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Beyond the static: dynamic radiative cooling materials and applications

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ABSTRACT

The urgent need for sustainable cooling solutions has propelled the development of passive radiative cooling (RC) technology. However, the static nature of traditional RC (SRC) designs limits their adaptability to varying thermal demands. Dynamic RC (DRC) materials and systems have emerged as a cutting-edge solution, enabling cooling performance modulation in response to the changing environment. This review provides an overview of the latest advancements in DRC research and explores the innovative material and structural designs of various DRC systems, highlighting their immense potential for enhancing thermal management in building- and city-related applications. The incorporation of SRC and DRC into various systems is discussed, such as building envelopes, heating, ventilation, air-conditioning and cooling systems, and evaporative cooling. The application of SRC and DRC materials at the urban scale is explored, focusing on their widespread implementation on roofs, walls, and pavements to reduce surface and ambient temperatures and mitigate the urban heat island (UHI) effect. Looking ahead, the key challenges and opportunities for the next generation of DRC research are defined. Overall, this review serves as a roadmap for pushing the boundaries of sustainable cooling technology and reshaping the material and system development for the future built environment.

1. Introduction

Radiative cooling (RC) is a renewable energy technology that achieves cooling by exploiting the radiative heat exchange between the Earth and the universe [1–3]. Regarding the universe, the dominant heat input to the Earth is solar irradiation emitted by the Sun at approximately 5500 °C, with wavelengths ranging from 0.25 to 2.5 μm [4]. Meanwhile, the extremely cold universe, with a temperature around −270 °C, acts as an infinite heat sink, accepting heat loss from the Earth [4]. The Earth maintains thermal balance through this radiative heat exchange of incoming solar heating and outgoing thermal emission. RC technology disrupts this equilibrium by optically engineering a material's surface to selectively emit thermal radiation in the transparent atmospheric window (AW) of 8–13 μm while minimizing absorption of solar irradiation, resulting in a net cooling effect. Traditional cooling methods like vapor-compression air-conditioning systems provide rapid cooling but suffer from low energy efficiency, contributing to environmental issues such as ozone depletion and climate change. In contrast, RC has emerged as a promising sustainable and energy-efficient alternative to meet growing global cooling demands. As an energy-free and refrigerant-free technology, RC spontaneously generates cooling [5–7], making it an attractive solution for sustainable cooling.

Initial studies on RC technology focused on nighttime applications when the absence of solar radiation allows for easier cooling below ambient air temperatures. The cooling performance at night depends on a surface's optical properties in the mid-to far-infrared wavelength range. According to Planck's law, a typical blackbody at room temperature radiates most strongly around 9 μm, coinciding with the AW which serves as the major heat dissipation channel from Earth to the cold universe. Outside this range, the opaque atmosphere radiates heat back, limiting the cooling potential. Therefore, for optimal sub-ambient cooling, RC materials must exhibit spectral selectivity. For deep sub-ambient temperature reduction, an ideal nighttime RC surface should be strongly emissive in the

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wavelength where the atmosphere is highly transparent to maximize heat dissipation to space while effectively reflecting other infrared wavelengths to minimize the radiation absorbed [8–10].

The potential to reduce building heat loads, minimize reliance on traditional cooling systems, and mitigate the urban heat island (UHI) effect has garnered significant attention for daytime applications. By incorporating RC materials into building envelopes, it is possible to achieve these benefits and improve overall energy efficiency. The indoor cooling demand is higher due to sunlight absorption by buildings [11], necessitating a shift in RC research toward all-day cooling performance instead of nighttime-only. In the past decade, a landmark research in all-day cooling was achieved by Raman et al., who developed the multilayer photonic RC device capable of sub-ambient cooling (4.9 °C) under direct sunlight [3]. This work spurred further research on daytime RC. Given the higher energy density of sunlight compared with mid-infrared radiation, researchers have emphasized improving sunlight reflectance over infrared selectivity. Various designs utilizing porous polymers [12–14], paints [15–17], films [18–20], bulk wood [21], ceramics [22–24], and other photonic materials have been developed exhibiting high solar reflectance and reliable mid-infrared emissivity for effective daytime cooling while considering practicality and scalability.

Despite the advancements made in optimizing optical performance and applications of RC designs for maximizing cooling, a notable limitation arises when considering the practical needs for indoor space thermal management. The continuous and uncontrollable nature of a cooling effect achieved by static optical properties poses challenges in adapting to varying thermal demands. The radiative heat exchange at the Earth's surface is influenced by celestial movements, resulting in temporal, spatial, and geographical variations [25] (Fig. 1a and b). Static RC (SRC) designs are promising for hot regions that rely on year-round air conditioning, as their consistent cooling can effectively reduce cooling loads and energy consumption. However, in colder regions or during cold periods, SRC can lead to excessive cooling, intensifying heating demands, and increasing energy use. This limitation highlights the need for dynamic RC solutions that can modulate their cooling effect based on specific climatic conditions and cooling requirements.

To address the challenge of adapting to varying thermal demands, researchers are developing DRC materials and structures that can adjust their optical properties in response to changing environmental conditions. This dynamic control is achieved through the design of optical properties in two key spectral ranges: the solar range affecting heat gain from solar irradiation, and the thermal range influencing radiative heat loss via the AW (Fig. 1c and d). In hot climates with high cooling demands, DRC materials adopt cooling-optimized properties similar to SRC designs: high solar reflectance to minimize solar absorption and high thermal emissivity to maximize radiative heat loss. However, DRC's key advantage lies in its ability to adapt to cold conditions that require heating or suppressed cooling. In such cases, DRC can switch to heat-optimized properties: high solar absorptance to maximize solar heat gain and high thermal reflectance to minimize radiative loss, contributing to heating.

This review provides a comprehensive summary of the latest research on DRC materials, structures, and applications. We delve into the various strategies employed to achieve DRC through material and structural designs, categorized as either passive or active based on the modulation method. Passive DRC materials rely on the inherent properties and responses of materials to environmental conditions, while active DRC incorporates external stimuli or control mechanisms. By examining representative works in detail, we elucidate the working principles, mechanisms, and performance of these designs, providing a comprehensive understanding of the state-of-the-art. Furthermore, we explore diverse DRC applications across sectors, focusing on thermal management and energy-saving potential. We analyze the feasibility and performance of DRC materials at various scales, from applications in individual buildings to entire cities, highlighting the technology's versatility and scalability for impacting energy efficiency and sustainability in the built environment. Finally, we discuss future research directions and challenges in the DRC field. By identifying key areas for improvement and potential avenues for exploration, we aim to provide insights and inspiration for advancing DRC technology. Addressing these challenges and opportunities will be crucial in unlocking DRC's full potential for enhancing thermal management and energy savings across applications.

2. Materials and structures for dynamic thermal regulation

2.1. Active DRC materials

Active DRC materials achieve optical regulation through external energy-consuming stimuli, such as mechanical forces or

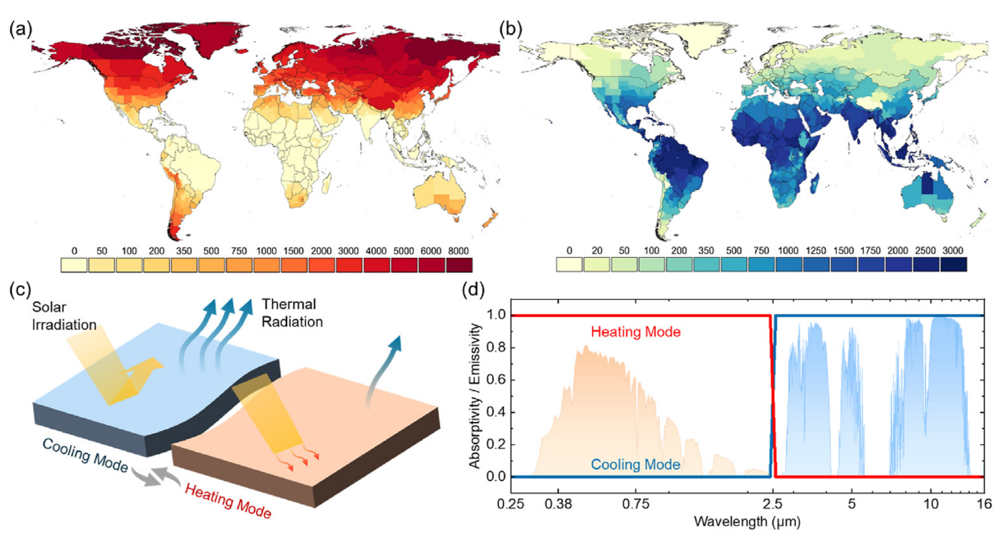

Fig. 1. Dynamic heating and cooling demand throughout the world and a schematic of DRC. Global maps of (a) heating degree days and (b) cooling degree days experienced across the years 2010–19 [25]. Copyright 2023 Springer Nature. (c) A schematic of DRC. (d) Ideal spectrum of DRC with standard solar irradiation of orange shading and atmospheric transmittance of blue shading.

electricity. These materials offer quick response and on-demand control, allowing for precise modulation of the cooling effect and rapid adaptation to changing thermal demands. However, enhanced control and responsiveness come at the cost of increased complexity and additional energy consumption. The need for external stimuli and control mechanisms often requires more intricate designs, potentially involving the integration of sensors, actuators, and control circuits. This added complexity can pose challenges in terms of material integration, reliability, and scalability. Despite these challenges, active DRC materials have garnered significant attention due to their potential for fine-tuned thermal regulation and ability to provide desired cooling or heating on-demand. In this section, we discuss the different types of active DRC materials with various regulation stimuli, including manual reconfiguration, mechanical strain, electricity, and reversible refractive index.

Recent research on active DRC materials has explored various strategies in achieving dynamic control over radiative heat transfer. Janus materials have emerged as a promising approach for achieving dynamic control over radiative heat transfer in active DRC materials. These materials are characterized by their asymmetric optical properties, with opposite sides of the material exhibiting contrasting optical behavior in the solar and/or long-wave infrared (LWIR) range. One key advantage of Janus materials is their ability to provide switchable thermal regulation without the need for complex mechanical actuation or reconfiguration. By simply flipping or rotating the material, the desired optical properties can be exposed to the incident radiation, allowing for a rapid and energy-efficient transition between cooling and heating modes. For example, Yang et al. developed a Janus aerogel composed of a porous cellulose nanofiber (CNF) skeleton with opposite sides of Mxene-CNF and CNF [26] (Fig. 2a). The CNF side exhibits solar reflectance of around 88%, making it suitable for radiative cooling, while the Mxene-CNF side displays solar absorptance of around 97.5%, enabling solar heating. Meanwhile, the porous CNF skeleton provides thermal insulation, minimizing conductive heat transfer between the two sides. This Janus aerogel achieved a surface temperature rise of around 4 °C under simulated winter conditions and maintained a surface temperature of around 7 °C below ambient temperature under simulated summer conditions. Similarly, Song et al. fabricated a Janus membrane by electrospinning polyvinylidene fluoride (PVDF) nanofibers and asymmetrically depositing functional materials on opposite sides [27]. The cooling side, composed of ZnO nanosheets and carbon nanotubes, achieved a solar reflectivity of 90.6% and an LWIR emissivity of 89.2%, with a sub-ambient temperature reduction above 8.2 °C in outdoor tests. The heating side, consisting of silver nanowires embedded in a polydimethylsiloxane (PDMS) matrix, exhibited a solar absorptivity of 74.1% and an LWIR emissivity of 74.1% with an above-ambient temperature rise of more than 3.8 °C in outdoor tests. In addition to Janus materials, reconfigurable structures have also been explored as a means of achieving dynamic control over radiative heat transfer in active DRC materials. Reconfigurable structures rely on dynamic modulation of their optical properties through mechanical actuation or reconfiguration. This can be achieved by integrating materials with contrasting optical properties into movable or switchable components, such as louvers, shutters, or micropatterned surfaces. Li et al. designed a dual-mode thermal regulator by integrating multiple functional layers on a flexible polyimide substrate [28] (Fig. 2b). The device consists of a cooling mode with an Ag layer for solar reflection, a PDMS layer embedded for LWIR emission, and a heating mode with a Cu-doped ZnS nanoparticle layer for solar absorption and an Au layer for LWIR reflection. Switched by an electrically controlled track system, the device achieved a solar reflectance of 97.3% and a LWIR emission of 94.1% in the cooling mode and a solar absorptance of 93.4% and LWIR emission of 14.2% in the heating mode. Furthermore, Yang et al. developed an innovative structure that emulates the design of louvers, which is capable of toggling between radiative cooling, solar heating, and natural lighting [29] (Fig. 2c). This is achieved through a dual-sided optical design on the blades, coupled with controlled rotation of the louvers. Ke et al. demonstrate a micropatterned surface which can switch between different optical properties by mechanically reconfiguring the interwoven surface structure [30].

