Nano Research Energy

ISSN 2791-0091 (print); 2790-8119 (online)
https://doi.org/10.26599/NRE.2023.9120107

Review Article

Radiative-coupled evaporative cooling: Fundamentals, development, and applications

Li Yu[1,2], Yimou Huang[1], Weihong Li[2], Changmin Shi[3], Brian W. Sheldon[3], Zhuo Chen[1], and Meijie Chen[1] (✉)

[1] School of Energy Science and Engineering, Central South University, Changsha 410083, China
[2] Department of Mechanical Engineering, City University of Hong Kong, Hong Kong 999077, China
[3] School of Engineering, Brown University, Providence, RI 02912, USA

Received: 14 September 2023 / **Revised:** 2 November 2023 / **Accepted:** 8 November 2023

ABSTRACT

As global energy demand continues to rise and climate change accelerates, the need for sustainable and energy-efficient cooling solutions has reached a critical level. Conventional air conditioning systems heavily rely on energy-intensive mechanical cooling, which significantly contributes to both electricity demand and greenhouse gas emissions. Passive cooling strategies, particularly radiative cooling (RC) and evaporative cooling (EC), present an alternative approach by harnessing natural processes for temperature regulation. While standalone RC can be affected by weather conditions and EC relies on water availability, Radiative-coupled EC (REC) offers a versatile and sustainable cooling solution suitable for various applications. Here we summarize an overview of the theoretical foundations and mathematical models of REC, encompassing REC by bulk water (REC-BW), REC by perspiration (REC-P), and REC by sorbed water (REC-SW). Moreover, we explore a range of applications, spanning from industrial processes to personal thermal management, and examine the advantages and challenges associated with each REC approach. The significance of REC lies in its potential to revolutionize cooling technology, reduce energy consumption, and minimize the environmental impact. REC-BW can conserve water resources in industrial cooling processes, while REC-P offers innovative solutions for wearable electronics and textiles. REC-SW's adaptability makes it suitable for food preservation and future potable cooling devices. By addressing the challenges posed by REC, including water consumption, textile design, and optimization of bilayer structures, we can unlock the transformative potential of REC and contribute to sustainable cooling technologies in a warming world.

KEYWORDS

radiative cooling, evaporative cooling, passive cooling, thermal radiation, mass transfer

1 Introduction

The energy global crisis presents a pressing and multifaceted challenge that affects the world's economy, environment, and security [1, 2]. In today's world, nearly 20% of the total electricity consumption in buildings is attributed to global cooling demands [3]. The escalating need for space cooling is straining electricity grids across various nations, leading to increased emissions and elevated urban temperatures. Passive cooling, in contrast to conventional air conditioning, emerges as a viable solution by reducing electricity consumption during operation and diversifying energy sources [4–7].

Radiative cooling (RC) and evaporative cooling (EC) are the two major passive cooling technologies. RC reflects solar irradiance; at the same time, it emits thermal radiation to outer space through a long-wave-infrared (LWIR) atmospheric window (~ 8–13 μm) [8]. RC materials can be classified into inorganic [9–11] and organic materials [12–17]. RC devices include mid-IR (MIR) emitters and medium-infrared transparent materials. The former can be used independently, while the latter requires a substrate with high infrared emissivity [18]. EC utilizes the latent heat of vaporization during the phase transition between gas and liquid, which can be categorized into three groups: direct/indirect evaporative cooling (DEC/IEC), sorption-driven evaporative cooling, and atmospheric water harvesting EC (AWH-EC) [6, 19–21].

However, RC and EC have encountered multiple challenges in their development. The limited cooling power of RC at room temperature requires substantial material consumption and is sensitive to environmental factors like humidity and air pollution [22, 23]. Specifically, direct EC, while operating efficiently, requires water supply systems and substantial water usage, exposing issues in arid regions [24]. Sorption-driven EC is promising but involves complex designs [25]. AWH-EC, a recently developed technology, aims to reduce water consumption for cooling but it requires further material and system enhancements [26].

Address correspondence to Meijie Chen, chenmeijie@csu.edu.cn

The combination of radiative cooling and evaporative cooling mitigates the limitations of the standalone methods, which not only promises to reshape cooling technologies but also fosters sustainability [27–29]. Radiative cooling materials, for instance, can lower evaporation temperatures, enhance water vapor mass transfer resistance, and prolong evaporation duration. While evaporative cooling can enhance the overall cooling capacity and resilience capability of the system against climatic fluctuations. Additionally, the study of the intricate interplay between evaporative and radiative cooling holds universal significance because omnipresent thermal radiation plays an inevitable role during the process of evaporative cooling. However, a definitive classification for radiative-coupled EC (REC) is presently absent.

REC can be categorized into three primary groups based on the resources of evaporative water: REC by bulk water (REC-BW), REC by perspiration (REC-P), and REC by sorbed water (REC-SW). REC-BW constitutes the initial manifestation of passive cooling integration, featuring separate radiative cooling panels and evaporative coolers (Fig. 1(a)). Evaporative coolers utilize bulk water to chill the supplied air. REC-P and REC-SW are emerging integrated passive cooling technologies. They share structural resemblance with RC materials or textiles placed over water sources. In REC-P, evaporation relies on vapor or sweat droplets generated by skin perspiration (Fig. 1(b)). While in REC-SW, water molecules remain immobile and are often stored in hydrogel (Fig. 1(c)).

In this review, we comprehensively go through REC technology, including the fundamental theories of REC, developments of the three major REC approaches, and their applications. By analyzing their strengths and limitations, we provide insights that have the potential to drive advancements in passive cooling, spanning from industrial applications to personal use. Our work equips researchers with valuable information to address challenges and leverage opportunities in REC, shaping energy-efficient cooling solutions for the future.

2 Fundamental theories

REC shows the combined effects of radiative-coupled evaporative cooling. RC mode focuses on the sky radiative cooling through regulating thermal radiation, while EC mode is mainly attributed to phase change by the mass transfer process. A more complex heat and mass transfer process occurs in the REC. Therefore, by leveraging the cooling potential of both mechanisms, REC systems maximize their overall cooling efficiency.

2.1 Mathematical models of radiative cooling

Fundamentally, thermal radiation is inherently emitted by any object with a temperature greater than absolute zero degree Celsius, propagating as electromagnetic waves [30]. Kirchhoff's law of thermal radiation establishes that all bodies exhibit equal efficiency as both thermal emitters and receivers, where emissivity always matches absorptivity at thermal equilibrium. Radiative cooling technology is rooted in these foundational principles. On the earth's surface, objects employ thermal radiation (P_{rad}, W·m^{-2}) to dissipate heat, primarily through the atmospheric window, as their temperature (~ 300 K) typically surpasses that of outer space (3 K). Conversely, these objects absorb thermal radiation from both the atmosphere (P_{atm}) and solar irradiance (P_{sun}) during daylight hours, alongside nonradiative heat exchange processes like convection and conduction with the ambient (P_{nonrad}). Therefore, the net RC power (P_{RC}) can be expressed as follows (Fig. 2(a)) [7, 31]

$$P_{RC} = P_{rad}(T) + P_{nonrad}(T, T_{amb}) - P_{sun} - P_{atm}(T_{amb}) \tag{1}$$

where T is the temperature of the cooling surface. T_{amb} is the ambient temperature which is assumed to be equal to the atmospheric temperature. P_{rad} can be formulated as [32]

$$P_{rad} = \int d\Omega \cos\theta \int_0^{\infty} d\lambda \varepsilon(\theta, \lambda) I_{BB}(T, \lambda) \tag{2}$$

where θ is the incident zenith angle, λ is the wavelength, dΩ is the angular integration over the space of the upper hemisphere, ε is the spectral directional emittance, I_{BB} (W·m^{-2}·Sr^{-1}·μm^{-1}) is the spectral irradiation of a blackbody at the temperature of T, which can be calculated by the following according to Planck's law [33]

$$I_{BB} = 2hc^2 / \left(\lambda^5 \left(e^{hc/(\lambda kT)} - 1\right)\right) \tag{3}$$

where h = 6.626 × 10^{-34} J·s is the Planck constant, k = 1.381 × 10^{-23} J·K^{-1} is the Boltzmann constant, and c = 3 × 10^{8} m·s^{-1} is the speed of light in a vacuum.

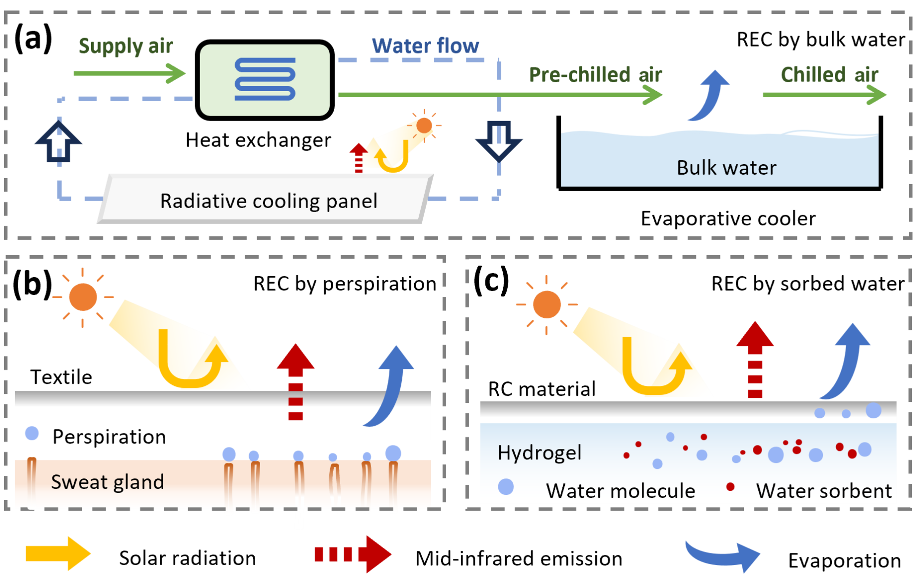

Figure 1 Schematic illustration of the three major REC approaches. (a) REC by bulk water. (b) REC by perspiration. (c) REC by sorbed water.

