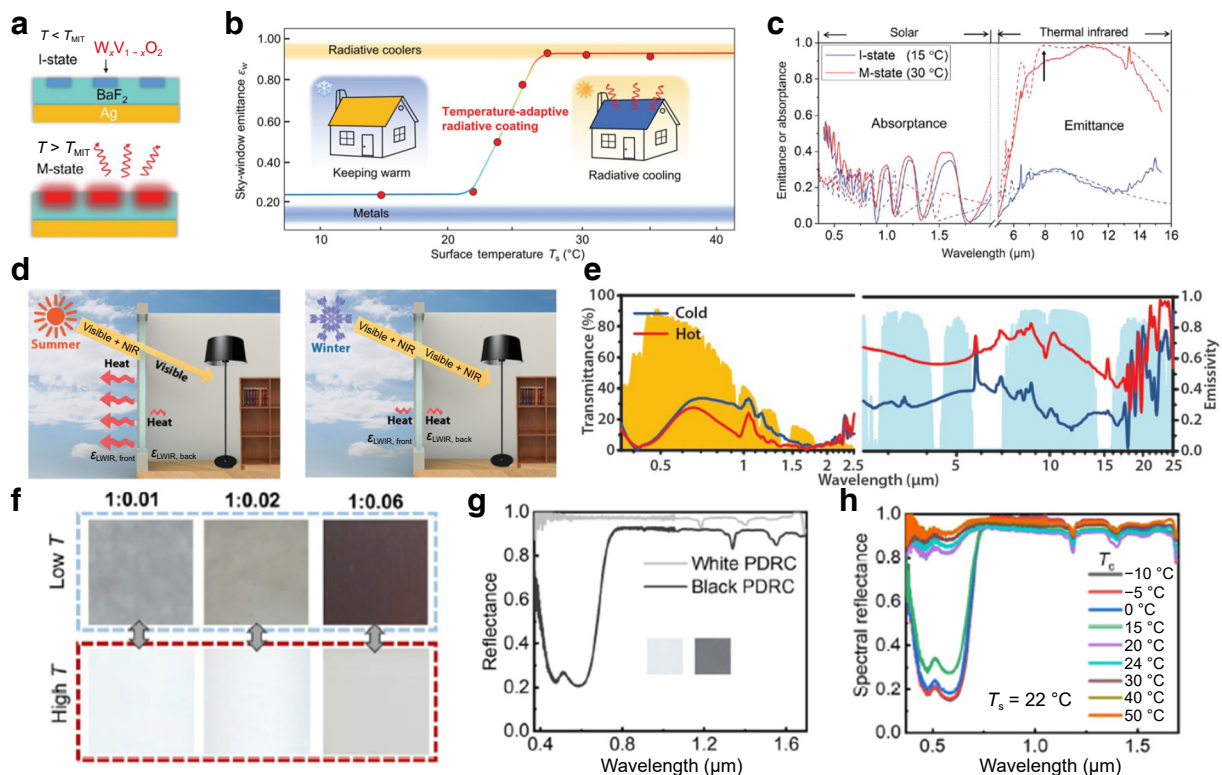


Fig. 21. Self-adaptive cooling radiative materials. **a**, Schematic illustration of the dynamic switching process. **b**, Schematic illustration of the switching modes and relative LWIR radiation under different temperatures. **c**, Spectral performance of different states. Reproduced with permission from Ref.²²⁰, © Tang, K. C. et al. 2021. **d**, Schematic illustration of dynamic thermochromic smart windows. **e**, Spectral performance in solar regions and LWIR regions between different states. Reproduced with permission from Ref.¹⁴⁵, © Wang, S. C. et al. 2021. **f**, Digital photos of thermochromic materials at different temperatures. **g, h**, Spectral performance in solar regions and LWIR regions between different states. Reproduced with permission from Ref.²²¹, © Wiley-VCH GmbH 2023.

on their spectral response in the visible wavelength range. Specifically, we focus on spectral design, material design, and preparation in the typically applied fields of PDRC materials, encompassing building thermal management, personal thermal management, water harvesting, and photovoltaic cooling, and make a summary of adaptive radiative thermal management, which is considered as future development of PDRC materials response to all-season command (Fig. 22). We also discussed the practical hurdles between PDRC technology with large-scale in detailed application scenarios to inspire future researchers to put effort into commercialization while outstanding cooling performance.

We are delighted to see that PDRC technology attracts more and more researchers to improve the cooling performance and to bridge the gap between academic research and practical application. However, there are still severe challenges for the PDRC technology.

(1) Lack of standard evaluation methods. Recent reports have designed test devices avoiding heat conduction and convection by insulated foam, Al foils, and PE films, however, detailed apparatus (size, thermocouple location, laying angles, etc.) are not strictly unified. The result is that practical cooling performances with different authors are difficult to compare. We recommend researchers to focus more on the tested system based on strict thermal and photonic concepts, avoiding systematic error brought by wrong conceptions.^{237, 238}

(2) Limited practical cooling power. The PDRC originates from the inherent temperature difference and transparent atmospheric windows between Earth and space, indicating a limited theoretical

heat dissipation power of $180 \text{ W} \cdot \text{m}^{-2}$ ($T_{\text{ambient}} = 20^\circ \text{C}$)⁹⁹. However, the limited cooling power may not suffice for the requirements of the heating equipment exposed to sunlight, which needs to be further studied and developed²³⁹. Thus, researchers attempted to integrate RC technology into large-scale cooling systems like thermoelectric cooling systems²⁴⁰, water cooling systems²⁴¹, evaporative systems^{150, 242}, or enlarged equipment²⁴³ to improve its real cooling power.