Applying mechanical stress is another way to actively modulate the optical properties of DRC materials. This approach leverages the deformation of flexible or stretchable materials to induce changes in their optical properties. Liu et al. proposed a reconfigurable photonic structure for DRC by continuously varying the emission spectra in the AW [31] (Fig. 2d). The structure consists of a PDMS layer embedded with SiC, Si_3N_4, and BN nanoparticles, on top of a 1D PDMS grating coated with a silver thin film. When mechanically strained, the thickness of the PDMS layer and period of grating change, allow tuning of the emissivity between 0.15 and 0.79 in the AW. Another interesting work conducted by Zhao et al. introduces dynamic silicone coatings that can be reversed and continuously adjusted from a highly porous state to a transparent solid state [32]. In the porous state, the coatings exhibit efficient solar reflection (93%) due to the scattering effect of the porous structure. When compressed into a transparent solid state, the coatings allow active sunlight transmission (95%), enabling solar heating through the absorption of sunlight by embedded carbon black particles.

Except for mechanical control, electrochromic material which changes the optical properties when subjected to an applied voltage is also an alternative to achieve active DRC. Zhao et al. demonstrated a dual-mode glazing panel able to switch between a highly transparent 'heating mode' and a highly reflective 'cooling mode' through reversible electrodeposition of a silver film on a transparent glass substrate [33]. The dynamic switching is achieved by reversible silver electrodeposition using a transparent electrolyte sandwiched between two indium tin oxide-coated glass panels (Fig. 3a). In the heating mode, the glazing allows around 70% transmission of incident sunlight, providing a heating power of around 400 W/m^2 on a cold winter day. In the cooling mode, the silver film gives 89% solar reflectance while the exterior side has a high-infrared emissivity. This enables radiative cooling of around 20–60 W/m^2 on a hot summer day, reducing cooling loads. Outdoor experiments confirmed the heating and cooling performance under real sun conditions. In heating mode, a 24 °C temperature rise above-ambient temperature was achieved, while in cooling mode, the glazing reached 2 °C sub-ambient temperature. While the dual-mode glazing panel utilizes silver electrodeposition, other electrochromic materials have also been explored for DRC applications. Sui et al. developed an electrically switchable device by employing a graphene ultra-wideband transparent conductive electrode and reversible copper electrodeposition [34]. The device realizes the LWIR emissivity modulation between 0.07 and 0.92 by the use of reversible copper deposition optical modulation, while consuming minimal electrical power. Another potential candidate of electrochromic material for DRC is WO_3. The electrochromism of WO_3 is achieved through the reversible insertion and extraction of ions, such as H+ or Li+, into and out of the WO_3 lattice. The inserted ions modify the material's electronic states, resulting in a change in optical properties [35]. With the increase of the applied voltage, the visible solar transmittance gradually decreased, accompanied by a deeper color change, which can be exploited for solar heating modulation [36]. Until now, WO_3 has mostly been explored for solar transmittance modulation in smart window applications. WO_3 is also capable of modulating thermal emittance for radiative

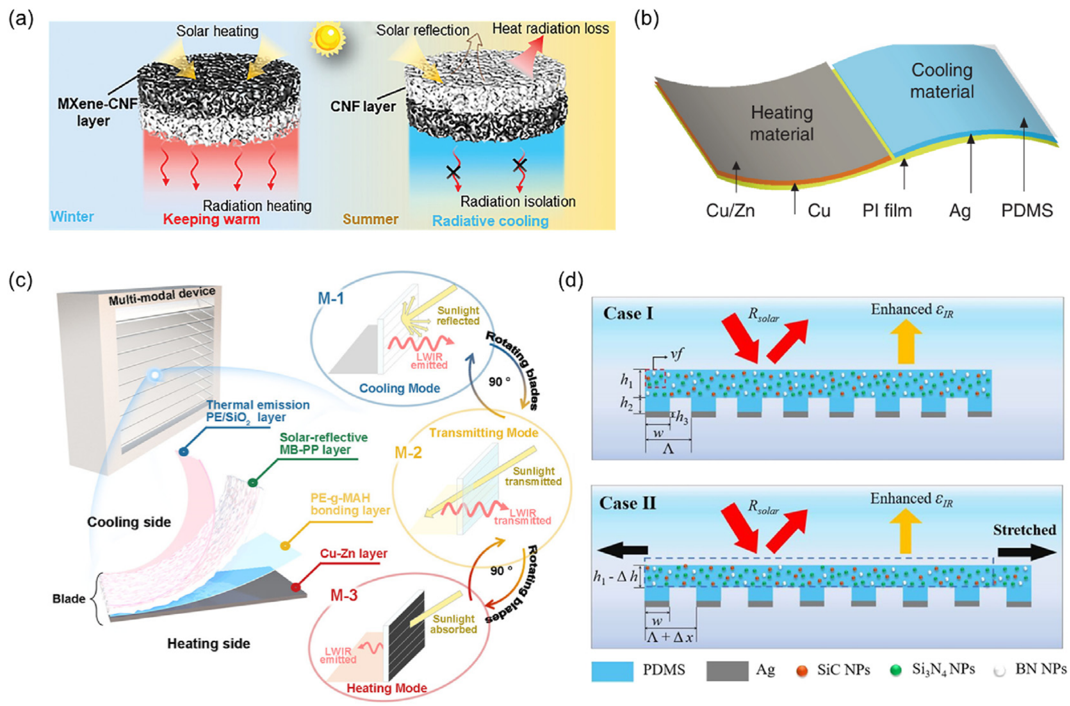

Fig. 2. Active DRC triggered by mechanical stimulus. (a) Schematic of a Janus aerogel with asymmetric optical properties on opposite sides [26]. Copyright 2023 Wiley-VCH. (b) Dual-mode thermal regulator with switching facilitated by an electrically controlled track system [28]. Copyright 2020 Springer Nature. (c) Dual-sided optical design on the blades with rotation controlled by the louvers [29]. Copyright 2022 American Chemical Society. (d) Reconfigurable photonic structure with optical modulation via stretching [31]. Copyright 2020 Springer Nature.

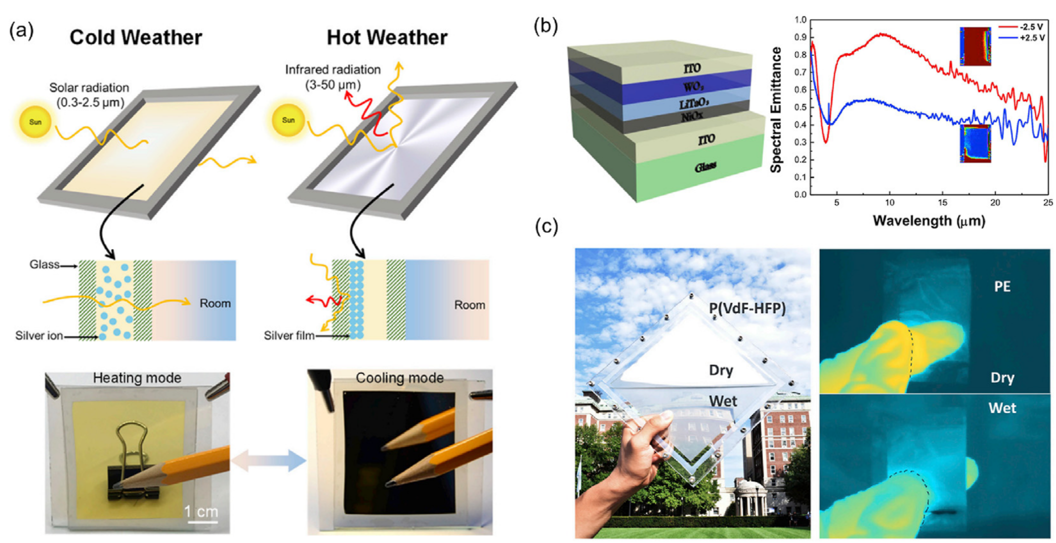

Fig. 3. Active DRC triggered by electrical and water stimulus. (a) A glazing panel via reversible electrodeposition of a silver film [33]. Copyright 2022 Elsevier. (b) WO_3-based all-solid-sate electrochromic device [37]. Copyright 2022 Elsevier. (c) Porous polymer-coating with reversible optical switching via adjusting refractive indices by wetting with liquids [38]. Copyright 2019 Elsevier.

cooling modulation. Zhang et al. reported on two all-solid-state electrochromic devices (ECDs) based on amorphous WO_3 (a-WO_3) and crystalline WO_3 (c-WO_3) as the electrochromic layers for modulating LWIR emittance [37] (Fig. 3b). The a-WO_3 and c-WO_3 films exhibited contrasting IR emittance behavior upon insertion/extraction of lithium-ion due to their different absorption and reflection characteristics. The IR emittance of the a-WO_3 ECD increased remarkably after $Li+$ insertion due to vibrational absorption, while the c-WO_3 ECD showed decreased emittance from its pseudo-metallic behavior. The a-WO_3 ECD demonstrated a higher IR emittance modulation of 0.37 in the 8−14 μm and 0.30 in the 2.5−25 μm ranges.

Another approach to achieving active DRC is by manipulating the refractive index mismatch between different components in a multi-interface scattering system. The refractive index mismatch between different components in a multi-interface scattering system is crucial in determining how light will behave as it passes through or reflects from these interfaces. Therefore, adjusting the refractive indices can also be used to engineer a desired optical regulation. Mandal et al. designed porous polymer coatings that can switch their optical transmittance upon reversible wetting with liquids like alcohol or water [38] (Fig. 3c). In solar wavelengths, originally reflective coating made of porous polymer becomes transparent when wet due to a decrease in refractive index contrast, allowing solar transmittance to change up to 0.74. Meanwhile, the infrared-transparent porous coating became opaque/emissive when wetted with LWIR-absorbing liquids, enabling modulation of 0.8 in LWIR transmittance.

2.2. Passive DRC materials

In contrast to active DRC materials, which rely on external energy-consuming stimuli, passive DRC materials achieve adaptive thermal regulation without the need for external energy input. These materials exploit the inherent optical and thermal properties of materials, as well as their response to environmental conditions, especially ambient temperature, to automatically adjust their optical properties for thermal regulation. In this section, we cover the passive thermal-regulation design, including VO_2-based materials, hydrogel-based materials, thermochromic-microcapsule-based materials, and shape-memory-based components.

Thermochromic materials, which exhibit reversible changes in their optical properties in response to temperature variations, have emerged as a promising choice for passive DRC materials. The thermal-induced functionality of these materials allows for autonomous switching between different optical states, enabling adaptive thermal regulation without the need for external energy input or complex control systems. As the ambient temperature fluctuates throughout the day or across seasons, thermochromic materials can automatically adjust their optical properties to optimize radiative heat transfer. The key advantage of using thermochromic materials in passive DRC structures lies in the fact that a building's thermal demands are inherently coupled with changing ambient conditions. In other words, the heating and cooling requirements of a building naturally vary according to the prevailing temperature and weather conditions. This coupling between thermal demands and environmental factors makes thermochromic materials particularly suitable for passive DRC applications.

