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Recent Advances in Thermoregulatory Clothing: Materials, Mechanisms, and Perspectives

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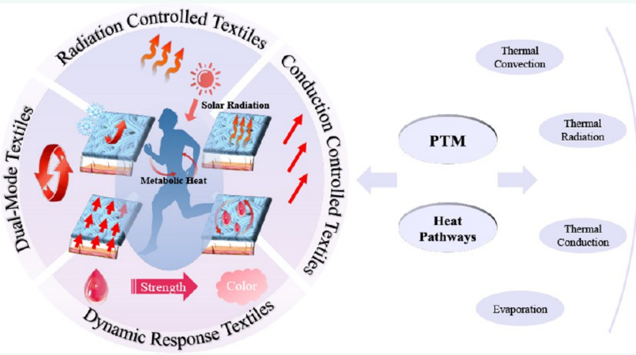
ABSTRACT: Personal thermal management (PTM) is a promising approach for maintaining the thermal comfort zone of the human body while minimizing the energy consumption of indoor buildings. Recent studies have reported the development of numerous advanced textiles that enable PTM systems to regulate body temperature and are comfortable to wear. Herein, recent advancements in thermoregulatory clothing for PTM are discussed. These advances in thermoregulatory clothing have focused on enhancing the control of heat dissipation between the skin and the localized environment. We primarily summarize research on advanced clothing that controls the heat dissipation pathways of the human body, such as radiation- and conductance-controlled clothing. Furthermore, adaptive clothing such as dual-mode textiles, which can regulate the microclimate of the human body, as well as responsive textiles that address both thermal performance (warming and/or cooling) and wearability are discussed. Finally, we include a discussion on significant challenges and perspectives in this field, including large-scale production, smart textiles, bioinspired clothing, and AI-assisted clothing. This comprehensive review aims to further the development of sustainably manufactured advanced clothing with superior thermal performance and outstanding wearability for PTM in practical applications.



KEYWORDS: *personal thermal management, heat pathways, radiation controlled, conductance controlled, dual-mode textiles, responsive textiles, thermal performance, thermoregulatory clothing*

INTRODUCTION

Throughout human civilization, textiles have been indispensable to our daily lives, which not only improve temperature regulation, but also play important cultural roles.[1−5] Textiles serve as a medium for designers who strive to increase the demand for garments by introducing innovative materials, improving techniques to prepare garments, and advancing fashion.[6−10] Various applications (i.e., fire protection, aerospace, and military) of contemporary fabrics have been investigated in terms of their numerous properties, such as wearability, flame resistance, lightweight nature, breathability, and water resistance.[11−14] Regardless of how human civilization evolves, the primary purpose of textiles will always be to deliver thermal comfort to the human body in various scenarios, for example, by warming us in a cold environment or cooling us in a hot environment, in addition to the various other attributes of functional textiles.[15−20] Traditional textiles may not always effectively suppress heat dissipation of the human body in cold environments, and heat transfer at high temperatures is similarly hindered, increasing skin temperature.[21−24] Fortunately, owing to progressive breakthroughs, advanced clothing specifically designed to better control heat dissipation of the human body has been reported recently (Figure 1).

To construct a thermally comfortable environment, heating, ventilation, and air-conditioning (HVAC) systems in buildings are commonly utilized for space cooling and heating, which requires substantial consumption of energy.[3,25−29] According

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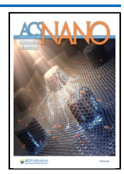