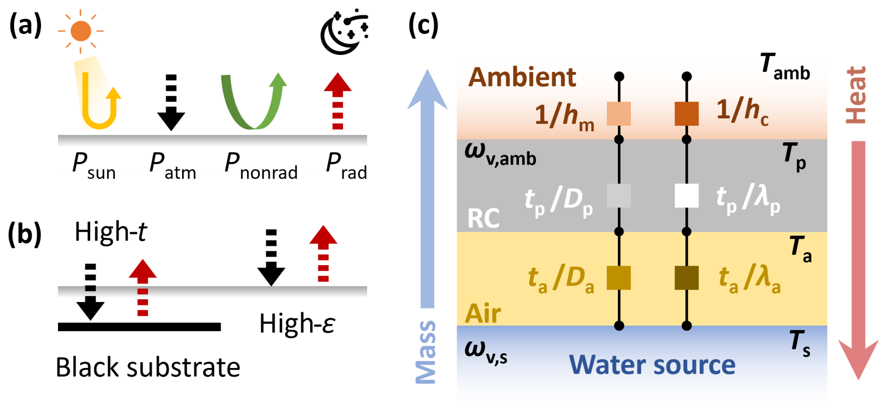

Figure 2 Schematics of theoretical models for radiative cooling and evaporative cooling. (a) Energy flow of radiative cooling. (b) Differences between infrared-transparent (high-t) and opaque (high-ε). (c) Mass and heat transfer of radiative coupled evaporative cooling.

The atmospheric radiation absorbed by a surface can be expressed as follows

$$P_{atm} = \int \cos\theta d\Omega \int_0^{\infty} d\lambda \varepsilon(\theta,\lambda) \varepsilon_{atm}(\theta,\lambda) I_{BB}(T_{amb},\lambda) \quad (4)$$

where ε_{atm} is atmospheric emissivity as a function of incident zenith angle θ and wavelength, which can be approximated by

$$\varepsilon_{atm} = 1-(\tau(\lambda))^{1/\cos\theta} \quad (5)$$

where τ is the atmospheric transmittance in the zenith direction.

The solar irradiation is mostly concentrated in the 0.3–2.5 μm, and the P_{sun} absorbed by a coating is related to the solar irradiation and the reflectivity of the surface within the solar spectrum

$$P_{sun} = \int_0^{\infty} \varepsilon(\theta,\lambda) I_{solar}(\lambda) d\lambda \quad (6)$$

where I_{solar} is the AM 1.5 solar intensity.

P_{nonrad} is the conductive and convective heat transfer between the surface and the ambient, which can be expressed as

$$P_{nonrad} = h_c(T_{amb}-T) \quad (7)$$

In this section, we neglect conduction effects and define h_c as simply the convective heat transfer coefficient.

There are two types of radiative cooling materials, including MIR emissive (high-ε) and mid-infrared transparent materials (high-t). The former can be used alone, while the latter needs to be combined with a substrate with high infrared emissivity (such as human skin) [34–36]. As shown in Fig. 2(b), outer MIR irradiation and thermal radiation of the substrate penetrate the high-t RC materials while confronting at the surface of the high-ε materials. When the RC materials are tightly attached to the substrate, cooling performances vary little between the two patterns. However, additional radiative heat resistance will be introduced if there is an air gap between the high-ε material and the substrate in Fig. 2(c). On the contrary, high-t material can effectively conduct radiation from the substrate to outer space, i.e., high-t material performs better than high-ε material in non-contact cooling scenarios.

2.2 Mathematical models of evaporative cooling

EC utilizes the latent heat of vaporization during the phase transition between the gas and liquid phase. Liquid water molecules form hydrogen bonds between adjacent hydroxyl groups, resulting in the highest enthalpy of vaporization at room temperature [20, 21]. In addition, water is inexpensive, abundant, non-toxic, and versatile. These advantages make water an important medium for evaporative cooling. For EC exposed to the sky, radiative and convective heat transfer should be considered as above. Additionally, the evaporative cooling power (P_{EC}) can be expressed as

$$P_{EC} = mH_v(T) \quad (8)$$

where H_v (J·kg^{-1}) is the latent heat of water, which can be calculated by [37]

$$H_v(T) = 1{,}918{,}460 \times \left(\frac{T}{T-33.91}\right)^2 \quad (9)$$

where m is the mass flow rate of vapor, which can be formulated as [38]

$$\omega_{v,s} - \omega_{v,amb} = \frac{m}{h_m} \quad (10)$$

where $\omega_{v,s}$ and $\omega_{v,amb}$ (kg·m^{-3}) are the vapor density of the evaporation surface and the ambient, respectively. h_m is the convective mass transfer coefficient (m·s^{-1}), which is connected with h_c [23] as

$$\frac{h_c}{h_m} = \rho_{air} c_{p,air} Le^{1-n} \quad (11)$$

where ρ_{air} (kg·m^{-3}) is the air density and $c_{p,air}$ (J·K^{-1}·kg^{-1}) is the specific heat capacity of air. Le is the Lewis number that describes the mutual effects of mass and heat transfer. N is 0.25 for a flat plate with a small mass flow rate. Le can be calculated as

$$Le = \frac{\rho_{air} c_{p,air} D_{vapor}}{\lambda_a} \quad (12)$$

where λ_a (W·m^{-1}·K^{-1}) is the air thermal conductivity. D_{vapor} (m^2·s^{-1}) is the diffusion coefficient for vapor in the air, which can be approximated as

$$D_{vapor} = D_0 \left(\frac{T_{amb}}{313}\right)^{\frac{3}{2}} \quad (13)$$

where D_0 = 2.88 × 10^{-5} m^2·s^{-1} is the standard diffusion coefficient, which is equal to D_{vapor} (T_{amb} = 313 K).

The density difference between the evaporation surface and the ambient can be directly calculated according to the ideal gas law

$$\omega_{v,s} - \omega_{v,amb} = \frac{M}{R_0}\left(\frac{p_{sat}(T)}{T} - \mathrm{RH} \times \frac{p_{sat}(T_{amb})}{T_{amb}}\right) \quad (14)$$

where M = 0.018 kg·mol^{-1} is the molecular weight of water atom, and R_0 = 8.314 J·mol^{-1}·K^{-1} is the ideal gas constant. RH is relative humidity. p_{sat} is the water vapor pressure at T, which can be approximated as [39]

$$p_{sat}(T) = 10^{A-B/(T-273+C)} \quad (15)$$

where A = 8.10765, B = 1750.286, C = 235 are the empirical constants when 273 K < T < 333 K.

In the structure depicted in Figs. 1(b) and 1(c), radiative cooling and evaporative cooling interact, involving more parameters that affect the system simultaneously (i.e., mass transfer resistance of radiative cooling coatings and porosity of hydrogels). Hence, Eq. (10) can be formulated as (Fig. 2(c))

$$\omega_{v,s} - \omega_{v,amb} = m\left(\frac{t_a}{D_a} + \frac{t_p}{D_p} + \frac{1}{h_m}\right) \quad (16)$$

where t_a and t_p (m) are the thicknesses of the air gap and RC materials, respectively; D_a and D_p are the diffusion coefficients of the air gap and RC materials, respectively. The vapor distribution in micropores can be simulated by diffusion equation [40]

$$\nabla(D\cdot\nabla\omega_v) - u\cdot\nabla\omega_v = 0 \quad (17)$$

where D is the diffusion coefficient and ω_v is the vapor density. u is the convective velocity obtained by the following equation [41]

$$\rho(u\cdot\nabla)u = \nabla\left(-p\boldsymbol{I} + \mu\left(\nabla u + (\nabla u)^{T}\right) - \boldsymbol{I}\right) \quad (18)$$

where μ (kg·m^{-1}·s^{-1}) is the viscosity, ρ is the density of the fluid, $\boldsymbol{I}$ is the unit matrix and ^{T} is the symbol of transposition. The heat and mass transfer enhancement of porous structure, obtained through simulations or experiments, can be reflected by the heat and mass transfer coefficients in Eq. (11).

2.3 Integration of radiative and evaporative cooling

From the view of energy conservation, the integrated cooling power of RC and EC (P_{REC}) can be clearly expressed as the sum of P_{RC} and P_{EC} when the ambient temperature is equal to the coating temperature (i.e., $T = T_{amb}$)

$$P_{REC}(T, T_{amb}) = P_{RC} + P_{EC} \quad (19)$$

In addition, a maximal temperature drop ΔT between the coating temperature and ambient temperature can be obtained by

$$\Delta T = P_{REC}(T, T_{amb})\left(\frac{t_a}{\lambda_a} + \frac{t_p}{\lambda_p} + \frac{1}{h_c}\right) \quad (20)$$

where λ_p is the thermal conductivity coefficient of the RC materials.

After gathering the physical properties of materials or media, the equations for RC and EC revolve around ambient temperature T, relative humidity RH, and convective heat/mass transfer coefficients h_c/h_m. The fundamental analysis of REC is to investigate the combined effects of these parameters on RC and EC.

The ambient temperature T and relative humidity RH together determine atmospheric precipitable water (PW), which is an important factor for the atmospheric transmittance τ [42, 43]. For radiative cooling, the LWIR atmospheric window from 8 to 13 μm is crucial, aligning with the peak of blackbody radiation at 300 K (~ 9 μm). τ decreases when T and RH increase, leading to more atmospheric irradiation received by the RC surface. In addition, P_{rad} and P_{atm} are proportional to the fourth power of T when P_{RC}= 0 (i.e., temperatures of the ambient and cooling surfaces are equal). Therefore, radiative cooling exhibits higher cooling power when the weather is hot.

For evaporative cooling, T determines the thermophysical properties of water and air. RH explains the water content in the air. As T goes up and RH goes down, water molecules become more energetic, intensifying the concentration gradient that drives diffusion, ultimately leading to a swifter rate of evaporation. Theoretical and experimental results show that EC performs better at low RH and high T, while RC is better positioned to work under low T or high RH conditions [23]. Hence the REC mitigates the vulnerability of the standalone passive cooling methods.

Convection in RC has a dual purpose. First, particularly for RC, an increase in convective heat transfer coefficient (h_c) leads to a reduction in temperature drop rate. Second, convection expedites the transfer of water vapor, thereby enhancing the process of evaporation. For REC-BW, h_c can be regulated to achieve great thermal insulation for RC and enhanced convection for EC. For more compact REC-P and REC-SW, more subtle designs should be proposed to balance the influence of convection on the temperature drop rate and evaporative duration for water sources.