Vanadium dioxide (VO_2) is a well-known thermochromic material that exhibits a reversible phase transition around 68 °C, switching between a low-temperature monoclinic insulating phase with transparent optical properties and a high-temperature tetragonal metallic phase with reflective optical properties. This transition involves a structural reconfiguration of vanadium atoms from a paired arrangement to an equidistant chain alignment, which closes the electronic bandgap and alters the material's optical properties, changing from transparent to reflective in the infrared region [39]. Pure VO_2 primarily regulates radiation in the near-infrared range, making it suitable for transparent envelope applications such as building windows. However, for the thermal regulation of opaque components, materials are expected to exhibit thermal reflection in low-temperature conditions to suppress heat loss while promoting thermal absorption/emission in high-temperature conditions for heat dissipation. This desired behavior contrasts with the inherent phase change characteristics of VO_2. To utilize the thermochromism of VO_2 in the mid-infrared range for modulating thermal radiation, delicate designs are often required. Ono et al. proposed a VO_2-MgF_2-W structure covered with a spectrally-selective filter, achieving a restricted optical modulation within the AW range [40] (Fig. 4a). This design can dynamically modulate the emittance from 0.636 in the metallic state to 0.054 in the insulating state within the 8−13 μm range. VO_2-dielectric-opaque reflective substrate structures are widely employed in VO_2-based thermochromic designs for thermal radiation regulation, taking advantage of Fabry−Perot resonance to enhance mid-infrared absorption via wave interference effects in the metallic state while enabling spectral tunability [41,42]. When the temperature exceeds the transition temperature of VO_2, metallic VO_2 serves as the top mirror for a Fabry−Perot resonator. The emissivity is designed for a specific mid-infrared range to achieve a cooling effect by tuning the thickness of the dielectric layer. Conversely, when the temperature falls below the transition temperature, insulating VO_2 becomes transparent to thermal radiation, and the overall design exhibits thermal reflection due to the underlying metal substrate. The choice of dielectric layer material for the Fabry−Perot resonator is diverse [43−46]. Tang et al. fabricated a flexible coating consisting of $W_xV_{1-x}O_2$-BaF_2-Ag, achieving a thermal emittance regulation of 0.7 [47] (Fig. 4b). Their design incorporates a three-dimensional photonic structure by inserting patterned $W_xV_{1-x}O_2$ as periodic blocks in the BaF_2 layer, enhancing the Fabry−Perot resonance and resulting in a thermal emission of 0.9 in the high-temperature condition. Liang et al. utilized germanium as the dielectric layer, achieving an emissivity of 0.78 at high temperatures and 0.10 at low temperatures [48] (Fig. 4c). Gu et al. designed VO_2-HfO_2-Al to achieve emittance tunability of 0.51 [45] (Fig. 4d). Polymers can serve as cost-effective alternatives. For example, Wang et al. employed poly(methyl methacrylate) (PMMA) as the dielectric layer in a Fabry−Perot resonator design, achieving a $\Delta\varepsilon_{LWIR} = 0.4$ for window applications [46] (Fig. 4e). In addition, the design shows a promising regulation in near-infrared transmittance with a solar transmittance modulation of 26.1%. Despite VO_2 having the closest transition temperature to room temperature among reported metal-insulator materials [49], its transition temperature remains too high to be triggered by typical environmental thermal changes.

Doping is the most popular approach to modify the transition temperature of VO_2. The presence of a small amount of dopant in VO_2 can cause significant changes in its lattice structure and energy landscape, leading to a lower phase transition temperature [50−52]. For instance, in the previously mentioned $W_xV_{1-x}O_2$-BaF_2-Ag design, tungsten is doped into VO_2. With an optimized doping concentration (X = 1.5), the phase change temperature of the overall design is reduced to approximately 22 °C.

Hydrogel, with thermochromism in the visible range, is another promising approach to achieve passive DRC. The thermochromic behavior of hydrogel is attributed to the transition between a hydrophilic state (below the lower critical solution temperature (LCST)) with high transmittance and a hydrophobic state (above the LCST) with low transmittance [53]. This transition is driven by the disruption or formation of intermolecular hydrogen bonds between the polymer chains and water molecules within the hydrogel network. In the study by Fang et al., a sandwich structure thermal homeostasiser was developed using a thermochromic hydrogel PNIPAm in combination with PVDF films [54] (Fig. 5a). The PVDF@PNIPAm film demonstrated excellent optical performance with significant modulation of visible light reflectance (70%) and transmittance (86.3%) and a high long-wave infrared emissivity of 0.96. Outdoor tests showed that the film could self-adaptively achieve efficient sub-ambient radiative cooling of 1.8−3.7 °C during hot daytime and above-ambient solar heating of 4.3−5.8 °C during cold daytime, resulting in a cooling-heating temperature difference of 9.5 °C. Besides, Mei et al. presented a self-adaptive film design based on a thermochromic PNIPAm hydrogel and PVDF film for passive radiative cooling and solar heating regulation. The film exhibited large visible light reflectance/transmittance modulation and high longwave infrared emissivity [55] (Fig. 5b). Quantitative analysis during outdoor tests demonstrated that the PVDF@PNIPAm film achieved a temperature drop of 3−4 °C at high

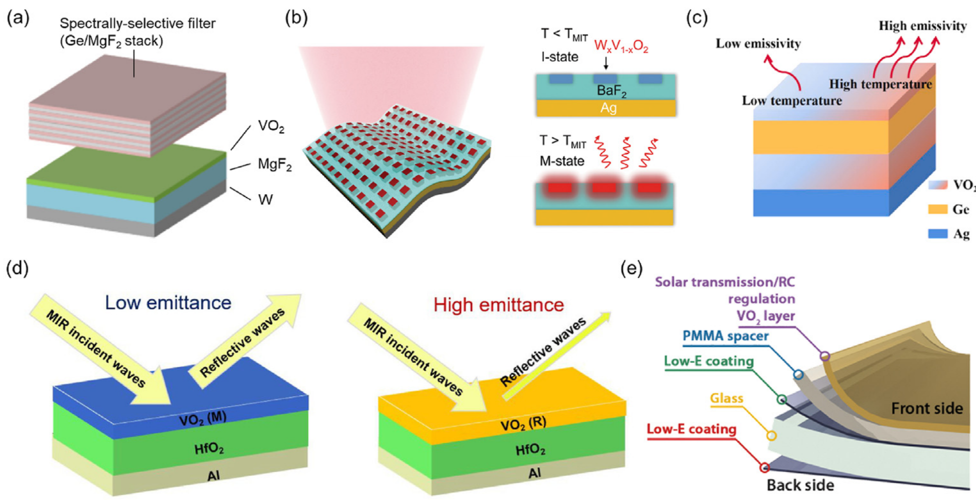

Fig. 4. VO_2-based passive DRC. (a) VO_2-MgF_2-W with solar filter for emissivity regulation within 8–13 μm [40]. Copyright 2023 Optical Publishing Group. (b) A flexible coating consisting of $W_xV_{1-x}O_2$-BaF_2-Ag, achieving a thermal emittance regulation [47]. Copyright 2021 The American Association for the Advancement of Science. (c) VO_2-Ge-Ag structure for mid-infrared optical regulation [48]. Copyright 2023 Elsevier. (d) VO_2/HfO_2/Al Fabry–Perot resonator for infrared radiation regulation [45]. Copyright 2022 American Chemical Society. (e) VO_2-doped PMMA coating in window application for visible, near-infrared, and mid-infrared optical regulation [46]. Copyright 2021 The American Association for the Advancement of Science.

temperatures at noon and a temperature increase of 4–6 °C higher than ambient temperature under sunlight in winter. The film's performance showcased its potential for cooling/heating applications in different geographic locations and weather conditions.

Thermochromic microcapsules, such as leuco dye [56,57], are another promising candidate for regulating optical properties in the solar spectrum. Unlike the thermochromism of hydrogels, which relies on the conversion between hydrophilicity and hydrophobicity, the thermochromic behavior of microcapsules results from chemical reactions within a three-component structure consisting of a color former, developer, and solvent. Thermochromic microcapsules typically come in the form of powder and are usually mixed with a binder to form a coating. These microcapsules exhibit low absorption in the visible range at low temperatures and high absorption at high temperatures. Thermochromic microcapsules absorb visible light when in a cold state, resulting in a colorful appearance. This helps address the aesthetic limitations of SRCs, which are typically limited to a static white appearance [58]. Dong et al. developed a thermochromic coating by doping leuco dye and other inorganic microparticles into a poly(vinylidene fluoride) matrix [59]. At high temperatures, where the thermochromic microcapsules feature low visible absorption, the inorganic microparticles scatter solar irradiation, resulting in high solar reflection (93%). Conversely, at low temperatures, the thermochromic microcapsules undergo colorization and become absorptive in the visible light range, leading to a low solar reflection of 50%. Similarly, Wang et al. prepared a thermochromic coating by mixing polymers and leuco dyes, achieving regulation in solar reflection of around 3.6%–6.8% with a critical thermochromic temperature of 25 °C [60]. Apart from monolayer coatings, microcapsule-based thermochromic coatings can also be achieved through dual-layer designs. Wang et al. dispersed leuco dye particles in a transparent polymer matrix and applied it as a top layer on a high solar reflection substrate [61] Fig. 5c). In this case, solar irradiance is highly transmitted through the top layer at high temperatures and is reflected by the bottom layer. At low temperatures, the leuco dye absorbs visible light for heating. The overall solar reflection can modulate between 91.25% and 72.71%, which is higher than that of monolayer designs. Using different color formers in the three-component structure of thermochromic microcapsules leads to different visible absorption spectra in hot conditions, resulting in different colors. This allows for greater flexibility in design and aesthetic applications. Moreover, the temperature at which the color change occurs can be finely tuned during the manufacturing process, providing precise control over the activation temperature.

Thermal-response folding materials are also a promising alternative for achieving DRC. Zhang et al. introduced a novel device comprising a temperature-sensitive actuator with high infrared emissivity and a visible thermochromic substrate [62]. The actuator is affixed to the substrate, which includes dispersed thermochromic microcapsules on a thin nitrile-butadiene rubber-coated aluminum foil, providing high solar reflection and low thermal emission properties. The actuator responds to temperature variations due to its programmed two-way shape memory polymer component. When the temperature exceeds the transition temperature, the actuator covers the substrate, leading to high solar reflection from the substrate and high thermal emission from the covered actuator. Conversely, at temperatures below the transition temperature, the actuator folds up, and the substrate facilitates heating through visible absorption and suppression of thermal radiation. Another design proposed by the same research group eliminates the use of thermochromic microcapsules for visible chromism, utilizing a temperature-sensitive actuator as a static solar reflector and the substrate as a static solar absorber [63] (Fig. 5d). In cooling mode, the device can reflect over 90% of solar radiation and exhibit high thermal emission of approximately 96%. Conversely, in heating mode, the device can absorb around 91% of solar radiation and maintain a low thermal emission of about 8%. Chai et al. also proposed a rooftop covering consisting of two layers: a temperature-responsive heating material at the top with high solar absorptance but low thermal emissivity, and a cooling material at the bottom with low solar absorptance but high thermal emissivity. The key mechanism enabling this synchronous modulation is the thermal-induced bending actuation of a metalized polyethylene (PE) film. When the rooftop surface temperature changes, the PE film undergoes thermal expansion or contraction, causing the material to bend toward the cooling material or remain flat [64] (Fig. 5e). The temperature-adaptive rooftop covering demonstrates high solar absorptance of 81% in the solar heating mode while maintaining a low thermal emissivity of 10% to minimize heat loss from the building. In the radiative cooling mode, the covering exhibits low solar absorptance of 8.5% to reflect solar heat