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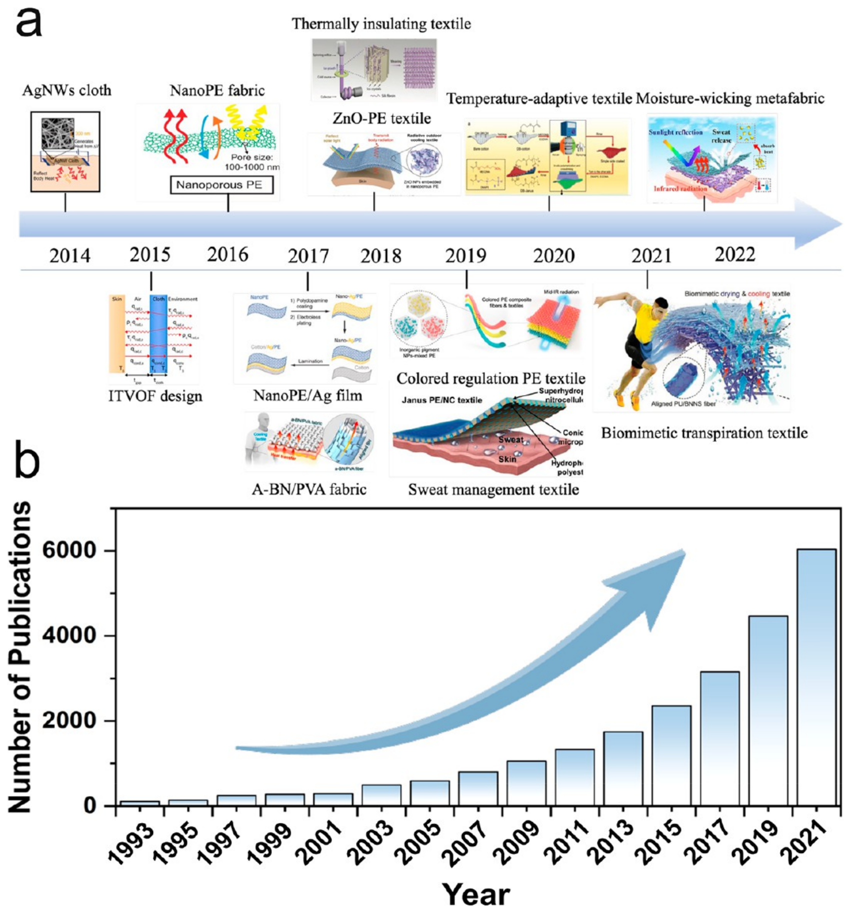

Figure 1. (a) Roadmap of recent advances in thermoregulatory clothing. Year 2014. Reprinted with permission from ref 153. Copyright 2014, American Chemical Society. Year 2015. Reprinted with permission from ref 105. Copyright 2015, American Chemical Society. Year 2016. Reprinted with permission from ref 107. Copyright 2016, American Association for the Advancement of Science. Year 2017. Reprinted with permission from ref 154. Copyright 2017, Springer Nature. Reprinted with permission from ref 179. Copyright 2017, American Chemical Society. Year 2018. Reprinted with permission from ref 75. Copyright 2018, John Wiley and Sons/Wiley-VCH. Reprinted with permission from ref 169. Copyright 2018, John Wiley and Sons/Wiley-VCH. Year 2019. Reprinted with permission from ref 211. Copyright 2019, Elsevier. Reprinted with permission from ref 216. Copyright 2019, John Wiley and Sons/Wiley-VCH. Year 2020. Reprinted with permission from ref 194. Copyright 2020, John Wiley and Sons/Wiley-VCH. Year 2021. Reprinted with permission from ref 217. Copyright 2021, John Wiley and Sons/Wiley-VCH. Year 2022. Reprinted with permission from ref 160. Copyright 2022, American Chemical Society. (b) Number of publications on thermal management in recent decades (Data retrieved from Web of Science by searching the key word "thermal management" on October 15th, 2022).

to a study conducted in the United States, the energy consumption of these HVAC systems accounts for 15.2% of domestic primary energy usage, and >30% of the total energy consumption in residential and commercial buildings.[7,22,30−33] Due to variations in thermal sensibility of individuals, research indicates that creating a specific and tailored microclimate could be preferable to altering the climate of the entire space. Therefore, introduction of innovative and cost-effective personal thermal management (PTM) techniques could lead to a large and measurable minimization of global energy usage.[14,23,34−39]