3 Three types of REC

3.1 REC by bulk water

REC-BW stands as the most straightforward approach within the REC realm. It involves the continuous flow of the cooling medium through separate radiative-coupled evaporative cooling units. In this scheme, water traverses the RC panel, which pre-cools the supply air (Figs. 3(a) and 3(b)) [44]. Subsequently, various evaporative coolers further cool down the air (Fig. 3(c)).

In the RC process, an RC panel is often used to cool circulating water. It is composed of an RC surface, coils, and insulation materials (Fig. 3(a)). For standalone radiative cooling, a water tank is employed to store pre-chilled water overnight (Fig. 3(b)). During the daytime, this cooled water absorbs heat from the supplied air via a cooling coil. DEC and IEC have been used in REC-BW [6]. In DEC, the cooling medium (e.g., air) contacts bulk water and carries water vapor. In contrast, IEC involves two physically separated air streams (Fig. 3(c)) [45]. The supplied air flows through the primary passage, exchanging heat with another air stream cooled through the evaporation of bulk water.

For example, the work of Heidarinejad and Farahani et al. showcased REC-BW systems built upon nocturnal radiative cooling (Fig. 3(d)) [25, 38, 39]. Their research revealed that REC-BW outperforms standalone direct evaporative cooling and two-stage direct/indirect evaporative cooling in terms of cooling effectiveness, energy consumption, and comfort conditions. The REC-BW can significantly reduce water temperature by approximately 10 °C at night through radiative cooling and lowers air temperature by around 16 °C during the daytime using both the cooling coil and evaporative coolers. System performance is enhanced through optimized device arrangement and fluid flow control mechanisms.

The advantage of REC-BW lies in its compatibility with mechanical vapor compression systems. Through existing evaluation metrics, the REC-BW holds the potential for promising commercialization. The saturation effectiveness (e) of the REC-BW can be calculated by the following equation [40]

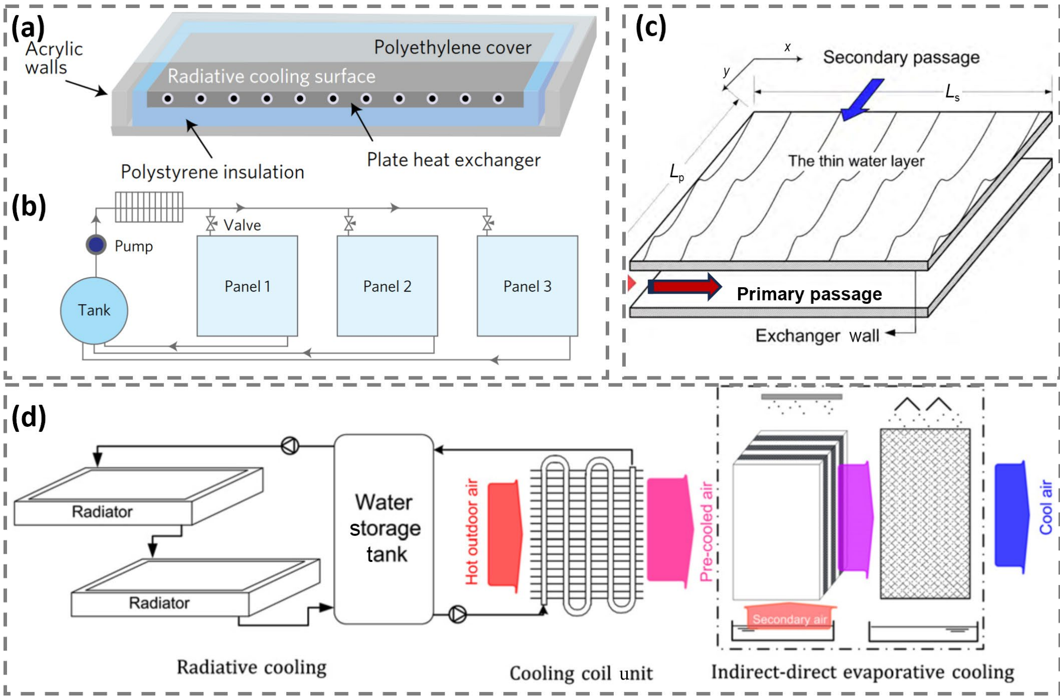

Figure 3 Illustrations of REC-BW. (a) Radiative cooling panels. (b) Standalone radiative cooling system to chill water overnight. ((a) and (b)) Reproduced with permission from Ref. [44], © Macmillan Publishers Limited, part of Springer Nature 2017. (c) Direct and indirect evaporative coolers. For the direct evaporator, only the secondary passage is used. For the indirect evaporative cooler, both passages are used. Reproduced with permission from Ref. [45], © Elsevier B.V. 2010. (d) Schematic of a REC-BW system. Reproduced with permission from Ref. [27], © Elsevier Ltd. 2010.

$$e = \frac{T_{a,in} - T_{a,out}}{T_{a,in} - T_{wb,in}} \quad (21)$$

where $T_{a,in}$ and $T_{a,out}$ are the primary air flow's inlet and outlet dry-bulb temperatures, respectively, while $T_{wb,in}$ is the inlet wet-bulb temperature of the secondary airflow. Standalone IEC or DEC units have an effectiveness lower than one. In contrast, in the REC-BW system, where the outlet dry-bulb temperature can be lower than the inlet wet-bulb temperature, the effectiveness can be higher than one [25].

However, challenges remain in scaling up REC-BW systems and optimizing water usage. The operational ranges of radiative cooling and evaporative cooling in nocturnal radiative cooling setups do not overlap. Thus, it is crucial to make efforts to minimize nighttime cooling losses while still ensuring optimal daytime cooling performance. Although standalone diurnal radiative cooling panels can achieve water temperature reduction below ambient when exposed to direct sunlight [10, 41], the implementation of all-day REC-BW systems has not been demonstrated yet. Moreover, electricity is required to power the circulation of working fluids in the REC-BW system, which limits its applicability when compared to other passive cooling technologies.

3.2 REC by perspiration

The concept of REC-P takes inspiration from the natural cooling mechanisms of human skin. Human skin has high infrared emittance (~ 0.98 from 2.5–20 μm), making it efficient in dissipating heat through radiative heat transfer. Moreover, perspiration, a vital function of the skin, aids in regulating body temperature [46]. REC-P leverages the skin's attributes in conjunction with RC textiles placed above the skin's surface (Fig. 1(b)).

Traditional RC materials have high emittance in the mid-infrared spectra. However, there is no tight adherence between human skin and fabric. Additional radiative heat resistance can be introduced due to the imperfection of emittance [47]. Therefore, materials with high infrared transparency, such as polyethylene (PE), are commonly employed in REC-P to mitigate radiative heat resistance, given the fact that the skin itself is already a proficient infrared emitter. Variants like nanoporous PE (nanoPE) exhibit exceptional IR transparency and are effective in scattering visible light.

Innovations like zinc oxide nanoparticle integration into PE have achieved impressive solar reflectance above 0.9, while maintaining transmittance within the LWIR atmospheric window (Fig. 4(a)) [48, 49]. Techniques like electrospinning [50] and creating porous PE aerogels [36, 47, 51, 52] have also been employed to enhance Mie scattering and reflectance, as well as to attain radiative cooling effects. Moreover, the design of infrared emittance has also been discussed. The optimization of infrared emittance has been explored, exemplified by designing polyoxymethylene (POM) nanotextiles, for example, that selectively emit in the atmospheric window while transmit in the mid-infrared wavebands [53].

In REC-P, the textiles not only trap water vapor on the skin's surface but also manage sweat evaporation. Thus, water vapor permeability, water-wicking ability, and transmission rate play pivotal roles in REC-P performance [54]. Advanced fabrics like directional liquid transport textiles allow one-way water flow and repel external liquid. The was obtained through gradient wettability in spatially distributed porous channels on hydrophobic fabric (Fig. 4(b)) [55]. Hierarchical fabrics with sweat-wicking channels, as demonstrated by Xu et al., also contribute to efficient directional water transport and enhanced evaporation [56].

Although water transport has been comprehensively studied, perspiration is less efficiently utilized if it is only transported

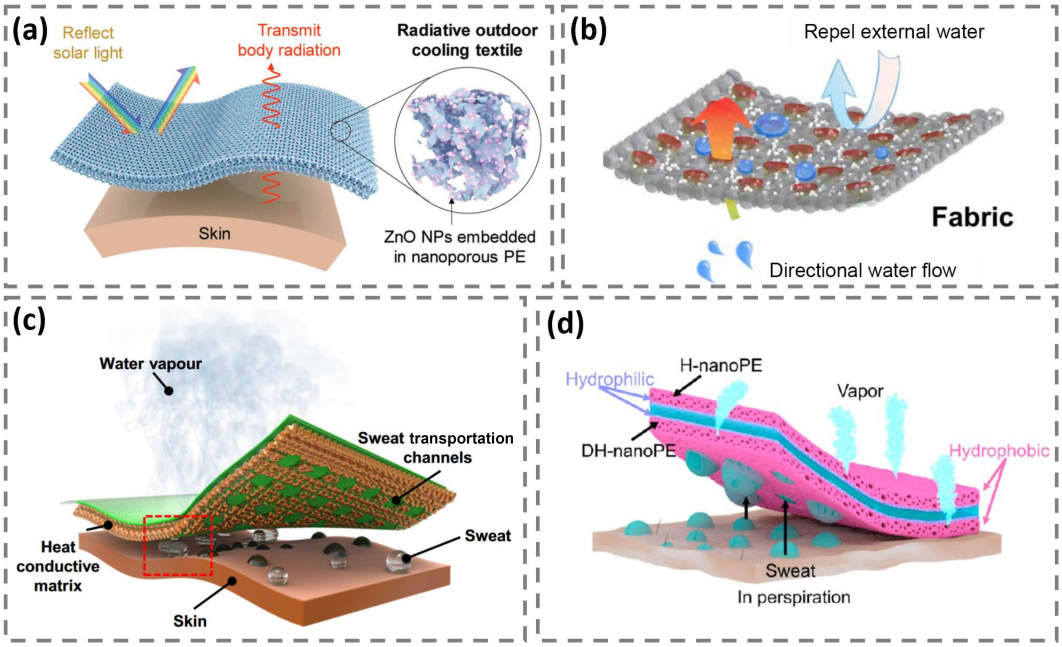

Figure 4 Illustrations of REC by perspiration. (a) PE materials embedded with nanoparticles have enhanced radiative cooling ability. Reproduced with permission from Ref. [49], © WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim 2018. (b) Fabrics that allow one-way water flow and repel external liquid to transport perspiration. Reproduced with permission from Ref. [55], © The Authors, some rights reserved; exclusive licensee American Association for the Advancement of Science 2020. (c) Fabrics that integrate heat conductive pathways and water transport channels for effective evaporation. Reproduced with permission from Ref. [29], © The Author(s) 2021. (d) Bilayer membranes with anisotropic wettability nanoPE exhibiting great REC-P. Reproduced with permission from Ref. [58], © American Chemical Society 2022.