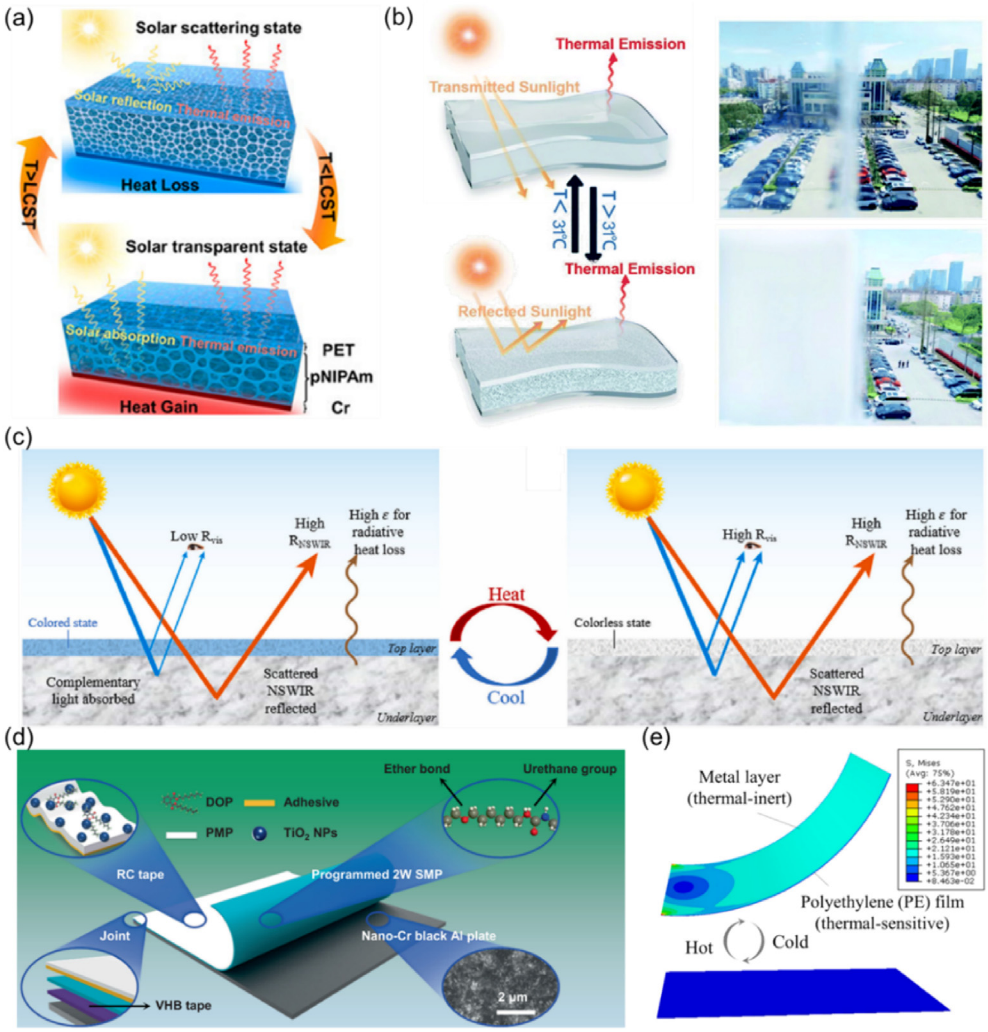

Fig. 5. Passive DRC based on hydrogel, thermochromic microcapsules, and other thermal-responsive materials. (a) A three-layer structure for solar spectrum modulation, consisting of top polyethylene terephthalate-based cooling layer, a PNIPAm-based thermochromic middle, and a Cr-based solar heating bottom [54]. Copyright 2022 American Chemical Society. (b) A sandwich structure based on a thermochromic PNIPAm hydrogel and polyvinylidene fluoride (PVDF) film for solar transmittance regulation [55]. Copyright 2022 Royal Society of Chemistry. (c) A dual-layer coating design with thermochromic microcapsules as top doping for visible absorption regulation [61]. Copyright 2023 Elsevier. (d) A self-folding design with top RC layer and bottom solar heating layer [63]. Copyright 2020 Springer Nature. (e) A covering design with solar absorptance modulation achieved by thermal-induced bending actuation of a metalized PE film [64]. Copyright 2023 Elsevier.

and reduce heat gain, along with a high thermal emissivity of 89% to facilitate heat dissipation and cooling of the building.

Perovskite manganese is a thermochromic material that exhibits thermal emission modulation with temperature variations. By finely tuning the doping concentration of alkaline-earth elements, perovskite manganese can undergo reversible metal-insulator transitions due to the double exchange effect [65]. Specifically, when the temperature is below the transition temperature, the material exhibits a ferromagnetic metallic state with a low thermal emissivity. When the temperature is above the transition temperature, the material transitions to a paramagnetic insulating state with a high thermal emissivity. Initially, Shimakawa et al. brought $La_{1-x}Sr_xMnO_3$ to people's attention [66]. By manipulating the doping concentration of lanthanum and strontium, $La_{1-x}Sr_xMnO_3$ performs thermal emissivity modulation over 0.3 with the temperature variance between 220 K and 340 K. The transition temperature can be customized from 270 K to 360 K by controlling the doping amount. Subsequently, investigations by Tachikawa et al. revealed that the perovskite manganese $La_{1-x}Ca_xMnO_3$ could achieve a tunable thermal emissivity of up to 0.41 [67]. Furthermore, Laffez et al. explored the potential of $Sm_{1-x}Ca_xMnO_3$, which displayed an emissivity modulation of 0.773 in the 8–14 μm range [68]. Collectively, these research findings have underscored the potential of perovskite manganese for passive thermal regulation applications. Over the past several years, many efforts have been made to enhance the application feasibility of perovskite manganese. Typically, the perovskite manganese-based designs have exhibited great rigidity and brittleness, which have hindered their application on non-planar surfaces. To address this challenge, Zhao et al. developed a triple layer design comprising a perovskite manganese top layer, a metal mirror as the middle layer and a flexible bottom substrate [69]. This design features mechanical flexibility while providing emittance contrast of 0.61 in the wavelength range of 2.5–25 μm. Building upon this work, the same research team subsequently developed another flexible perovskite manganese strategy by depositing $La_{0.7}Ca_{0.3-x}K_xMnO_3$ on a flexible yttria-stabilized zirconia substrate. This alternative approach demonstrated an emittance contrast of 0.47 in the 2.5–25 μm wavelength range. Furthermore, the ultra-thin and lightweight properties of this design further extended its potential applicability

[70]. It is important to note that perovskite manganese typically exhibits high absorption in the solar spectrum, resulting in a dark appearance, which is undesirable when daytime RC is the desired application. To address this limitation, Fan et al. proposed a design wherein a thin layer with high solar reflectance and long-wave transmittance was deposited atop the perovskite manganese materials [71]. This thin deposition possesses long-wave transmissivity of 0.87 and decreases the solar absorptivity from 0.78 to 0.28. On the other hand, the large optical contrast of perovskite manganese typically arises from temperature variations. However, the optical contrast is not significant within the typical room temperature variation range. This remains a research gap that needs to be further addressed for practical applications.

Thermal-responsive material can also be utilized for thermal-resistance modulation and therefore control the cooling power. Zhang et al. realized a thermal switch based on employed nickel-titanium alloy springs with thermal-response ability. The switch modulates the conductive heat transfer between the internal environment to the external RC module with low-thermal resistance in hot weather and high-thermal resistance in cold weather [72]. Applying the switchable radiative cooler enabled a temperature reduction of 11 °C at daytime and a temperature increase of 4 °C at nighttime. Table 1 summarizes the relevant literature on active and passive DRC designs.

3. Integration with building envelope systems

Applying RC materials to roof and facade surfaces allows buildings to take advantage of the materials' ability to emit infrared radiation to the cold outer space while reflecting solar irradiation, facilitating sub-ambient cooling and reducing cooling energy consumption. Meanwhile, DRC materials add adaptive capabilities by dynamically regulating radiative properties based on changing environmental conditions and building thermal loads. Incorporating these materials into the outermost building envelope layers is a strategic implementation that maximizes their impact on the overall building thermal performance. In this sector, we firstly review and conclude the strategies of integrating SRC materials into building envelopes and corresponding analyses of their performance impacts. Subsequently, we will explore the potential of DRC materials to provide additional advantages through dynamic regulation of radiative properties based on changing environmental conditions and thermal loads.

Among building envelope components, roof surfaces receive the most intensive solar radiation, particularly for buildings with high roof-to-wall ratios. This solar heat gain accounts for a substantial portion of total building energy consumption, ranging from 5% to 10%, and can exceed 40% electricity consumption for top-floor spaces [73]. Consequently, improving the cooling capacity of roof structures is crucial for reducing cooling electricity consumption of air-conditioning systems and maximizing energy-saving potential in buildings. To address this challenge, cool roof schemes have gained widespread popularity [74]. Originating in the United States, cool roofs have been implemented across various countries as a well-known practice to reduce building energy consumption [75], including Britain [76], Greece [77], Singapore [78], France [79], Italy [80], Malaysia [81], among others.

Numerous studies have demonstrated the benefits of cool roofs to save building energy across different climates. However, the materials primarily used in current cool roof products suffer from suboptimal optical performance, hampering their ability to deliver exceptional cooling capabilities, especially under exposure to direct sunlight. Conventional white cool roof coatings typically contain TiO_2 pigments [82] which absorb ultraviolet, violet light in addition to the near-infrared absorption by the polymer binders. As a result, even the best commercially available TiO_2-based cool roof paints have a solar reflectance below 0.86 [83]. This limited reflectance significantly restricts their achievement of sub-ambient passive radiative cooling during daytime periods when cooling demands are the highest. With rapid advancements in RC technology, emerging daytime RC materials exhibit excellent solar reflectance and thermal emittance properties. For example, porous polymer cooling coatings can achieve solar reflectance over 0.98 and thermal emittance over 0.97 [12], enabling practical attainment of sub-

Table 1
Performance comparison of active and passive DRC designs and structures.

DRC materials and structures			Cooling			Heating		
			R_{Solar}	A_{Solar}	E	R_{Solar}	A_{Solar}	E
Active	Janus membranes	Yang et al. [26]		0.12			0.975	
		Song et al. [27]	0.91		0.98	0.74		0.1
	Louver	Li et al. [28]	0.97		0.94		0.93	0.14
		Yang et al. [29]	0.97		0.82		0.91	0.04
	Strain-responsive materials	Ke et al. [30]		0.05	0.91		0.98	0.38
		Liu et al. [31]	0.92		0.79	0.95		0.15
		Zhao et al. [32]	0.93		0.94		0.95	
	Reversible metal electrodeposition	Zhao et al. [33]	0.89			0.17		
Passive	VO_2	Ono et al. [40]			0.64			0.05
		Wu et al. [43]			0.83			0.47
		Wang et al. [46]			0.61			0.21
		Tang et al. [47]			0.90			0.21
		Liang et al. [48]			0.78			0.1
	Hydrogel	Mei et al. [55]	0.82 @ visible		0.96	0.12 @ visible		0.96
	Thermochromic microcapsules	Dong et al. [59]	0.93		0.94	0.7		0.94
		Wang et al. [61]	0.91			0.73		
	Thermochromic microcapsules + thermal-response folding	Zhang et al. [62]	0.65 @ visible		0.95		0.73 @ visible	0.28
		Zhang et al. [63]	0.85		0.97		0.91	0.08
	Thermal-response folding	Chai et al. [64]		0.05	0.93		0.81	0.10
	Perovskite manganese	Shimakawa et al. [66]			0.67			0.37
		Zhao et al. [69]			0.69 (173 K)			0.06 (373 K)
		Zhao et al. [70]			0.68 (103 K)			0.21 (373 K)
		Fan et al. [71]			0.62 (350 K)			0.39 (243 K)

R_{Solar}: solar reflection; A_{Solar}: solar absorption; E: emission.

ambient cooling even under direct exposure to sunlight. Utilizing these cutting-edge radiative cooling materials with outstanding spectral selectivity can unlock the potential benefits for improving building thermal and energy performance compared with conventional cool roof technologies. It is crucial to comprehensively evaluate the incorporation of state-of-the-art RC materials with outstanding spectral properties into buildings as passive envelope strategies.