Compared with conventional HVAC systems, a state-of-the-art PTM system (PTMS) facilitates the design of wearable, precise, and individual-specific textiles by employing energy conversion technologies such as radiative cooling and Joule heating.[40−44] Researchers are intrigued by PTMSs that may economically harness the excess heat of the human body to generate power or precisely control temperature for thermal comfort.[45,46] A PTMS focuses on three functions: (1) personal thermoregulation with the aim of regulating the body temperature, (2) energy harvesting with an emphasis on heat recovery, and (3) thermal insulation based on sustainable energy conservation.[21,23,47−50] PTMS may be a promising candidate, given the limitations of centralized space thermoregulatory systems (i.e., HVAC systems) because they have the potential to enhance adaptability at the individual level as well as in a wide range of outdoor circumstances, including athletics, military, and specific occupations. The emergence of PTMSs, which strive to deliver optimal thermal comfort, is a response to these growing demands.[51−59]

In this review, we shall discuss innovative developments in advanced clothing for PTMSs while highlighting the most significant achievements. First, fundamental theories are introduced, for example, the basic concept of thermal comfort and the heat pathway to the human body and the concepts of thermal radiation and thermal conduction. Second, we discuss emerging thermoregulatory fabrics based on various heat transfer pathways utilizing passive textiles for warming and cooling (that is, radiation-controlled, conduction-controlled, dual-mode, and responsive textiles). These textiles often make

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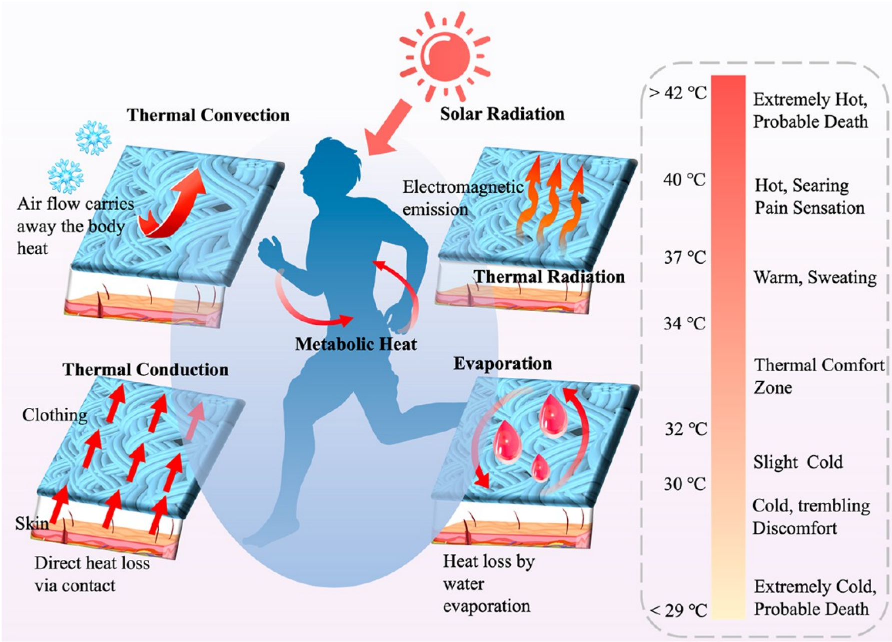

Figure 2. Heat transfer pathway between the human body and outer environment as well as adverse physiological responses to variations in core body temperature. Metabolic heat and solar absorption are two heat input mechanisms. Output channels include conduction, convection, radiation, and evaporation.

use of cutting-edge material design to increase or decrease body heat dissipation throughout the textile in an energy-free way. Finally, the recent advancements in thermoregulatory clothing including their challenges, opportunities, functions, and applications are summarized and discussed.