without evaporation. Alberghini et al. demonstrated fabrics with engineered moisture transport that achieve efficient evaporative cooling performance [57]. It turns out that moisture wicking and spreading via capillary transport led to a high evaporation rate and uniform temperature distribution. Notably, while REC-BW incorporates a cooling medium, REC-P's primary objective is to directly reduce the skin's temperature. To meet this goal, Peng et al. integrated heat-conductive pathways and water transport channels within fabrics to facilitate sweat evaporation, resulting in a cooling capacity three times greater than that of exposed skin. (Fig. 4(c)) [29]. However, investigations into radiative cooling within these studies are limited.

Several studies have recognized the potential of REC-P and explored the synergy between textiles and skin for passive cooling integration. Examples include the development of bilayer membranes with anisotropic wettability nanoPE, (Fig. 4(d)) [58] as well as the incorporation of nanoPE into a thermoplastic polyurethane urea polymer matrix through electrospinning and vapor welding [50]. These designs emphasize spectral properties, water transmission, and wicking capabilities, demonstrating superior cooling performance when compared to conventional cotton fabrics, especially in perspiration-prone conditions.

Due to the close connection between human skin, REC-P faces many constraints that need to be overcome. For example, the dyeability of REC-P fabrics is an essential property of commercial value. Hence, attention should be given to regulating the visible and infrared spectral properties of REC-P to fulfill both cooling and aesthetic requirements [59]. In addition, material choices for REC-P are relatively restricted when considering the demands for wearability and safety [54].

3.3 REC by sorbed water

The concept of REC-SW introduces a novel strategy by utilizing hydrogels to create semi-solid water sources, where water molecules are confined within organic molecular chains and sorbents [60, 61]. This approach offers unique advantages such as flexibility in system design, multifunctionality, lightweight, and compactness when compared to other cooling systems. REC-SW operates through two main structural configurations: monolayer and bilayer structures. The monolayer REC-SW consists of a hydrogel with microstructures designed for sunlight scattering, while the bilayer REC-SW integrates RC materials above water sources to prevent solar heating.

Traditional hydrogels used by monolayer REC-SW have exceptional IR emittance but lack solar reflectance. To address this, nanoparticles and microstructures are incorporated to enhance light scattering on the hydrogel's surface. Notable examples include Xu et al.'s polyacrylamide (PAAm)/polyvinyl alcohol (PVA) hydrogel with nanoparticles for REC-SW (Fig. 5(a)) [62, 63]. The hydrogel was mixed with nanoparticles by natural deep eutectic solvent to enhance its solar reflection. Additionally, Yang et al. proposed a poly(N-isopropyl acrylamide) hydrogel [64]. The hydrogel was prepared via polymerization-induced phase separation to form a bi-continuous structure with a heterogenous skeleton. This structure enabled the hydrogel with extremely high solar reflectance. While monolayer REC-SW focuses predominantly on spectral properties, discussions on its evaporative regulation remain limited.

The bilayer REC-SW mainly relies on two auxiliaries to enhance evaporation: AWH and insulation. The utilization of atmospheric water as an evaporative source has gained significant attention due to its potential to alleviate water resource demands in cooling applications [26, 65–67]. Researchers have explored AWH for evaporative cooling by leveraging hydrogels or metal-organic frameworks as carriers for water sorbents [68, 69].

Various studies have embraced AWH-based REC-SW designs [70–72]. Sun et al. proposed a composite fabric with a top layer of porous poly(vinylidene fluoride-co-hexafluoropropylene) (P(VdF-

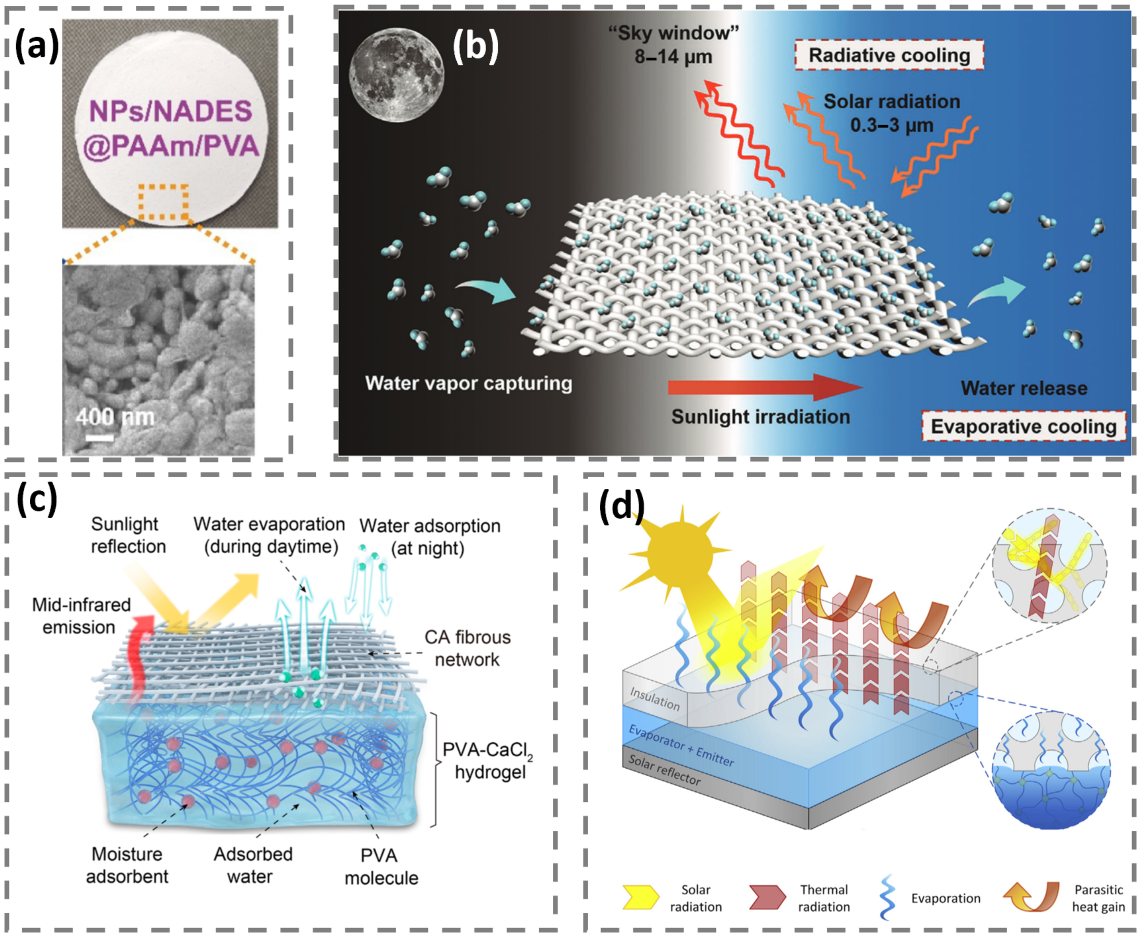

Figure 5 Illustrations of REC by sorbed water. (a) Monolayer REC-SW by PAAm hydrogel with nanoparticles. Reproduced with permission from Ref. [62], © Elsevier B.V. 2023. (b) Bilayer REC-SW based on AWH by P(VdF-HFP) and cotton-polyester fibers doped with $CaCl_2$. Reproduced with permission from Ref. [73], © Wiley-VCH GmbH 2021. (c) Bilayer REC-SW based on AWH by cellulose acetate fibers and PVA-$CaCl_2$ hydrogel. Reproduced with permission from Ref. [74], © The Authors, some rights reserved; exclusive licensee American Association for the Advancement of Science 2022. (d) Bilayer REC-SW based on insulation by PE aerogel. Reproduced with permission from Ref. [28], © The Author(s) 2022.

HFP)) and a bottom layer of cotton-polyester fibers, with uniformly distributed $CaCl_2$ to achieve atmospheric water harvesting (Fig. 5(b)) [73]. While the fabric exhibited effective evaporative cooling under sunlight, there is a need to improve its moisture sorption capacity to enhance its extended outdoor applicability. Hydrogels have also been attractive as carriers for water sorbents in REC-SW designs, such as the bilayer structure consisting of cellulose acetate (CA) fibers and PVA-$CaCl_2$ hydrogel (Fig. 5(c)) [74]. The microporous structure of this hydrogel provides abundant moisture/vapor paths for moisture capture and water evaporation. Its applicability under various weather conditions was verified, showing desirable cooling performance and durable evaporation.

Thermal insulation structures have recently emerged as another avenue to enhance REC-SW performance. While REC-SW based on AWH focuses on intermediate water replenishment by daytime evaporation and nighttime sorption, the insulation structure aims to directly extend the "life span" of the hydrogel.

Inspired by camel fur, Lu et al. introduced an air–water gel structure incorporating silica aerogel to delay evaporation and extend cooling time [38]. By introducing silica aerogel into the top layer of the water gel, water vapor mass transfer resistance was increased to delay evaporation, thereby extending the cooling time by 400% with a marginal decrease in cooling temperature. This concept serves as inspiration for the design of REC-SW by substituting silica aerogel with PE aerogel (Fig. 5(d)) [28] which has high reflectance in the solar spectrum and high IR transmittance for radiative cooling [34].