Recognizing the need to accurately assess the potential of emerging high-performance RC materials, Chen et al. [84] developed a new RC roof cooling model that fully accounts for the spectral selectivity of these materials and atmospheric effects like infrared radiation from precipitable water vapor, which enabled precise evaluation of RC roof performance under various conditions. Leveraging this model, Chen et al. conducted a comprehensive techno-economic and environmental analysis of implementing advanced RC 'super-cool' roof strategies across typical climates in China. Their study revealed that in hot climate cities, employing super-cool roofs can lead to significant annual roof-induced electricity savings for cooling, ranging from 42.9 to 97.8 kWh/m^2 depending on the air-conditioning system efficiency (coefficient of performance(COP) values) (Fig. 6a) [85]. The maximum acceptable incremental cost of implementing the super-cool roof was found to be 34.6–64.7\$/m^2 for a 5-year simple payback period. Hong Kong exhibited the most favorable economics, with net cost savings of 6.9–15.8 \$/(m^2·yr). Moreover, the electricity reductions from the super-cool roof adoption translated to substantial reductions in associated carbon emissions from power generation, averaging 24.6–56.1 kg/(m^2·yr) across the climates analyzed.

To maximize building energy-saving potential, Chen et al. [86] proposed a comprehensive passive envelope retrofit strategy that incorporates RC-based super-cool roofs, colored cooling walls, and thermally insulating glazing into a standard commercial building model. For wall surfaces, a key consideration is avoiding glare issues from high reflectance while providing visual comfort and aesthetics. Chen et al. employed a colored and paintable bilayer RC coating [87] as the wall retrofit material, selectively absorbing visible wavelengths for desired colors while strongly reflecting near-infrared wavelength to minimize solar heat gain. This colored cooling wall was combined with the super-cool roof and low-e windows to form an integrated passive envelope cooling system. Colored RC materials that selectively absorb specific parts of visible light to exhibit desired colors, while strongly reflecting near-to-short wavelength infrared radiation to minimize solar heat absorption, are highly desirable for building facades, especially for wall surfaces. Taking these factors into account, and analyzing a single-story U.S. commercial building archetype, the super-cool roof achieved 8.2–29.7% cooling electricity savings across varying climates. The colored cooling walls provided lower but still significant 3.5–9.3% annual cooling energy reductions. Optimal designs maximized regional cost savings from 0.03 to 2.13 \$/(m^2·yr), avoiding 0.11–16.72 kg/(m^2·yr) CO_2 emissions [86]. Importantly, these proposed passive envelope strategies for building cooling can also be applied to multistory buildings, offering significant energy and economic benefits [88]. However, it is worth noting that the benefits may vary across different floors in high-rise buildings. Super-cool white roofs can lead to annual cooling electricity savings ranging from 2.5% to 6.1% for the entire building and from 7.0% to 17.1% for the top floor, depending on climate characteristics [88]. On the other hand, colored cooling walls can provide nearly equivalent energy-saving benefits for each floor [89]. Overall, integrating RC materials into advanced passive envelope systems contributes substantially to realizing energy-efficient, low-carbon buildings.

While SRC materials offer significant benefits in hot climates requiring year-round cooling, the development of DRC modules becomes crucial in enabling smart thermal regulation of building

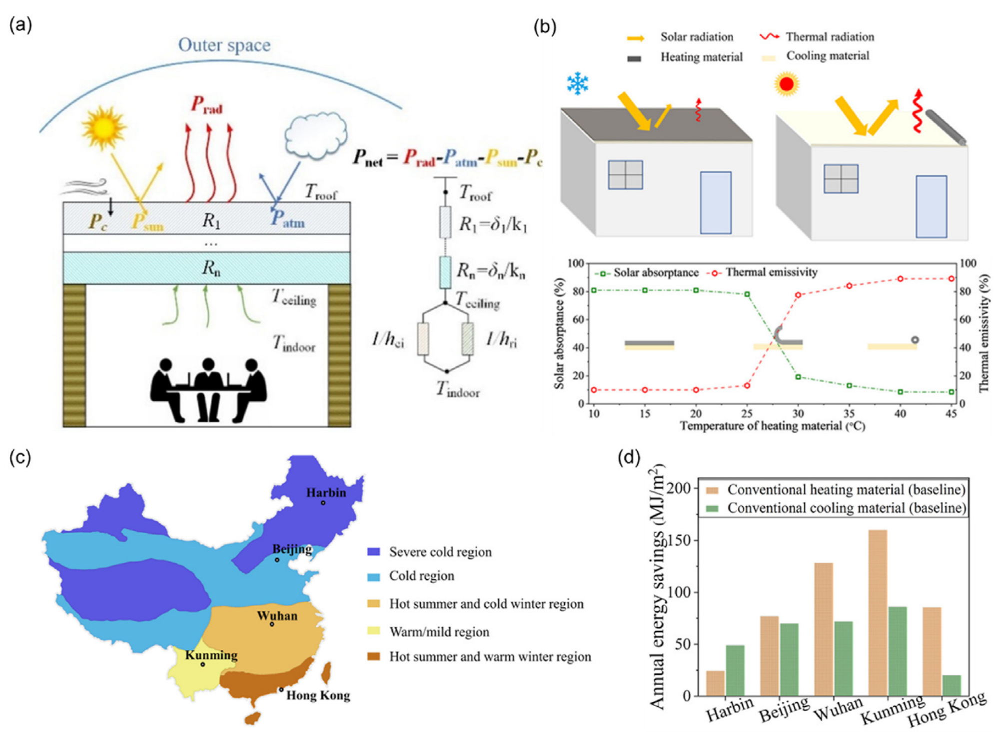

Fig. 6. DRC integrated as building envelopes. (a) An advanced calculation model for evaluation of techno-economic and environmental performance of RC-based super-cool roof applications in China [85]. Copyright 2021 Elsevier. (b) A DRC design for roof covering application [92]. Copyright 2023 Elsevier. (c) Location maps of the investigated cities for DRC energy-saving evaluation [92]. Copyright 2023 Elsevier. (d) DRC-induced annual building energy savings in five typical cities [92]. Copyright 2023 Elsevier.

envelopes in regions with distinct heating and cooling seasons. This allows maximizing energy savings across varying conditions. Therefore, the development of DRC modules becomes crucial for smart thermal regulation of building envelope systems to maximize energy-saving performance. Gong et al. [90] proposed a novel envelope module that incorporates paraffin wax as the cover, along with an RC [91] as the underlying component. This design resulted in the development of a DRC with two different working modes and dynamic optical properties. The DRC can automatically adjust its solar reflectance and thermal emittance in response to changing external ambient temperatures, due to the liquid-solid transition of paraffin wax. This dual-mode spectral characteristic enables the DRC to switch between cooling and heating modes. The study found that in cold climate conditions, the DRC can be warmer than a single radiative cooler by over 3 °C, while maintaining high cooling power in hot climates. This innovative cooling design demonstrates its energy-saving capability as a rooftop strategy across different climate regions. Comprehensive energy-saving performance evaluations were conducted by implementing DRC in buildings as a rooftop strategy. The evaluations took into account specific assumptions related to heating requirements when the indoor air temperature falls below the phase change temperature, as well as cooling requirements when the indoor air temperature surpasses the transition temperature of the paraffin wax. The numerical simulation results, which considered various climates in four representative cities in China, revealed that DRC offers substantial yearly energy savings compared with SRC with fixed spectral properties. In the hot and humid climate of Hong Kong, DRCs exhibited an impressive energy-saving efficiency of 52.0% when compared with a bare roof lacking radiative cooling coatings. Moreover, this saving rate was 9.6% higher than that achieved by SRC. Notably, the disparity between DRC and SRC was even more significant in the dry climate of Beijing, reaching up to 15%. These findings clearly demonstrate the promising potential of DRC in achieving energy savings for buildings.

Moreover, from the mechanical modulation perspective, Chai et al. [92] developed a DRC cover using easily implemented processes for synergetic modulation of solar and thermal radiation (Fig. 6b). Extensive energy simulations were conducted to assess the energy-saving potential of a developed rooftop covering in different climatic regions of China. A standard-compliant office building was constructed in five cities, incorporating the covering as a roof retrofitting strategy. The results revealed that the proposed covering yielded significant energy savings when compared with traditional heating and cooling roof materials in all five selected cities. In particular, taking the city of Wuhan located in a hot summer and cold winter climate region as an example, the annual energy savings were remarkable, amounting to 128 MJ/m^2 higher when compared with traditional heating materials and 72 MJ/m^2 higher when compared with traditional cooling materials (Fig. 6c and d). These findings underscore the substantial benefits that can be derived from implementing the proposed DRC rooftop covering module, making a significant contribution toward sustainable building practices.

4. Integration with building service systems

While RC materials have been directly implemented on building envelopes to provide passive cooling for walls and roofs, these technologies have also been integrated with various building service systems to indirectly utilize their cooling capabilities [93,94]. This section first reviews the different ways SRC has been incorporated into building services like heating, ventilation, air conditioning (HVAC) and refrigeration systems. Then, we look into the potential of a DRC-integrated system on performance enhancement and climate adaptability of building service systems.

In general, the indirect utilization of the cooling capability can be achieved by either air [95,96] or water [97,98] flowing though the SRC system. While the cooled air can be supplied indoors, the cooled water is commonly used with a heat exchanger connected with the SRC panel, i.e., the cooling is collected at the SRC panel and then released at the heat exchanger. The cooling power from this SRC panel/heat exchanger configuration can then be used to directly cool the supply air stream passing through the heat exchanger [99] (Fig. 7a). However, while straightforward, using solely the SRC cooling is typically insufficient for meeting indoor cooling demands. Therefore, SRC is rarely implemented as the sole cooling source in this manner. Instead, SRC is commonly integrated as a supplemental cooling source with various HVAC systems. This is facilitated by the compatibility of the SRC panel/heat exchanger configuration with different air-conditioning systems. For example, in systems with a water chiller connected to a cold water storage tank and indoor radiant cooling pipes (e.g., ceiling cooling pipes [100] (Fig. 7b) and radiant surface cooling pipes [101]), which increases the overall system cooling capacity. Additionally, for air systems with a water chiller and cooling coil for conditioning the air supply, an SRC-integrated heat exchanger can provide further cooling to the air stream to reduce the cooling load on the chiller [102] (Fig. 7c).

SRC has also been combined with direct evaporative cooling (DEC) systems [103] and indirect evaporative cooling (IEC) systems [104]. In these integrations, the cooling power collected by the SRC panel pre-cools the incoming fresh air stream passing through the connected heat exchanger. For the combination with DEC systems, the cooling effectiveness, as defined in the study [103], improved to over 100 for the hybrid DEC system, compared with the value of below 80 for the pure DEC system. For the combination with IEC systems, it was found that water and electricity consumption of the hybrid IEC system were 44.2% and 53.4% lower than the pure IEC system [104]. In the latest research conducted by Hu et al., it was demonstrated that the SRC-IEC system can further decrease the supply air temperature by 0.88 °C, compared with the IEC-only system. Correspondingly, the dew-point effectiveness and cooling power gain were increased by 11.91% and 9.94%, respectively [105]. It is well-established that evaporative cooling technologies, which rely on the latent heat of vaporization to provide cooling, exhibit diminished performance in humid ambient conditions [106,107]. As the moisture content of air increases, the evaporative cooling potential decreases due to the air becoming more saturated with water vapor. Consequently, evaporative cooling systems require supplemental dehumidification or additional cooling capacity in humid climates to maintain effectiveness. Notably, the cooling capabilities of SRC are also adversely impacted by high humidity levels in the atmosphere [108,109]. The presence of moisture inhibits the efficient radiative heat dissipation to the cold universe. Therefore, while the integration of SRC can augment the overall cooling capacity of evaporative systems under dry conditions, this hybrid approach does not represent an ideal solution for humid climates. The performance degradation experienced by both SRC and evaporative cooling in humid environments means SRC cannot sufficiently compensate for the inherent limitations of evaporative technologies under these conditions.