In addition to limitations in cooling power density, the overall power availability of PDRC materials is a significant constraint. Maximizing the area of these materials and orienting them toward the sky are crucial for fully harnessing the PDRC effect. However, many practical applications, such as vertical building walls or clothing, do not face the sky directly. The cooling effectiveness of these non-sky-facing surfaces depends on the proportion of their area exposed to the sky and their ability to minimize heat absorption from other directions, such as the ground, surrounding buildings, or nearby people. Recently, zigzag-shaped PDRC materials with directionally selective spectral properties have been developed to enhance cooling on non-sky-facing surfaces^{59, 98, 244}. However, these materials remain at the proof-of-concept stage. Future research should focus on developing cost-effective, scalable fabrication methods to enable the practical application of non-sky-oriented PDRC materials.

(3) Limited applied scenarios and functionality. Effective temperature reduction and cooling are crucial across various everyday scenarios, such as in buildings, machinery, and for human comfort^{149, 245–247}. Different conditions demand tailored PDRC

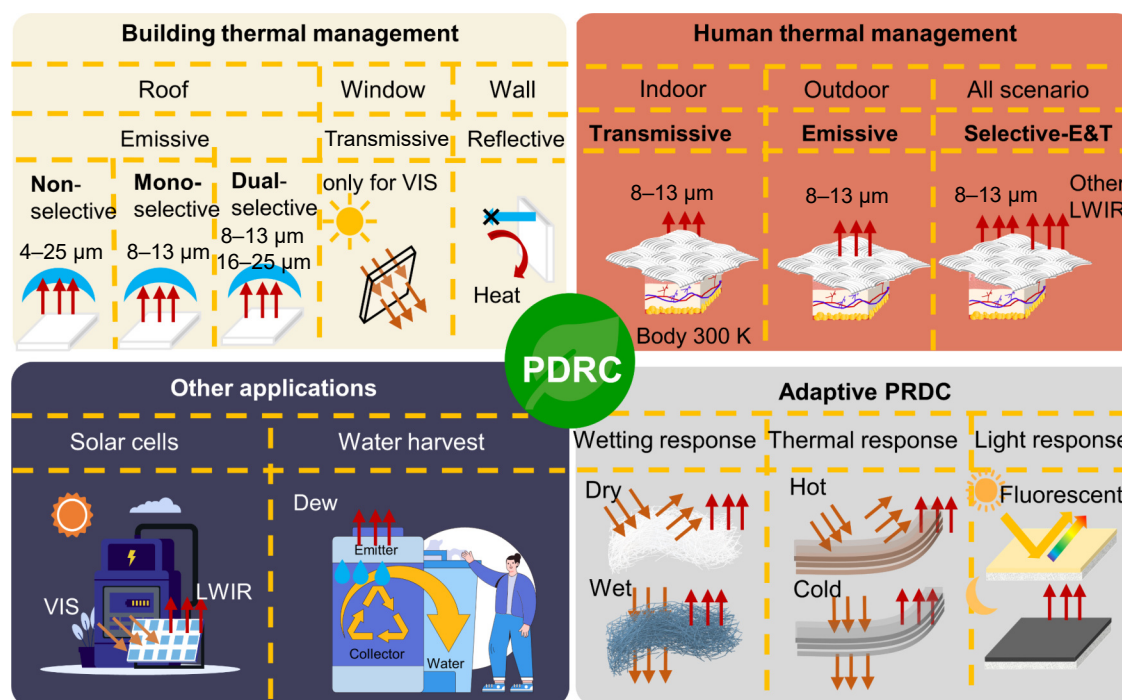


Fig. 22. The review and overlook of PDRC materials.

materials, including specific spectral designs and other tailored properties. However, the current material systems fail to meet the diverse demands, thus restricting their large-scale applications. In fact, there are still various fields calling for cooling technology with low energy consumption. To adapt complex and delicate commands for specific applied scenarios, more refined spectral segmentation of solar band and LWIR spectrum is necessary, along with the adoption of corresponding nano-microstructural designs and molecular engineering approaches^{58, 248, 249}.

(4) Cost of synthesis and deployment. The high cost associated with complex synthesis processes and the deployment of reliable materials at a larger scale also hinders the practical application of PDRC, particularly due to the intricate nanostructures involved. As a viable product, radiative cooling materials must offer a balance of affordability and high performance. It is urgent to develop more scalable and stable PDRC materials for potential large-scale and long-term applications.

In summary, PDRC materials represent a promising technology for achieving low-carbon objectives and addressing the dual challenge of energy conservation and temperature regulation. However, for practical application, existing materials must overcome several hurdles to ensure their practical viability, including enhancing durability, improving cooling performance, and expanding functionality. We believe that high-performance materials with low cost could definitely advance the development of smart materials in human being's daily life.

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Data availability

Not applicable.

Acknowledgements

The authors acknowledge the support from the National Key Research and Development Program of China (Nos. 2020YFA0210702 and 2020YFC2201103) and the Tongcheng Research and Development Foundation.

Author contributions

Z. J. Z., S. M. Z., J. Q. X., and X. K. W. prepared the initial manuscript. R. F. Z., Y. H., and Z. Y. G. revised the manuscript. All authors confirmed the final version of the manuscript.

Competing interests

The authors have no competing interests to declare that are relevant to this article.

Use of AI statement

None.



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