The additional cooling power of radiative cooling can further improve the evaporation durability of the water source [75]. Zhao et al. proposed a hydrophobized bacterial cellulose (BC) aerogel/PVA hydrogel bilayer gel to achieve REC-SW [76]. Tang et al. suggested modifying the micro-pore structure of the top layer of aerogel can optimize its spectral properties and thermal conductivity, thereby enhancing evaporative cooling performance at the bottom [77]. However, the study of insulation structures in radiative-evaporative cooling technology is limited, urging further exploration of their synergistic effects in this context.

In bilayer REC-SW, efficient water vapor permeability through the radiative cooling layer during evaporation is critical. Assuming the sorption and evaporation processes are subject to the same resistance of the radiative cooling materials, for bilayer REC-SW relying on AWH, it is essential to minimize water vapor permeability to enhance daytime evaporation and nighttime sorption. For REC-SW based on insulative aerogel, hydrogels are disposable and cannot be self-moisturizing. Hence, it becomes essential to introduce a suitable water vapor mass resistance to prolong the evaporation rate while simultaneously preserving a temperature differential between the hydrogel bottom and the ambient.

In addition, REC-SW systems exhibit dynamic cooling performance due to changing solar radiation and humidity levels. Daytime cooling peaks with efficient evaporation, but nighttime humidity reduces its efficacy, particularly in AWH designs. This property has the potential to realize smart passive cooling by shifting part of the cooling load at night to enhance daytime REC. However, future studies should find a balance between evaporation and sorption. Many self-sustained REC-SW have difficulty in exhibiting the massive cooling power of evaporation. This problem leads to a compromised cooling performance in the daytime with evidence of only slightly higher than standalone radiative cooling.

Moreover, REC-SW's intricate interplay between hydrogel-based sorption and evaporation has overshadowed most research. Understanding how water molecules interact with hydrogels in different conditions is crucial. Developing models to describe this synergy will guide REC-SW designs that optimize cooling performance in diverse scenarios [78, 79].

4 Applications of REC

REC offers versatile applications across various scales, encompassing both large-scale industrial settings and smaller-scale applications like personal thermal management and electronics cooling. It holds significant promise to optimize and/or replace conventional active cooling methods, demonstrating impressive energy-saving potential and efficient cooling performance.

4.1 Applications of REC by bulk water

Regarding thermal power plants using evaporative cooling for condensing steam from turbines, one prime example lies in REC-BW, which offers a pathway to curtail the water consumption associated with traditional evaporative cooling systems. This method dissipates waste heat and consumes substantial water resources. Aili et al. demonstrated the water-saving capability of REC-BW in power plants. Their findings revealed potential water savings of 30%–60% in arid regions, making REC-BW an appealing solution for water conservation (Fig. 6(a)) [80].

Furthermore, REC-BW has transformative potential for building cooling. For instance, Katramiz et al. proposed a REC-BW system tailored to Kuwait's hot climate [81]. Notably, this system outperforms traditional cooling methods by reducing water consumption by 44.2% and electrical energy usage by 53.4%, when compared to standalone evaporative cooling units and conventional air conditioning systems. Integration of atmospheric water harvesting enhances sustainability, creating a self-sustained system with reduced water consumption. Moreover, REC-BW's adaptability can extend to building cooling systems, presenting flexible and practical solutions [82, 83].

4.2 Applications of REC by perspiration

By applying REC-P on textiles, different passive cooling textiles can be fabricated. PE fibers are infrared transparent and exhibit high water transmittance under processes such as oxygen plasma and mechanical friction, thus becoming prevailing materials for REC-P (Fig. 6(b)) [54]. Beyond established materials, ongoing research is uncovering novel possibilities. Li et al. demonstrated a moisture-responsive nylon-Ag–SEBS (polystyrene-block-poly (ethylene-ran-butylene)block-polystyrene) heterostructure for REC-P (Fig. 6(c)) [84]. In response to perspiration-induced high humidity, this structure undergoes physical deformation, fostering convection, radiation, and sweat evaporation. It led to a substantial enhancement in thermoregulation when compared to traditional textiles and nonmetallized nylon.

Additionally, Zhu et al. proposed a nano-processed silk that can achieve sub-ambient daytime radiative cooling and a commendable water vapor transmission rate akin to conventional silk (Fig. 6(d)) [48]. Moreover, the application scope of REC-P can extend to wearable electronic devices, enhancing their comfort and wearability. Zhu et al. proposed an aerogel electronic skin for wearable physical-electrophysiological-chemical analysis (Fig. 6(e)) [85]. With an intricately porous structure, the designed aerogel scatters sunlight while facilitating water vapor channels, effectively managing heat, and ensuring user comfort.

4.3 Applications of REC by sorbed water

In terms of versatility and adaptability, REC-SW stands out as a superior choice compared to REC-BW and REC-P. Its compatibility makes it suitable for a wide range of applications, including building roofs to enhance air conditioning systems. Feng et al. proposed an efficient REC-SW solution through a bilayer porous polymer film consisting of a hygroscopic hydrogel and a hydrophobic top layer with hierarchical pores (Fig. 6(f)) [86]. This innovative design combined self-adaptive evaporative and radiative cooling during the daytime, achieving substantial cooling power. At night, the film can utilize radiative cooling and water sorbents to regenerate evaporated water, resulting in impressive sub-ambient temperature drops of ~ 7 °C and an effective cooling power of ~ 150 $W \cdot m^{-2}$.

REC-SW also shows remarkable application potential in food preservation. Xu et al. explored the cooling effects of monolayer REC-SW for ice or food under sunlight (Fig. 6(g)) [62, 63]. It revealed that monolayer REC-SW efficiently blocked sunlight and reduced food temperature, preventing ice from melting and safeguarding food from macromolecular decompositions. Notably, portable REC-SW shows promise for the final stage of the cold chain.

Yao et al. proposed intriguing applications for REC-SW, such as bonding it to a metal-based adhesive tape through covalent cross-linking [87]. The cooling tape can be adhered to common substrates like glass, polyethylene terephthalate, aluminum sheets, and wood sheets, underscoring the broad compatibility and usability of REC-SW (Fig. 6(h)). Furthermore, their work demonstrates that by directing water flow through porous hydrogels, REC can be combined to achieve an impressive cooling power of 710 $W \cdot m^{-2}$.

5 Conclusions and perspectives

In conclusion, this review discusses REC in depth from three aspects: fundamentals, developments, and applications. REC technologies are divided into three types based on the water source, which exhibit different advantages and challenges respectively.

Overall, REC strategies offer compelling opportunities for passive cooling solutions in diverse applications: (1) REC-BW harnesses the cooling potential of bulk water through radiative-coupled evaporative processes, showing promise in industrial and building cooling applications. (2) REC-P utilizes perspiration-inspired textiles to regulate human thermal comfort and has the potential to revolutionize wearable electronics. (3) REC-SW, with its adaptability and compatibility, opens new possibilities for food preservation, portable passive cooling, and more (Fig. 7).

However, the implementation of REC is not without challenges:

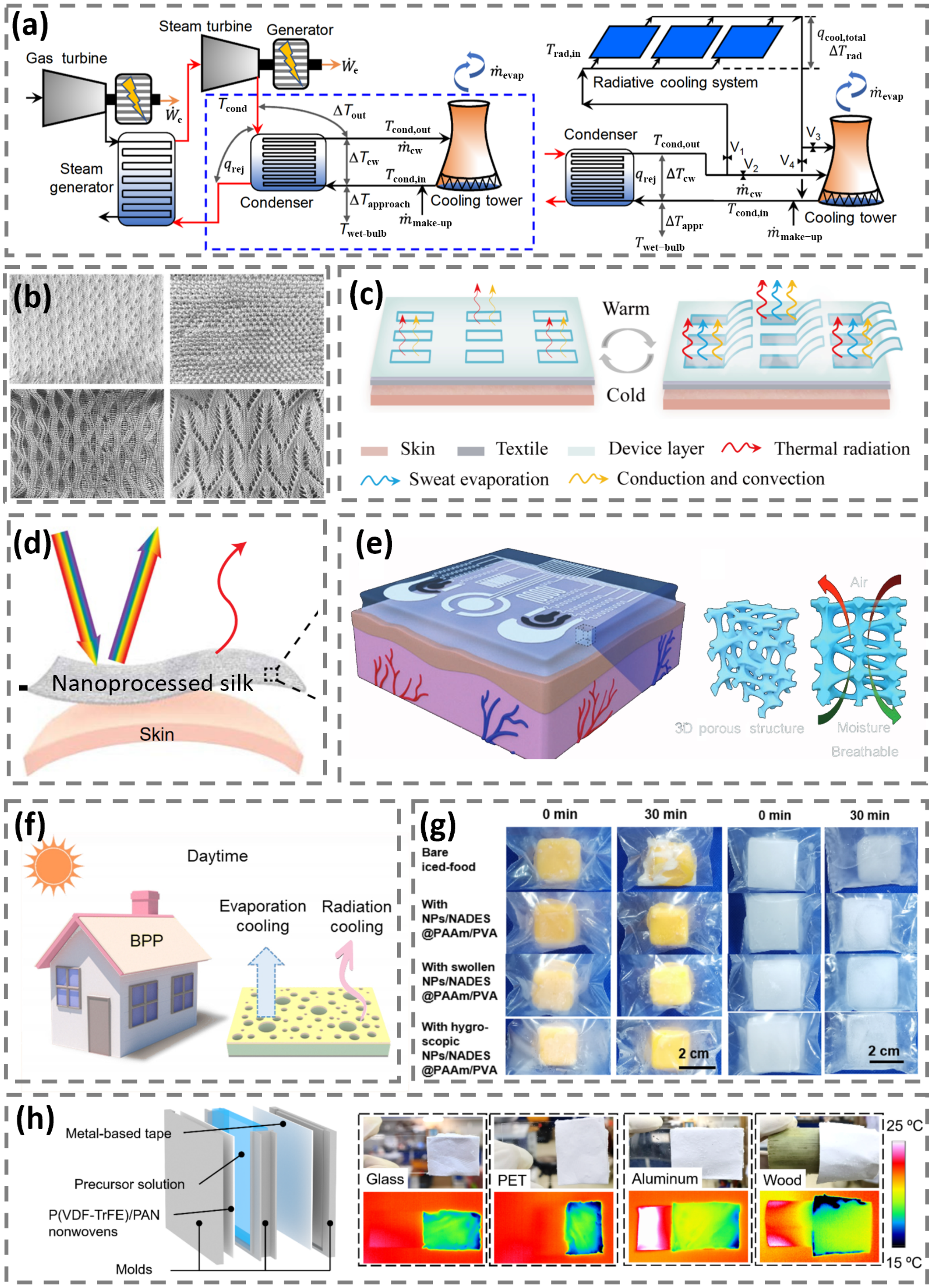

Figure 6 Applications of REC. (a) Water saving potential of REC-BW in power plants. Reproduced with permission from Ref. [80], © Elsevier Ltd. 2021. (b) Fabrication of passive cooling textiles with REC-P. Reproduced with permission from Ref. [54], © Elsevier Inc. 2021. (c) Moisture-responsive heterostructure REC-P for human thermal management. Reproduced with permission from Ref. [84], © The Authors, some rights reserved; exclusive licensee American Association for the Advancement of Science 2021. (d) Nano-processed silk for REC-P. Reproduced with permission from Ref. [48], © The Author(s), under exclusive licence to Springer Nature Limited 2021. (e) Aerogel electronic skin for wearable analysis, with wearability improved by REC-P. Reproduced with permission from Ref. [85], © Wiley-VCH GmbH 2023. (f) Bilayer REC-SW for green buildings. Reproduced with permission from Ref. [86], © Elsevier Ltd. 2021. (g) Monolayer REC-SW for food preservation. Reproduced with permission from Ref. [62], © Elsevier B.V. 2023. (h) Metal-based REC-SW cooling tape. Reproduced with permission from Ref. [87], © The Author(s) 2023.

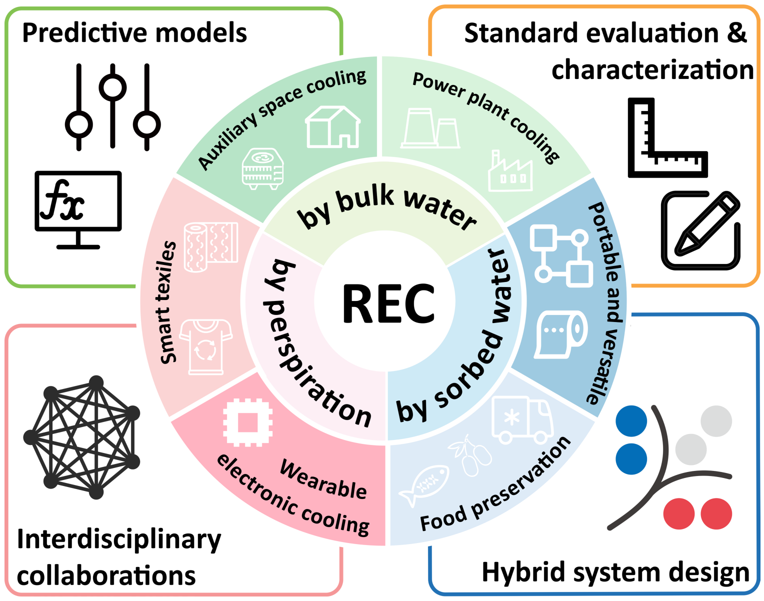

Figure 7 Perspectives of REC. Different RECs have unique advantages in different cooling scenarios. Predictive models, standard evaluation and characterization, interdisciplinary collaborations, and hybrid system design are promising methods to promote the future development of REC.

(1) REC-BW consumes a large amount of bulk water which limits its application in water-scarce regions. Although REC-BW seems to be compatible with existing space cooling systems, commercial practices are not demonstrated. (2) REC-P faces challenges in designing textiles that effectively balance radiative cooling and moisture management. Integrating REC-P technology into daily life also requires enhancing wear comfort and meeting aesthetic requirements. (3) REC-SW faces challenges in optimizing the integration of atmospheric water harvesting and insulation mechanisms within bilayer structures. Achieving a balance of water evaporation and sorption capacity is crucial for achieving effective temperature reduction and duration.

Embracing these challenges as opportunities will be crucial in realizing the transformative potential of REC in sustainable cooling technologies. The following perspectives are worth considering (Fig. 7):

(1) The kinetics of water sorption and evaporation in hygroscopic materials need further study for REC to achieving consistent and durable cooling effects over various environmental conditions. Predictive models based on the understanding above can optimize REC design and performance.

(2) Standard characterization methods for REC are necessary to instruct further research. Valid characterization of REC's cooling performance has not been paid enough attention in the published results. Due to diverse global climates, REC exhibits varied cooling and sustainable performance in different climate zones with different surroundings.

(3) Interdisciplinary collaborations between material scientists, engineers, and environmental experts are required to address existing challenges.

(4) Further research into advanced materials, coatings, and hybrid cooling strategies could enhance the robustness of REC systems.

Acknowledgements

This work was financially supported by the Natural Science Foundation of Hunan Province (No. 2021JJ40732) and the Central South University Innovation-Driven Research Program (No. 2023CXQD012).

Declaration of conflicting interests

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

Data availability

All data needed to support the conclusions in the paper are presented in the manuscript and/or the Supplementary Materials. Additional data related to this paper may be requested from the corresponding author upon request.

References

[1] Brosemer, K.; Schelly, C.; Gagnon, V.; Arola, K. L.; Pearce, J. M.; Bessette, D.; Schmitt Olabisi, L. The energy crises revealed by COVID: Intersections of indigeneity, inequity, and health. *Energy Res. Soc. Sci.* **2020**, *68*, 101661.

[2] Aktar, M. A.; Alam, M.; Al-Amin, A. Q. Global economic crisis, energy use, CO_2 emissions, and policy roadmap amid COVID-19. *Sustain. Prod. Consum.* **2021**, *26*, 770–781.

[3] IEA. *The Global Energy Crisis-World Energy Outlook 2022-Analysis* [Online]. https//www.iea.org/reports/world-energy-outlook-2022/the-global-energy-crisis (accessed Aug 20, 2023).

[4] Akeiber, H.; Nejat, P.; Majid, M. Z. A.; Wahid, M. A.; Jomehzadeh, F.; Zeynali Famileh, I.; Calautit, J. K.; Hughes, B. R.; Zaki, S. A. A review on phase change material (PCM) for sustainable passive cooling in building envelopes. *Renew. Sustain. Energy Rev.* **2016**, *60*, 1470–1497.

[5] Soares, N.; Costa, J. J.; Gaspar, A. R.; Santos, P. Review of passive PCM latent heat thermal energy storage systems towards buildings' energy efficiency. *Energy Build.* **2013**, *59*, 82–103.

[6] Yang, Y. F.; Cui, G.; Lan, C. Q. Developments in evaporative cooling and enhanced evaporative cooling—A review. *Renew. Sustain. Energy Rev.* **2019**, *113*, 109230.

[7] Chen, M. J.; Pang, D.; Chen, X. Y.; Yan, H. J.; Yang, Y. Passive daytime radiative cooling: Fundamentals, material designs, and applications. *EcoMat* **2022**, *4*, e12153.

[8] Yu, L.; Xi, Z. Y.; Li, S.; Pang, D.; Yan, H. J.; Chen, M. J. All-day continuous electrical power generator by solar heating and radiative cooling from the sky. *Appl. Energy* **2022**, *322*, 119403.

[9] Zhai, Y.; Ma, Y. G.; David, S. N.; Zhao, D. L.; Lou, R. N.; Tan, G.; Yang, R. G.; Yin, X. B. Scalable-manufactured randomized glass-