Another application utilizing the SRC panel and heat exchanger configuration is SRC-assisted thermoelectric cooling systems [110] (Fig. 7d). Compared with conventional indoor cooling systems, thermoelectric coolers have a simpler configuration and are more environmentally friendly [111,112]. However, thermoelectric cooling systems typically suffer from low COP and limited cooling

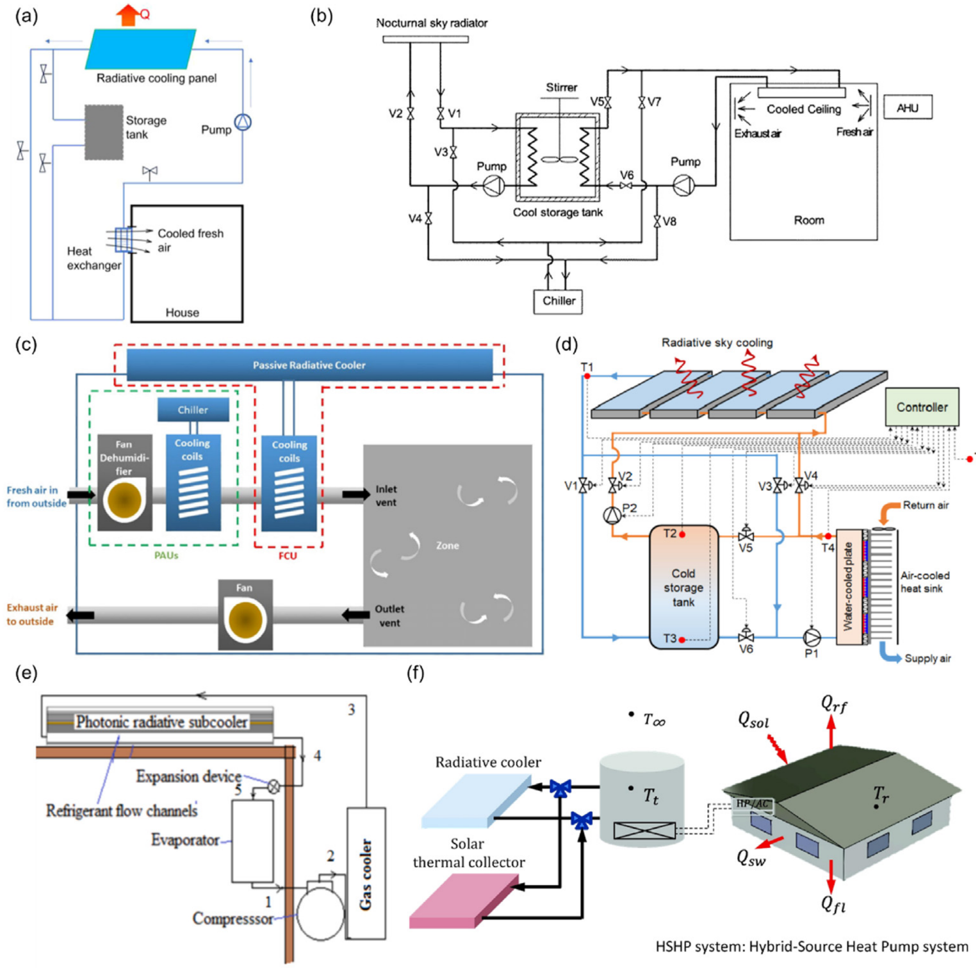

Fig. 7. The integration of SRC technology with building service systems. (a) Schematic of an air-conditioning system where supply air is cooled by a heat exchanger connected with SRC [99]. Copyright 2021 Elsevier. (b) Schematic of an air-conditioning system where SRC assists the water chiller for indoor radiative cooling through ceiling cooling pipes [100]. Copyright 2012 Elsevier. (c) Schematic of an air-conditioning system where SRC assists the water chiller for indoor radiative cooling through cooling coils [102]. Copyright 2018 Springer Nature. (d) Schematic of an SRC-assisted thermoelectric cooling system [110]. Copyright 2020 Elsevier. (e) Schematic of an SRC-assisted CO_2 vapor-compressor air-conditioning system [118]. Copyright 2021 Elsevier. (f) Schematic of the air-conditioning system with both SRC panel and solar collector [122]. Copyright 2021 Elsevier.

capacities. In this integrated system, the water-cooled heat exchanger, which has its cooling power provided by the connected SRC panel, serves to remove heat from the hot side of the thermoelectric coolers. This active cooling approach is more effective at rejecting heat than simply relying on natural air cooling of the hot side. By enabling better heat sinking, the SRC-assisted cooling augments the thermoelectric system's overall COP and cooling capacity beyond what could be achieved by the thermoelectric components alone.

Ground-source heat pump (GSHP) systems are a heating/cooling technology that leverage the relatively stable and high thermal mass of the ground as a heat source/sink [113,114]. Heat is exchanged with the ground via ground heat exchangers (GHEs), extracting heat from or rejecting heat to the ground, which has a more moderate temperature than the ambient air. In hot climates with a predominant cooling demand, the potential exists to integrate GSHP systems with SRC technologies [115–117]. Over extended periods of cooling operation, the ground temperature surrounding the GHEs gradually increases as more heat is injected into the ground than extracted. This imbalanced thermal condition leads to a decrease in system COP and can eventually cause the system to become inoperable if the ground gets too hot, compromising long-term sustainability. SRC offers a solution by providing an effective means to reject and dissipate the excess heat building up in the ground loop. By acting as a supplemental heat sink, SRC helps maintain balanced ground thermal conditions during long operating periods. This prevents detrimental ground temperature rise, preserving the system COP and enabling sustained operation of the GSHP system.

Additionally, SRC panels have been utilized to cool the CO_2 refrigerant in vapor-compression air-conditioning systems [118] (Fig. 7e). The research conducted by Bijarniya et al. suggests that the use of SRC panels can reduce the cooling load of the CO_2 air conditioner. The RC-hybrid system demonstrated a 33.8% increase in COP and a 29.1% improvement in energy efficiency compared with the standalone vapor-compression system. Furthermore, SRC has been incorporated into solar absorption cooling systems to enable all-day cooling operation [119]. During daytime, the solar absorption chiller utilizes heat collected by photothermal panels to drive the generator, separating the lithium bromide and water working pair [120]. However, realizing nighttime operation with a conventional solar absorption system requires bulky thermal energy storage and complex installations [121]. To overcome this, SRC materials were applied to the underside of the photothermal panels, allowing them to provide radiative cooling to the indoor space at night. However, this design requires flipping the photothermal panels between day and night operations. Moreover, there may be a transition period for the SRC materials to sufficiently cool the panels after they are heated during daytime operation. Nonetheless, this integration represents a compelling approach to provide space cooling entirely through renewable energy sources.

As discussed in the review of RC materials used as building envelopes, it was argued that SRC materials can lead to unwanted cooling effects during cold weather conditions, which is undesirable. DRC materials that can modulate their radiative cooling properties were suggested as an improved building envelope solution, especially for regions experiencing distinct hot summer and cold winter seasons. Similarly, for building service systems integrated with SRC cannot provide the flexibility to modulate cooling power in response to varying environmental conditions and system operating requirements while DRC enables more effective utilization aligned with heating/cooling demands.

Recognizing the need for DRC control, Yoon et al. proposed an air-conditioning system integrating SRC panels with solar collectors to enable seasonal switching operation [122] (Fig. 7f). The panels provide cooling during hot summer conditions, while the solar collectors deliver heating in winter. Although this design leverages renewable energy sources, it requires significant space for the SRC and solar collector components, which may not be economically viable. In contrast, if the SRC technology itself is optically adaptive, a single panel could operate in a cooling mode during summer and a heating mode in winter for the indoor environment. In other words, the DRC panel functions as both RC panel and solar collector simultaneously. This dynamic, dual-mode operation is applicable not only to the various air-conditioning system configurations [99–102], but also to the evaporative cooling systems [103,104] by simply disabling evaporative operation seasonally. Under the circumstances that DRC is utilized in the various air-conditioning systems [99–105] instead of SRC, the hybrid air conditioners will have the ability of providing heating in cold weather. Specifically, the panel with DRC can both cool and heat the supply air passing through the heat exchanger, in contrast to the panel with SRC which can only cool the supply air [92]. The capability of providing cooling in summer and heating in winter is also achievable for water chillers connected to a water storage tank and indoor radiant pipes [93,94]. For DEC and IEC air-conditioning systems, the use of DRC instead of SRC can also provide heating in cold weather [96,97]. Moreover, for the solar absorption cooling system integration [119], the use of DRC materials would eliminate the need to physically flip the orientation of the photothermal panels between daytime and nighttime operation. The DRC could transition between solar heat collection and RC modes as needed.

For GSHP systems, while SRC is suitable for hot regions with a dominant cooling load, and solar heating is a good choice for cold regions with a dominant heating load to maintain ground thermal balance, DRC technologies are especially advantageous for regions experiencing distinct hot summers and cold winters. During hot summer conditions, panels with DRC materials can function as standard RC panels to provide supplemental cooling, helping avoid excessive heat accumulation in the ground loop. Conversely, in winter, these same DRC panels can operate in a solar heating mode, providing useful heat gain to counteract overcooling of the ground loop. By leveraging DRC in this manner, the overall performance and sustainability of the GSHP system can be improved across all seasons while maintaining balanced ground thermal conditions for continuous operation. The integration of DRC materials with various air-conditioning systems, as discussed, has demonstrated improvements in system performance and cooling capacity. Looking ahead, DRC technologies hold significant potential to further enhance the seasonal adaptability and multifunctional capabilities of diverse air-conditioning system configurations.

5. UHI mitigation

Looking beyond individual buildings, sustainable cooling solutions are also critically needed at the urban scale to mitigate the UHI effect. The UHI effect constitutes a significantly escalating environmental phenomenon, delineated by conspicuously elevated temperatures in urban areas as opposed to their suburban counterparts, thus representing a critical environmental challenge [123]. As global urbanization intensifies, the implications of the UHI effect on urban environmental integrity, public health, and energy demand become increasingly significant. Initially, it fosters dependency among city dwellers on air-conditioning and cooling mechanisms, thus elevating energy consumption and imposing additional burdens on electrical power systems [124]. Furthermore, the heightened urban temperatures aggravate air quality issues [125], elevating the levels of detrimental airborne contaminants. This deterioration in air quality poses substantial risks to public health, adversely affecting human health and well-being [126]. Moreover, the UHI effect amplifies the severity of heat waves, significantly heightening the likelihood of heat-induced illnesses and fatalities due to the amplified thermal stress [127]. Notably, the exacerbation of the UHI effect is closely intertwined with climate change, reinforcing a vicious cycle that further warms urban environments, thereby magnifying their heat intensity beyond the natural climate warming trends observed globally [128]. Considering the complexity and grave consequences of the UHI effect, it is imperative to devise and implement innovative, sustainable cooling approaches like RC to alleviate these ramifications at a city-wide scale. This section begins with a review of the extensive research conducted on RC applied to building surfaces and urban roads in cities. Subsequently, we will explore the value and potential of other applications of DRC in mitigating the UHI effect.