BASIC CONCEPT OF THERMAL COMFORT AND THE HEAT PATHWAY

Thermal comfort is the psychological state of being satisfied with the temperature of the surroundings, that is, not being too cold or too hot. Since it is a subjective feeling associated with a person's reaction to their surroundings, such as cold or hot sensations, quantitatively defining thermal comfort is challenging.[8,17,60] The seven-point thermal sensory scale proposed by the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), wherein a neutral sensation is viewed as a condition of satisfaction in various temperature scenarios, seems to be the most extensively used approach for assessing thermal comfort.[23,50,61] Environmental stimuli like cold or heat, the duration of stimulation, and the individual baseline physiological and psychological states impact thermal sensation.[47,50,62−65]

Hot, warm, a little warm, moderate, somewhat cold, frigid, and cold are states on the standard seven-point scale used to assess thermal comfort. The skin is commonly utilized as a physical indicator of thermal comfort for three reasons:[66−70] (1) the skin is the most significant organ for direct heat transfer between the human body and its surroundings and thermal envelope; (2) the skin has densely packed temperature-detecting thermoreceptors; and (3) external devices, such as thermocouples and infrared (IR) cameras, can assess the temperature of the skin on the human body with relative ease. Nevertheless, depending on the physical activity, metabolic level, and temperature susceptibility, each of us has varying degrees of comfort with similar thermal sensations. In any case, thermal comfort is analogous to the heat homeostasis of the human body.[23,69]

Prior to conducting a heat evaluation of the PTMS, initial and boundary conditions, such as heat sources, should be considered. Figure 2 shows the heat exchange between the human body and the surrounding environment as well as the detrimental physiological response to variations in personal core body temperature.[21,23] The body maintains a steady temperature by balancing heat intake and loss. This equilibrium can be represented by the body heat balance equation, which can be calculated as follows:[23,28]

$$P_{sun} + P_{gen} = P_{rad} + P_{cond} + P_{conv} + P_{evap} + P_{stor} \quad (1)$$

For an outdoor scenario, P_{sun} is the rate of heat absorption from solar irradiation, and it will decrease for the indoor case. P_{gen} is the rate of metabolic production of the body. P_{rad}, P_{cond}, P_{conv}, and P_{evap} are the net heat loss rates via radiation, conduction, convection, and evaporation, respectively. P_{stor} is the heat stored by the body.

Even though the equation (eq 1) is based on different principles, they all incorporate the generation, transfer, and preservation of the body heat. Thermal radiation, thermal conduction, air convection, and sweat evaporation are all ways for the human body to release heat into the environment. Other heat transfer mechanisms, such as convective or evaporative respiration, are not included in eq 1, but they may play an essential role in certain instances. In conclusion, the heat production and dissipation of the human body eventually lead to heat retention.[60]

A percentage of metabolic production is utilized to keep the body functioning daily; the oxidation of different meal components (carbohydrates, lipids, and proteins) yields different metabolic heat rates, which differ significantly depending on physical exercise. Particularly, P_{gen} is the major source of heat for the human body, which is generated in a multitude of methods, including blood circulation, skeletal

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muscle functioning, and chemical heat from the oxidation of nutrients consumed by the human body.[61] The typical P_{gen} values can be categorized based on different activity levels according to ISOEN 8996: people in relaxation, sedentary people, and standing people can generate 58, 70, 96 W m^{-2} of energy, respectively.[71,72] The human body absorbs sunlight when exposed to the sun, whereas inside, the sunlight absorption is negligible. P_{sun} is the surplus heat gain of the human body under the sun, which can be calculated as follows:[23,53]

$$P_{sun} = \int_{0.3}^{4} I_{AM1.5}(\lambda)\cdot\alpha(\lambda)\ d(\lambda) \tag{2}$$

where $I_{AM1.5}(\lambda)$ is the air mass (AM) 1.5 global solar radiation spectrum, λ is the radiative wavelength, and $\alpha(\lambda)$ is the solar energy absorbance of the textiles.[73,74] Notably, the overall power density of the solar spectrum is roughly 1000 W m^{-2}, with a majority of it concentrated in the visible and near-IR (NIR) regions between 0.3 and 4 μm.[75]