polymer hybrid metamaterial for daytime radiative cooling. *Science* **2017**, *355*, 1062–1066.
[10] Raman, A. P.; Anoma, M. A.; Zhu, L. X.; Rephaeli, E.; Fan, S. H. Passive radiative cooling below ambient air temperature under direct sunlight. *Nature* **2014**, *515*, 540–544.
[11] Atiganyanun, S.; Plumley, J. B.; Han, S. J.; Hsu, K.; Cytrynbaum, J.; Peng, T. L.; Han, S. M.; Han, S. E. Effective radiative cooling by paint-format microsphere-based photonic random media. *ACS Photonics* **2018**, *5*, 1181–1187.
[12] Chen, M. J.; Pang, D.; Mandal, J.; Chen, X. Y.; Yan, H. J.; He, Y. R.; Yu, N. F.; Yang, Y. Designing mesoporous photonic structures for high-performance passive daytime radiative cooling. *Nano Lett.* **2021**, *21*, 1412–1418.
[13] Song, J.; Seo, J.; Han, J.; Lee, J.; Lee, B. J. Ultrahigh emissivity of grating-patterned PDMS film from 8 to 13 μm wavelength regime. *Appl. Phys. Lett.* **2020**, *117*, 094101.
[14] Aili, A.; Wei, Z. Y.; Chen, Y. Z.; Zhao, D. L.; Yang, R. G.; Yin, X. B. Selection of polymers with functional groups for daytime radiative cooling. *Mater. Today Phys.* **2019**, *10*, 100127.
[15] Zhu, R. K.; Hu, D. W.; Chen, Z.; Xu, X. B.; Zou, Y. S.; Wang, L.; Gu, Y. Plasmon-enhanced infrared emission approaching the theoretical limit of radiative cooling ability. *Nano Lett.* **2020**, *20*, 6974–6980.
[16] Chen, M. J.; Pang, D.; Yan, H. J. Colored passive daytime radiative cooling coatings based on dielectric and plasmonic spheres. *Appl. Therm. Eng.* **2022**, *216*, 119125.
[17] Chen, M. J.; Pang, D.; Yan, H. J. Sustainable and self-cleaning bilayer coatings for high-efficiency daytime radiative cooling. *J. Mater. Chem. C* **2022**, *10*, 8329–8338.
[18] Liang, J.; Wu, J. W.; Guo, J.; Li, H. G.; Zhou, X. J.; Liang, S.; Qiu, C. W.; Tao, G. M. Radiative cooling for passive thermal management towards sustainable carbon neutrality. *Natl. Sci. Rev.* **2023**, *10*, nwac208.
[19] Li, R. Y.; Wang, W. B.; Shi, Y. F.; Wang, A. C.; Wang, P. Advanced material design and engineering for water-based evaporative cooling. *Adv. Mater*., in press, DOI: 10.1002/adma.202209460.
[20] Xuan, Y. M.; Xiao, F.; Niu, X. F.; Huang, X.; Wang, S. W. Research and applications of evaporative cooling in China: A review (II)-systems and equipment. *Renew. Sustain. Energy Rev.* **2012**, *16*, 3523–3534.
[21] Xuan, Y. M.; Xiao, F.; Niu, X. F.; Huang, X.; Wang, S. W. Research and application of evaporative cooling in China: A review (I)—Research. *Renew. Sustain. Energy Rev.* **2012**, *16*, 3535–3546.
[22] Han, D.; Ng, B. F.; Wan, M. P. Preliminary study of passive radiative cooling under Singapore's tropical climate. *Solar Energy Mater. Solar Cells* **2020**, *206*, 110270.
[23] Aili, A.; Yin, X. B.; Yang, R. G. Passive sub-ambient cooling: Radiative cooling versus evaporative cooling. *Appl. Therm. Eng.* **2022**, *202*, 117909.
[24] Mekonnen, M. M.; Hoekstra, A. Y. Four billion people facing severe water scarcity. *Sci. Adv.* **2016**, *2*, e1500323.
[25] Wu, M. C.; Li, R. Y.; Shi, Y.; Altunkaya, M.; Aleid, S.; Zhang, C. L.; Wang, W. B.; Wang, P. Metal- and halide-free, solid-state polymeric water vapor sorbents for efficient water-sorption-driven cooling and atmospheric water harvesting. *Mater. Horiz.* **2021**, *8*, 1518–1527.
[26] Tu, Y. D.; Wang, R. Z.; Zhang, Y. N.; Wang, J. Y. Progress and expectation of atmospheric water harvesting. *Joule* **2018**, *2*, 1452–1475.
[27] Heidarinejad, G.; Farmahini Farahani, M.; Delfani, S. Investigation of a hybrid system of nocturnal radiative cooling and direct evaporative cooling. *Build. Environ.* **2010**, *45*, 1521–1528.
[28] Lu, Z. M.; Leroy, A.; Zhang, L. N.; Patil, J. J.; Wang, E. N.; Grossman, J. C. Significantly enhanced sub-ambient passive cooling enabled by evaporation, radiation, and insulation. *Cell Rep. Phys. Sci.* **2022**, *3*, 101068.
[29] Peng, Y. C.; Li, W.; Liu, B. F.; Jin, W. L.; Schaadt, J.; Tang, J.; Zhou, G. M.; Wang, G. Y.; Zhou, J. W.; Zhang, V. et al. Integrated cooling (i-Cool) textile of heat conduction and sweat transportation for personal perspiration management. *Nat. Commun.* **2021**, *12*, 6122.
[30] Zhao, D. L.; Aili, A.; Zhai, Y.; Xu, S. Y.; Tan, G.; Yin, X. B.; Yang, R. G. Radiative sky cooling: Fundamental principles, materials, and applications. *Appl. Phys. Rev.* **2019**, *6*, 021306.
[31] Zhou, L.; Rada, J.; Tian, Y. P.; Han, Y.; Lai, Z. P.; McCabe, M. F.; Gan, Q. Q. Radiative cooling for energy sustainability: Materials, systems, and applications. *Phys. Rev. Mater.* **2022**, *6*, 090201.
[32] Chowdhury, F. I.; Xu, Q. W.; Sinha, K.; Wang, X. H. Cellulose-upgraded polymer films for radiative sky cooling. *J. Quant. Spectrosc. Radiat. Transf.* **2021**, *272*, 107824.
[33] Xi, Z. Y.; Li, S.; Yu, L.; Yan, H. J.; Chen, M. J. All-day fresh water harvesting by selective solar absorption and radiative cooling. *ACS Appl. Mater. Interfaces.* **2022**, *14*, 26255–26263.
[34] Leroy, A.; Bhatia, B.; Kelsall, C. C.; Castillejo-Cuberos, A.; Di Capua H., M.; Zhao, L.; Zhang, L.; Guzman, A. M.; Wang, E. N. High-performance subambient radiative cooling enabled by optically selective and thermally insulating polyethylene aerogel. *Sci. Adv.* **2019**, *5*, eaat9480.
[35] Wu, S. L.; Cao, Y. J.; Li, Y. Q.; Sun, W. Recent advances in material engineering and applications for passive daytime radiative cooling. *Adv. Opt. Mater.* **2023**, *11*, 2202163.
[36] Chen, M. J.; Pang, D.; Yan, H. J. Highly solar reflectance and infrared transparent porous coating for non-contact heat dissipations. *iScience* **2022**, *25*, 104726.
[37] Ibrahim, I.; Seo, D. H.; McDonagh, A. M.; Shon, H. K.; Tijing, L. Semiconductor photothermal materials enabling efficient solar steam generation toward desalination and wastewater treatment. *Desalination* **2021**, *500*, 114853.
[38] Lu, Z. M.; Strobach, E.; Chen, N. X.; Ferralis, N.; Grossman, J. C. Passive sub-ambient cooling from a transparent evaporation-insulation bilayer. *Joule* **2020**, *4*, 2693–2701.
[39] Thomson, G. W. The Antoine equation for vapor-pressure data. *Chem. Rev.* **1946**, *38*, 1–39.
[40] Li, J. L.; Wang, X. Y.; Lin, Z. H.; Xu, N.; Li, X. Q.; Liang, J.; Zhao, W.; Lin, R. X.; Zhu, B.; Liu, G. L. et al. Over 10 $kg\cdot m^{-2}\cdot h^{-1}$ evaporation rate enabled by a 3D interconnected porous carbon foam. *Joule* **2020**, *4*, 928–937.
[41] Halder, A.; Dhall, A.; Datta, A. K. Modeling transport in porous media with phase change: Applications to food processing. *J. Heat Transfer.* **2011**, *133*, 031010.
[42] Dong, M. H.; Chen, N.; Zhao, X. D.; Fan, S. H.; Chen, Z. Nighttime radiative cooling in hot and humid climates. *Opt. Express* **2019**, *27*, 31587–31598.
[43] Huang, J. Y.; Lin, C. J.; Li, Y.; Huang, B. L. Effects of humidity, aerosol, and cloud on subambient radiative cooling. *Int. J. Heat Mass Transf.* **2022**, *186*, 122438.
[44] Goldstein, E. A.; Raman, A. P.; Fan, S. H. Sub-ambient non-evaporative fluid cooling with the sky. *Nat. Energy* **2017**, *2*, 17143.
[45] Farmahini Farahani, M.; Heidarinejad, G.; Delfani, S. A two-stage system of nocturnal radiative and indirect evaporative cooling for conditions in Tehran. *Energy Build.* **2010**, *42*, 2131–2138.
[46] Lillywhite, H. B. Water relations of tetrapod integument. *J. Exp. Biol.* **2006**, *209*, 202–226.
[47] Hsu, P. C.; Song, A. Y.; Catrysse, P. B.; Liu, C.; Peng, Y. C.; Xie, J.; Fan, S. H.; Cui, Y. Radiative human body cooling by nanoporous polyethylene textile. *Science* **2016**, *353*, 1019–1023.
[48] Zhu, B.; Li, W.; Zhang, Q.; Li, D.; Liu, X.; Wang, Y. X.; Xu, N.; Wu, Z.; Li, J. L.; Li, X. Q. et al. Subambient daytime radiative cooling textile based on nanoprocessed silk. *Nat. Nanotechnol.* **2021**, *16*, 1342–1348.
[49] Cai, L. L.; Song, A. Y.; Li, W.; Hsu, P. C.; Lin, D. C.; Catrysse, P. B.; Liu, Y. Y.; Peng, Y. C.; Chen, J.; Wang, H. X. et al. Spectrally selective nanocomposite textile for outdoor personal cooling. *Adv. Mater.* **2018**, *30*, 1802152.
[50] Iqbal, M. I.; Shi, S.; Kumar, G. M. S.; Hu, J. L. Evaporative/radiative