To deal with the UHI phenomenon, countries globally have undertaken extensive research and initiatives aimed at identifying and deploying effective mitigation strategies. Qin et al. [129] conducted a comprehensive review of existing UHI mitigation approaches, revealing that around 40% focus on two primary areas: 'Cool Roof and Pavement Technologies' and 'Energy Efficiency.' A key strategy in these areas is the large-scale deployment of RC materials across urban surfaces like roofs and pavements. The widespread application of high LWIR emissivity RC materials can provide a city-wide cooling effect by enhancing radiative heat expulsion from built environments to the colder atmospheric temperatures. This passive cooling capacity reduces the reliance on energy-intensive air conditioning, leading to lower city-scale energy consumption and greenhouse gas emissions. Moreover, by mitigating surface temperatures of roofs, pavements, and other urban infrastructure, RC materials can directly combat the elevated temperatures characteristic of UHI. Beyond individual building applications, the effective implementation of RC technologies across entire city districts or urban cores could produce a compounded cooling impact. The cumulative effects of RC surfaces could counter the heat trapping and amplification effects inherent to densely built environments. Therefore, city-scale adoption of RC represents a promising pathway for sustainable UHI mitigation.

Yuan et al. [130] illustrated the efficacy of implementing daytime RC technology in standalone structures through a comprehensive 72-h field study on a prototype dwelling with dimensions of 4 m × 3 m × 2.4 m (Fig. 8a). This investigation revealed that, under direct solar radiation peaking at 720 W/m^2, the RC film consistently reduced the roof surface temperature of the model house by 2–9 °C relative to the surrounding air temperature. Moreover, the interior air temperature within the house fitted with the RC film was maintained at 2–14 °C below the external air temperature during daylight hours, suggesting a significant potential for diminishing active cooling energy demands. In a subsequent study by Wang et al. [131], the scope was broadened to include larger structures, specifically a commercial warehouse spanning 152.0 m × 54.0 m × 11.5 m, which was fitted with RC metamaterial films produced using scalable methods (Fig. 8b). This study assessed indoor air temperature, roof temperature, and overall cooling energy consumption. The findings indicated that, in comparison with a traditional steel roof, the RC roofing yielded annual cooling energy savings of 22.4% (5.9 kWh/m^2) in Greenville, USA, 21.2% (9.3 kWh/m^2) in Cairo, Egypt, 53.0% (16.6 kWh/m^2) in Jimma, Ethiopia, and 65.2% (10.1 kWh/m^2) in Mexico City, Mexico, thereby highlighting the substantial cooling energy efficiency benefits of RC technology.

For larger-scale buildings, Xu et al. [132] conducted a study investigating the impact of RC materials on the microclimates within residential communities across six typical neighborhoods in Nanjing, China, employing computational fluid dynamics (CFD) modeling (Fig. 9a). The findings revealed that the cooling effectiveness of these materials is significantly affected by the buildings' morphology, height, and orientation. Specifically, tall buildings with large, south-facing facades benefit more from cooling materials than low-rise structures. Generally, during the summer months, the application of RC materials resulted in a temperature reduction of approximately 13.5 °C on roofs and 3.5 °C on walls. Furthermore, the use of RC materials was shown to enhance ventilation capacity within the residential areas by approximately 6% in summer, contributing to a reduction in ambient air temperatures, though the improvement was moderate. Building upon neighborhood-scale studies, Li et al. [133] expanded the simulation scope to model the effects of RC materials across the urban environment of Xi'an, China, using COMSOL modeling validated against actual meteorological data (Fig. 9b). Their research specifically focused on assessing the thermal mitigation benefits of integrating RC within urban infrastructure at the city-scale. The study demonstrated that the application of RC materials to both roofs and walls resulted in notable temperature reductions of 2.9 °C and 3.5 °C, respectively, on selected summer days across the modeled urban area. To quantify the influence on urban thermal

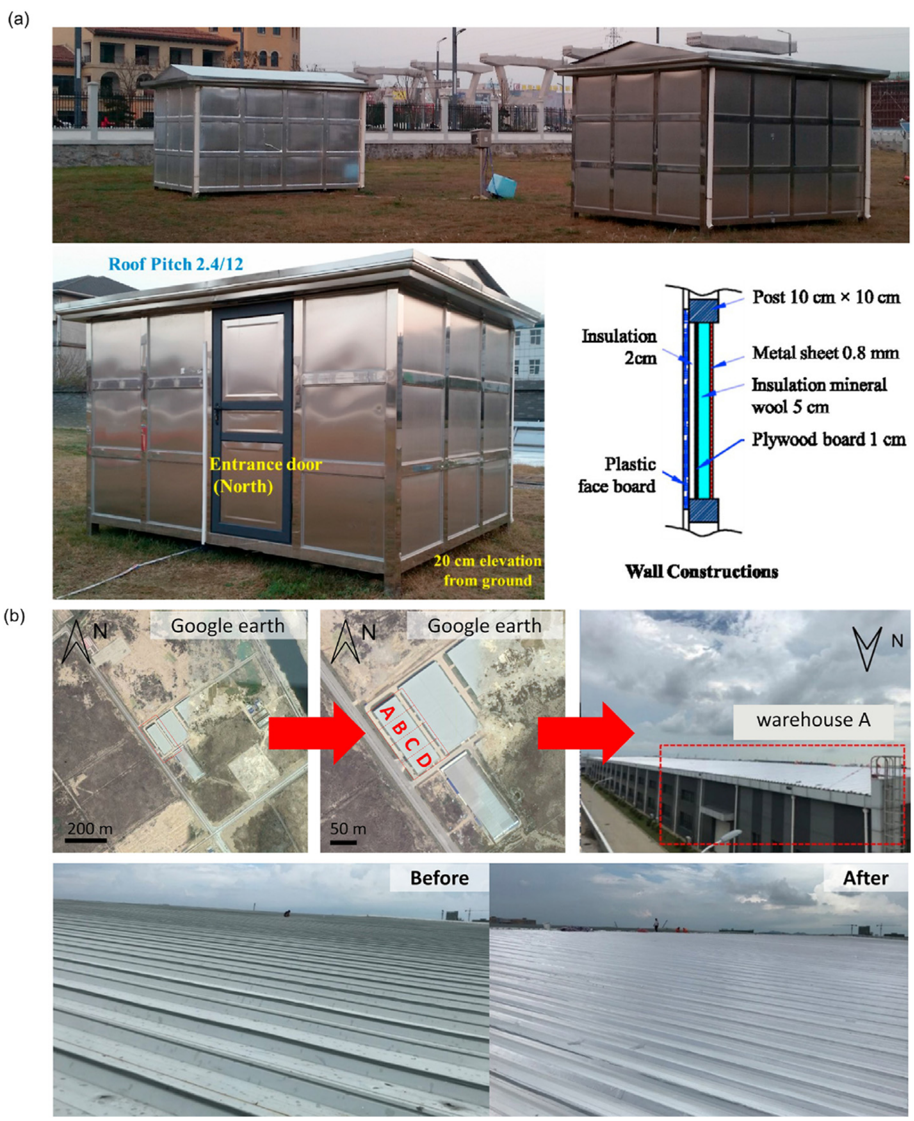

Fig. 8. The investigation of RC effect at the scale of a single building. (a) Model houses (Left: RC-film model house; Right: metal sheet model house) with construction schematic [130]. Copyright 2021 Elsevier. (b) Google Earth images and photographs of the warehouse and exterior of the roof before/after applying the RC film [131]. Copyright 2021 Elsevier.

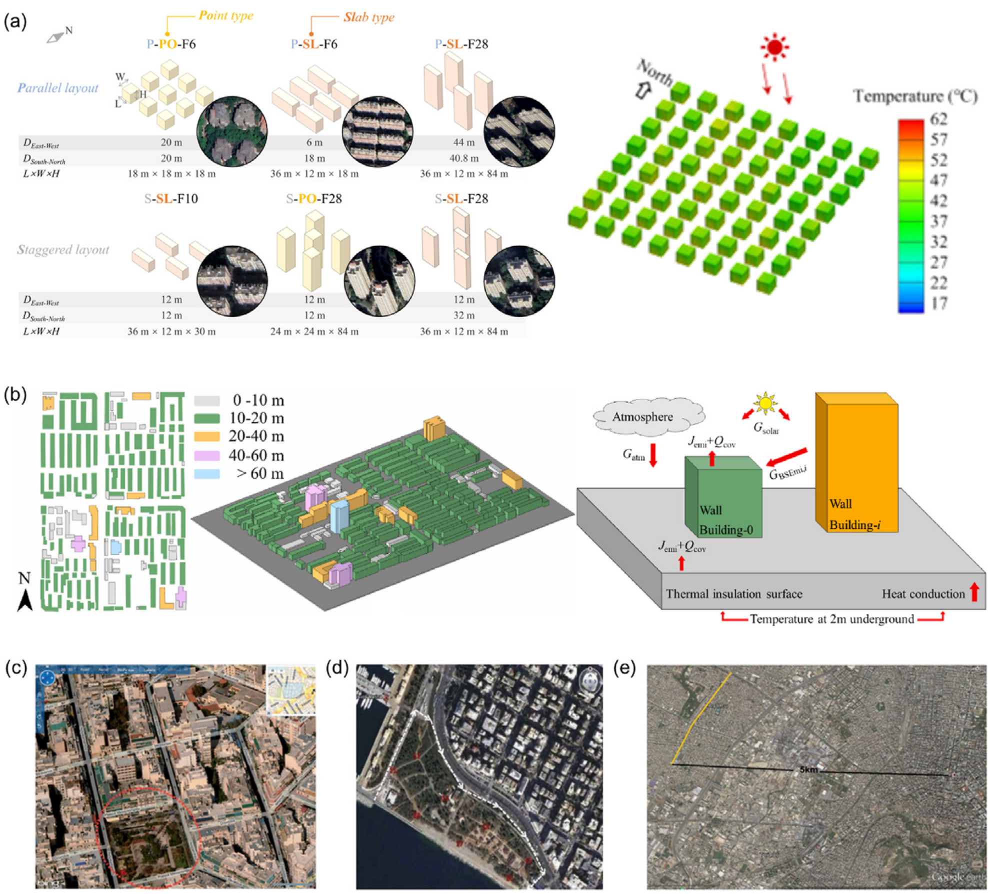

Fig. 9. The investigation of RC effect in the scale of neighborhood or city. (a) The schemes of building layouts for case study and contours of building surface temperature applied with RC materials [132]. Copyright 2023 Elsevier. (b) Investigation on building layout and thermal interaction among buildings for RC application [133]. Copyright 2023 Elsevier. Satellite images of large-scale applications of paving in Greece: (c) Athenian Central Square [135]. Copyright 2011 SAGE Publications. (d) Athenian City Park [136]. Copyright 2012 Elsevier. (e) Main transport corridor in western Athens [137]. Copyright 2018 Elsevier.

characteristics, the UHI intensity (UHII), and Heat Field Intensity Index metrics were analyzed. Results showed a pronounced increase in UHI effects during daytime hours when radiative cooling was omitted from the simulations, with a UHII level of 6 and average building temperatures reaching up to 55 °C for the original cement roof and concrete wall cases. However, the widespread deployment of RC materials across the urban area had a negligible mitigating impact on the nocturnal UHI effect, even when applied concurrently to both roofs and walls.