electrospun membrane for personal cooling. *Nano Res.* **2023**, *16*, 2563–2571.
[51] Cao, D.; Li, X. M.; Gu, Y. Highly optically selective polyethylene porous films as versatile optical shields for daytime radiative cooling applications. *Solar Energy Mater. Solar Cells* **2022**, *240*, 111727.
[52] Peng, Y. C.; Chen, J.; Song, A. Y.; Catrysse, P. B.; Hsu, P. C.; Cai, L. L.; Liu, B. F.; Zhu, Y. Y.; Zhou, G. M.; Wu, D. S. et al. Nanoporous polyethylene microfibres for large-scale radiative cooling fabric. *Nat. Sustain.* **2018**, *1*, 105–112.
[53] Wu, X. K.; Li, J. L.; Jiang, Q. Y.; Zhang, W. S.; Wang, B. S.; Li, R.; Zhao, S. M.; Wang, F.; Huang, Y.; Lyu, P. et al. An all-weather radiative human body cooling textile. *Nat. Sustain*., in press, DOI: 10.1038/s41893-023-01200-x.
[54] Fang, Y. S.; Zhao, X.; Chen, G. R.; Tat, T.; Chen, J. Smart polyethylene textiles for radiative and evaporative cooling. *Joule* **2021**, *5*, 752–754.
[55] Lao, L.; Shou, D.; Wu, Y. S.; Fan, J. T. “Skin-like” fabric for personal moisture management. *Sci. Adv.* **2020**, *6*, eaaz0013.
[56] Xu, D.; Chen, Z.; Liu, Y. C.; Ge, C.; Gao, C.; Jiao, L. A.; Guo, W. Q.; Zhang, Q.; Fang, J.; Xu, W. L. Hump-inspired hierarchical fabric for personal thermal protection and thermal comfort management. *Adv. Funct. Mater.* **2023**, *33*, 2212626.
[57] Alberghini, M.; Hong, S.; Lozano, L. M.; Korolovych, V.; Huang, Y.; Signorato, F.; Zandavi, S. H.; Fucetola, C.; Uluturk, I.; Tolstorukov, M. Y. et al. Sustainable polyethylene fabrics with engineered moisture transport for passive cooling. *Nat. Sustain.* **2021**, *4*, 715–724.
[58] Hu, R. J.; Wang, N.; Hou, L. L.; Liu, J. C.; Cui, Z. M.; Zhang, C. H.; Zhao, Y. Bilayer nanoporous polyethylene membrane with anisotropic wettability for rapid water transportation/evaporation and radiative cooling. *ACS Appl. Mater. Interfaces* **2022**, *14*, 9833–9843.
[59] Cai, L. L.; Peng, Y. C.; Xu, J. W.; Zhou, C. Y.; Zhou, C. X.; Wu, P. L.; Lin, D. C.; Fan, S. H.; Cui, Y. Temperature regulation in colored infrared-transparent polyethylene textiles. *Joule* **2019**, *3*, 1478–1486.
[60] Galib, R. H.; Tian, Y. P.; Lei, Y.; Dang, S. C.; Li, X. L.; Yudhanto, A.; Lubineau, G.; Gan, Q. Q. Atmospheric-moisture-induced polyacrylate hydrogels for hybrid passive cooling. *Nat. Commun.* **2023**, *14*, 6707.
[61] Wang, G.; Li, Y.; Qiu, H. H.; Yan, H.; Zhou, Y. G. High-performance and wide relative humidity passive evaporative cooling utilizing atmospheric water. *Droplet* **2023**, *2*, e32.
[62] Xu, L.; Sun, D. W.; Tian, Y.; Fan, T. H.; Zhu, Z. W. Nanocomposite hydrogel for daytime passive cooling enabled by combined effects of radiative and evaporative cooling. *Chem. Eng. J.* **2023**, *457*, 141231.
[63] Xu, L.; Sun, D. W.; Tian, Y.; Sun, L. B.; Fan, T. H.; Zhu, Z. W. Combined effects of radiative and evaporative cooling on fruit preservation under solar radiation: Sunburn resistance and temperature stabilization. *ACS Appl. Mater. Interfaces* **2022**, *14*, 45788–45799.
[64] Yang, M.; Zou, W. Z.; Luo, H.; Liu, Y.; Zhao, N.; Xu, J. Bright-white hydrogels for on-demand passive cooling. *Sci. China Chem.* **2023**, *66*, 1511–1519.
[65] Zhang, Y. X.; Nandakumar, D. K.; Tan, S. C. Digestion of ambient humidity for energy generation. *Joule* **2020**, *4*, 2532–2536.
[66] Lord, J.; Thomas, A.; Treat, N.; Forkin, M.; Bain, R.; Dulac, P.; Behroozi, C. H.; Mamutov, T.; Fongheiser, J.; Kobilansky, N. et al. Global potential for harvesting drinking water from air using solar energy. *Nature* **2021**, *598*, 611–617.
[67] Li, R. Y.; Shi, Y.; Wu, M. C.; Hong, S.; Wang, P. Improving atmospheric water production yield: Enabling multiple water harvesting cycles with nano sorbent. *Nano Energy* **2020**, *67*, 104255.
[68] Wang, C. X.; Hua, L. J.; Yan, H. Z.; Li, B. J.; Tu, Y. D.; Wang, R. Z. A thermal management strategy for electronic devices based on moisture sorption–desorption processes. *Joule* **2020**, *4*, 435–447.
[69] Pu, S. R.; Fu, J.; Liao, Y. T.; Ge, L. R.; Zhou, Y. H.; Zhang, S. L.; Zhao, S. L.; Liu, X. W.; Hu, X. J.; Liu, K. et al. Promoting energy efficiency via a self-adaptive evaporative cooling hydrogel. *Adv. Mater.* **2020**, *32*, 1907307.
[70] Chen, Z. H.; Song, S. Y.; Ma, B. C.; Li, Y. Q.; Shao, Y.; Shi, J. W.; Liu, M. C.; Jin, H.; Jing, D. W. Recent progress on sorption/desorption-based atmospheric water harvesting powered by solar energy. *Solar Energy Mater. Solar Cells* **2021**, *230*, 111233.
[71] Li, Z. P.; Ma, T.; Ji, F.; Shan, H.; Dai, Y. J.; Wang, R. Z. A hygroscopic composite backplate enabling passive cooling of photovoltaic panels. *ACS Energy Lett.* **2023**, *8*, 1921–1928.
[72] Ni, F.; Xiao, P.; Zhang, C.; Zhou, W.; Liu, D. P.; Kuo, S. W.; Chen, T. Atmospheric hygroscopic ionogels with dynamically stable cooling interfaces enable a durable thermoelectric performance enhancement. *Adv. Mater.* **2021**, *33*, 2103937.
[73] Sun, Y. L.; Ji, Y. T.; Javed, M.; Li, X. Y.; Fan, Z. Z.; Wang, Y. Q.; Cai, Z. S.; Xu, B. Preparation of passive daytime cooling fabric with the synergistic effect of radiative cooling and evaporative cooling. *Adv. Mater. Technol.* **2022**, *7*, 2100803.
[74] Li, J. L.; Wang, X. Y.; Liang, D.; Xu, N.; Zhu, B.; Li, W.; Yao, P. C.; Jiang, Y.; Min, X. Z.; Huang, Z. Z. et al. A tandem radiative/evaporative cooler for weather-insensitive and high-performance daytime passive cooling. *Sci. Adv.* **2022**, *8*, eabq0411.
[75] Chen, S. R.; Lin, K. X.; Pan, A. Q.; Ho, T. C.; Zhu, Y. H.; Tso, C. Y. Study of a passive radiative cooling coating on chemical storage tanks for evaporative loss control. *Renew. Energy* **2023**, *211*, 326–335.
[76] Zhao, B. C.; Yue, X. J.; Tian, Q.; Qiu, F. X.; Li, Y. Q.; Zhang, T. Bio-inspired BC aerogel/PVA hydrogel bilayer gel for enhanced daytime sub-ambient building cooling. *Cellulose* **2022**, *29*, 7775–7787.
[77] Tang, H. J.; Guo, C. Y.; Xu, Q. H.; Zhao, D. L. Boosting evaporative cooling performance with microporous aerogel. *Micromachines* **2023**, *14*, 219.
[78] Díaz-Marín, C. D.; Zhang, L. N.; El Fil, B.; Lu, Z. M.; Alshrah, M.; Grossman, J. C.; Wang, E. N. Heat and mass transfer in hygroscopic hydrogels. *Int. J. Heat Mass Transf.* **2022**, *195*, 123103.
[79] Díaz-Marín, C. D.; Zhang, L. N.; Lu, Z. M.; Alshrah, M.; Grossman, J. C.; Wang, E. N. Kinetics of sorption in hygroscopic hydrogels. *Nano Lett.* **2022**, *22*, 1100–1107.
[80] Aili, A.; Zhao, D. L.; Tan, G.; Yin, X. B.; Yang, R. G. Reduction of water consumption in thermal power plants with radiative sky cooling. *Appl. Energy* **2021**, *302*, 117515.
[81] Katramiz, E.; Al Jebaei, H.; Alotaibi, S.; Chakroun, W.; Ghaddar, N.; Ghali, K. Sustainable cooling system for Kuwait hot climate combining diurnal radiative cooling and indirect evaporative cooling system. *Energy* **2020**, *213*, 119045.
[82] Pires, L.; Silva, P. D.; Castro Gomes, J. P. Performance of textile and building materials for a particular evaporative cooling purpose. *Exp. Therm. Fluid Sci.* **2011**, *35*, 670–675.
[83] Peng, Y. C.; Lai, J. C.; Xiao, X.; Jin, W. L.; Zhou, J. W.; Yang, Y. F.; Gao, X.; Tang, J.; Fan, L. L.; Fan, S. H. et al. Colorful low-emissivity paints for space heating and cooling energy savings. *Proc. Natl. Acad. Sci. USA* **2023**, *120*, e2300856120.
[84] Li, X. Q.; Ma, B. R.; Dai, J. Y.; Sui, C. X.; Pande, D.; Smith, D. R.; Brinson, L. C.; Hsu, P. C. Metalized polyamide heterostructure as a moisture-responsive actuator for multimodal adaptive personal heat management. *Sci. Adv.* **2021**, *7*, eabj7906.
[85] Zhu, Y. Z.; Haghniaz, R.; Hartel, M. C.; Guan, S. H.; Bahari, J.; Li, Z. J.; Baidya, A.; Cao, K.; Gao, X. X.; Li, J. H. et al. A breathable, passive-cooling, non-inflammatory, and biodegradable aerogel electronic skin for wearable physical-electrophysiological-chemical analysis. *Adv. Mater.* **2023**, *35*, 2209300.
[86] Feng, C. Z.; Yang, P. H.; Liu, H. D.; Mao, M. R.; Liu, Y. P.; Xue, T.; Fu, J.; Cheng, T.; Hu, X. J.; Fan, H. J. et al. Bilayer porous polymer for efficient passive building cooling. *Nano Energy* **2021**, *85*, 105971.
[87] Yao, H. Z.; Cheng, H. H.; Liao, Q. H.; Hao, X. Z.; Zhu, K. X.; Hu, Y. J.; Qu, L. T. Integrated radiative and evaporative cooling beyond daytime passive cooling power limit. *Nano Res. Energy* **2023**, *2*, e9120060.

Li Yu received his B.S. degree in New Energy Science and Engineering from Central South University in 2023. He is currently a research assistant at the Department of Mechanical Engineering in City University of Hong Kong. His research mainly focuses on solar energy conversion and thermal management through passive cooling.

Meijie Chen is an associate professor in the School of Energy Science and Engineering at Central South University. He received his B.Eng., M.Eng., and Ph.D. degrees from the School of Energy Science and Engineering at Harbin Institute of Technology in 2014, 2016, and 2019, respectively. He was a visiting graduate student at Columbia University funded by China Scholarship Council (CSC) graduate scholarship in 2018. His research interests are in thermal radiation regulation for solar thermal, radiative cooling, water collection, and thermal management.