In addition to building roofs and facades, pavements (including streets and sidewalks) constitute a significant portion of urban surface area [134]. Greece has been a leader in researching large-scale applications of reflective cool pavements, with a cumulative deployment area reaching 44,400 m^2 from 2011 to 2018. Gaitani et al. [135] initiated a study in a densely populated central Athens square, covering 4160 m^2 with concrete tiles characterized by average solar reflectance and emissivity values of 0.45 and 0.87, respectively (Fig. 9c). Their daytime field experiments demonstrated that these reflective tiles reduced the road surface temperature by 4.8 °C. Furthermore, validated CFD simulations indicated that such cool pavements could lower nearby air temperatures by 1.6 °C at a height of 1.5 m. Similarly, Santamouris et al. [136] found that reflective pavements could decrease surface temperatures by up to 12 °C over an area of 4500 m^2, with simulations indicating a reduction of 1.9 °C during a typical summer day (Fig. 9d). In 2018, Kyriakodis and Santamouris [137] further expanded their investigations to a major traffic corridor in western Athens, covering nearly 37,000 m^2 with cool-colored thin-layer asphalt and reflective concrete pavements (Fig. 9e). They highlighted the potential of cooling pavements that lower ambient temperatures by 1.5 °C and achieve a maximum surface temperature reduction of 11.5 °C. Moreover, several U.S. studies have directly measured the cooling effects of reflective roads on ambient air temperatures. Middel et al. [138] undertook large-scale cooling road surface projects in Los Angeles (13,000 m^2). Schneider et al. [139] conducted a seven-month solar reflective pavement experiment on 58-km of residential streets in Phoenix, Arizona. These field studies confirmed that reflective road surfaces could significantly lower road surface temperatures by 9–16 °C and reduce nearby air temperatures by approximately 0.5 °C.

However, reflective coatings may have certain negative impacts during winter. Therefore, dynamic road coatings, such as thermochromic (TCM) coatings, have been developed for temperature regulation on road surfaces. Zhang et al. developed two TCM coatings, red and black, which showed cooling effects 2–5 °C higher than cooling coatings of the same color [140]. Additionally, CFD simulation results indicated that the average air temperature over a 1.5 m thermochromic road surface was approximately 0.5 °C lower than that of a traditional reflective road surface. Li et al. developed a composite coating containing thermochromic (TCM) materials and snow melting and ice suppression (SMIS) functional fillers [141]. The optimal dual-layer coating structure with TCM at the bottom and SMIS on the top achieved a cooling effect of 9 °C in summer and maintained a road surface ice temperature of 5 °C in winter, with faster ice melting rates. Zhao et al. applied blue thermochromic materials as a binder in matrix asphalt and replaced a certain proportion of mineral fillers with low freezing point materials, developing an asphalt pavement with temperature regulation capabilities [142]. The research results demonstrated that the temperature-regulating asphalt mixture performed better in terms of cooling and de-icing compared with unmodified asphalt mixtures.

Cool roofs and facades utilizing sky radiative cooling, high-reflectance road surfaces, and thermochromic road surfaces, as discussed, have demonstrated their capability to address and mitigate the UHI phenomenon through dynamic/static radiative cooling approaches. In the future, DRC (dynamic radiative cooling) technology can be integrated with other urban heat management strategies, such as personal heat management, vehicle heat management, and atmospheric water harvesting, to achieve a more comprehensive approach to mitigate the UHI effect. By supplementing and integrating these strategies, it is possible to create a more sustainable and livable urban environment.

6. Future outlook and opportunities

This review has provided a comprehensive overview of DRC technologies, from materials enabling optical switching to integrated system designs, and their diverse applications spanning building and city scales. External stimuli-triggered active DRC systems were introduced. VO_2 and other phase change materials exhibiting temperature-driven optical modulation were highlighted as promising candidates for passive DRC. Various possible system configurations were discussed, including integrating optical switching materials into roof/facade assemblies, solar collectors, and ground-source heat pumps to dynamically control radiative cooling versus solar heating. Importantly, research into large-scale UHI mitigation using RC materials is an emerging area, with investigations thus far focused primarily on deploying SRC materials like cool roofs and pavements across city districts. These studies on SRC's impacts on building and city scales provide great guidance for future work evaluating DRC technologies in urban environments. Multiple field studies validated simulations showing reduced ambient and surface temperatures through large-area cool building envelope and cool pavement implementations, with the compounding impacts helping counteract amplified heat trapping in dense urban environments. Lastly, we will discuss the remaining research gaps in DRC and their potential applications below (Fig. 10).

While DRC represents a more advanced technology capable of providing active cooling and heating compared with SRC materials, the thermal performance of DRC systems still encounters challenges similar to those faced by SRC. A key issue is that the radiative cooling capacity is affected by external atmospheric factors, particularly atmospheric transmittance. On the other hand, the heating capacity is highly dependent on changing solar irradiation. Overcoming this unstable thermal performance represents a critical research gap.

SRC and DRC technologies demonstrate maximal effectiveness under conditions of unobstructed exposure to the sky, which is one of the reasons why current research focuses on application to building roofs. In contrast, ground surfaces in urban settings, frequently the lowest points encountered in daily life, are subject to obstructions by buildings, vehicles, and pedestrians. Consequently, the radiation reflected or emitted by ground surfaces does not ideally propagate into the sky. Such strategies, aimed at redistributing heat within urban areas, may inadvertently contribute to the exacerbation of UHI phenomena rather than mitigating them. For instance, research by Yaghoobian and Kleissl [143] simulated

Fig. 10. The outlook for future development and application of DRC technology.

the effects of enhanced solar reflectance on an urban area in Phoenix, Arizona, revealing an 11% increase in the annual cooling load for nearby buildings following an increase in road surface reflectance from 0.1 to 0.5. Similarly, Qin's investigation [144] into the impact of the aspect ratio of urban canyons on urban canyon albedo underscored that reflective road surfaces are beneficial only when the canyon's aspect ratio is less than or equal to 1. Moreover, heightened reflectivity may intensify thermal discomfort for pedestrians, with studies such as that by Lynn et al. [145] indicating a significant escalation in heat stress, where a reflectivity increase from 0.15 to 0.50 could augment the maximum net heat flux experienced by individuals by approximately 80 W/m^2.

DRC materials are typically designed with broadband solar reflection properties to maximize radiative cooling performance in the 'cooling mode.' However, in architectural design, appearance and aesthetics are crucial considerations that cannot be ignored. As color scientist Pernão states, 'Light and color are inseparable elements in spatial perception, promoting its quality, aesthetic relevance, functionality, and human comfort [146].' Therefore, the appearance and color selection of a building facade must be carefully coordinated with the surrounding environment, cultural context, and overall design style to create the desired ambiance and visual identity. Some architectural projects may prioritize adhering to specific color schemes that align with branding, community guidelines, or market preferences. In such cases, a single white or off-white broadband reflective coating, while optimal for radiative cooling, may fail to meet the requisite design specifications and intended appearance. This represents a key challenge where maximizing DRC performance may conflict with achieving certain aesthetic goals through selective spectral reflectance properties. Overcoming this will likely require research into DRC materials and coatings that can provide dynamic tunability not just between cooling and heating modes, but also enabling on-demand control over reflected color/appearance while maintaining sufficient radiative cooling functionality.

Considering the challenges associated with the integration, cost, and durability of DRC technology in construction and road applications, it is imperative to pursue further exploration of integration scenarios and design innovations. This should encompass the development of lightweight, multifunctional materials capable of efficiently regulating the surface temperature of buildings and roads, while also being seamlessly integrated into urban infrastructure and public spaces. The objective extends beyond fulfilling cooling requirements to enhancing aesthetic appeal. Concurrently, research efforts should concentrate on diminishing the cost and improving the durability and maintenance efficiency of these materials and technologies, thereby facilitating their widespread adoption and long-term application in DRC technology.

In addition to the application scenarios discussed in this paper, the future application of RC in greenhouses also warrants attention. Greenhouses are important facilities in agricultural production, providing controlled environmental conditions to promote crop growth and yield. However, the increase in internal greenhouse temperature can lead to crop stress and poor growth. Employing RC materials atop greenhouse coverings [147] or at the soil surface [148] not only facilitates the management and moderation of internal temperatures but also mitigates the risk of overheating and resultant crop distress. The adoption of RC technology within greenhouse settings, nevertheless, is not without its hurdles. Selecting RC materials requires careful consideration of their compatibility, endurance, and effectiveness under diverse humidity levels and weather conditions. The implications of using RC mulch on soil microbiota, nutrient absorption by roots, and pest dynamics also remain to be fully understood. The advancement of RC technology in overcoming agricultural challenges is likely to benefit from the synergistic efforts across disciplines, such as materials science, agronomy, plant physiology, and horticulture.

DRC textiles enable efficient and energy-free personal thermal management. If widely implemented in urban areas, they have the potential to reduce energy consumption for active cooling or heating, thereby contributing to the mitigation of the UHI effect. For instance, some engineered textiles with fiber/yarn architectures have been developed to possess infrared radiation adaptability [149,150]. The yarns in these textiles autonomously expand and contract based on heat and humidity, thereby altering the fiber spacing to achieve cooling at high temperatures and insulation at low temperatures. These DRC textiles are instrumental in creating wearable garments for personal thermal management. Furthermore, the application of humidity-sensitive polymer materials that modify the heat transfer resistance by adjusting the gaps between fabric layers can also regulate personal comfort [151].

Vehicles (such as cars, buses, and trains) are the most prevalent means of transportation on urban surfaces. To achieve more energy-efficient vehicle thermal management, adaptive thermal response has been applied. Inspired by chameleons, Yan et al. [152] developed a temperature-sensitive RC nanocomposite material that provides both cooling and heating functionalities. Experimental results demonstrated that when applied to the surface of a vehicle, the material achieved a cooling effect of 14.0 °C internally, but its actual insulation performance was not reported. Furthermore, the application of DRC in atmospheric water collection strategies is highly valuable for inland cities facing water scarcity. RC not only provides effective air humidity through cooling during the adsorption process but also serves as a condenser for water collection during daytime. On one hand, it reduces the use of active energy sources, and on the other hand, the collected water can be utilized for irrigation of green spaces and plants, thereby enhancing the coverage of green infrastructure, improving the urban landscape and microclimate, and mitigating the UHI effect.

Lastly, an intriguing opportunity lies in combining DRC technologies with power generation modules to further extend the flexibility of passive cooling power. One possible method is to integrate DRC technology with thermoelectric technology [153]. Compared with SRC, DRC not only harvests energy from the cold universe for cooling purposes, but it also leverages solar energy for heating. This provides thermoelectric systems with a greater range of thermal sources to work with, potentially enhancing their overall efficiency and effectiveness. Another potential research is droplet-based electricity generation material to extend the power generation to more weather conditions. While DRC systems excel at providing thermal regulation through dynamic modulation of radiative properties, the performance is highly suppressed during overcast or rainy conditions when clouds block solar absorption and outgoing thermal radiation. However, rainy weather is conducive to exploiting droplet-based electricity generation [154–156]. The configuration of a droplet electricity generation device has been greatly simplified with a straightforward fabrication process, e.g. casting and deposition, which make it easy to integrate with DRC materials. Droplet electricity generation relies on the coupled phenomena of surface electron transfer and electrochemical reactions occurring when droplets make contact with specific classes of materials and electrodes. The energy harvested could potentially power low-power devices or supplement a building's electrical needs. By integrating DRC materials with tailored droplet electricity generation surfaces, this synergistic material system could continue in providing value even when cloud cover renders radiative cooling ineffective. In essence, DRC layers could enable thermal regulation via radiative cooling on clear days, while pivoting to electrical generation mode driven by water droplet interactions during precipitation events. This multifunctional approach turns an atmospheric condition that currently diminishes DRC into an opportunity for electricity production. Such all-weather energy generation capabilities could significantly enhance the versatility and year-round value proposition of DRC in the built environment.

CRediT authorship contribution statement

Kaixin Lin: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Conceptualization. **Jianheng Chen:** Writing – review & editing, Writing – original draft, Investigation. **Aiqiang Pan:** Writing – review & editing, Writing – original draft, Investigation. **Hao Li:** Writing – review & editing, Writing – original draft, Investigation. **Yang Fu:** Writing – review & editing. **Chui Ting Kwok:** Writing – review & editing. **Lin Liang:** Writing – review & editing. **Luke Chao:** Writing – review & editing. **Yihao Zhu:** Writing – review & editing. **Qingping Sun:** Writing – review & editing, Funding acquisition. **Chi Yan Tso:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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