Thermal conduction, convection, radiation, and evaporation are the four primary routes of heat dissipation for individuals. Temperature gradients in a medium facilitate heat conduction.[76] For PTM, subcutaneous fat is predominantly responsible for heat transfer between the skin and textiles. Since both fat and textiles are weak conductors, conduction heat dissipation in passive heat transfer settings is approximately 3%.[77] Thermal convection is the process of dissipating heat by the movement of air or a liquid. Compared to natural convection, induced convection using electric fans or blowers can significantly enhance the heat transfer coefficient.[21,76] One factor to consider when calculating the convective heat transfer efficiency of individual garments is air/vapor permeability, since greater permeability implies better heat transfer via convection and evaporation between the body and its surroundings. The source of radiation is electromagnetic waves emitted by any object at a finite temperature. The Stefan−Boltzmann law states that the dissipated energy is determined by the temperature disparity between the human body and surrounding environment, the surface emissivity, and the effective body surface area.[67]

The temperature gradient and thermal expansion coefficient of the medium affect thermal conductivity (P_{cond}). The thermal conductivity of textiles has a massive impact on heat transfer across the skin and textiles, indicating that thermal conductivity can be used to regulate heat transfer in the human body. Furthermore, air convection (P_{conv}) has a variable influence on heat transmitted between the skin, textile, and environment, which depends on the individual activities, the inherent properties of textiles, and the specific circumstance. Combining the conduction and convection coefficients, the effective heat transfer coefficient determines the rate of heat transfer in the skin−textile−environment system.[52]

Sweat evaporation (P_{evap}) is a distinctive cooling mechanism of the human body that occurs beneath the skin when the relative humidity is excessive. The transfer of perspiration from the skin to the outermost layer is ascribed to the capillary action of textiles.[39] The perspiration on the surface of the textile is then conveyed by the heat transferred over the epidermis, effectively augmenting the heat dissipation of the human body due to substantial residual heat of water sublimation. Apparently, the power of evaporated perspiration absorbed by passive heatsinks is associated with the moisture-wicking capabilities of textiles and the heat transfer coefficient. Therefore, researchers have tweaked the heat transfer coefficient and moisture permeability of fabrics to design innovative textiles for PTMSs.[77]

Radiant heat dissipation (P_{rad}) by the human body accounts for more than half of the overall thermal dissipation.[73,74,78] Passive radiative cooling, in which the sky-facing surfaces of Earth cool themselves by radiating heat into the supercooled outer space through the atmospheric long-wave IR-transparent window (8−13 μm), has received a great deal of interest. The human body emits mid-IR (MIR) thermal radiation with a peak of 9.5 μm in the wavelength range of 7−14 μm and an IR emissivity of 0.98.[77,79] This low-temperature radiation spectrum corresponds to the transparent window in the atmosphere of Earth that permits successful emission of body heat into space (3 K).[80] Radiative cooling is a sophisticated strategy of cooling that involves reflecting energy into the outer space through atmospheric windows.[81,82] The amount of heat lost by the human body owing to thermal radiation dissipation can be calculated as follows:[21,40,52]

$$P_{rad} = \int_{0}^{\infty} d\lambda\cdot I_{BB}(T,\lambda)\cdot\varepsilon(\lambda) \tag{3}$$

and

$$I_{BB}(T,\lambda) = \frac{2h\cdot c^2}{\lambda^5}\cdot\frac{1}{e^{hc/\lambda k_B T} - 1} \tag{4}$$

where I_{BB} is the spectrum radiation of the blackbody at temperature (T), $\varepsilon(\lambda)$ is the surface spectral emissivity of the skin or textile, h is Planck's constant, c is the velocity of light, and k_B is Boltzmann's constant.

Therefore, we can conclude that the human skin has a significant effect on the heat exchange between the body and its surroundings. Textiles are an integral part of the human body and can be thought of as a second layer of the skin.[83] Garments, as a boundary requirement of the interior microclimate, have an influence on thermoregulatory applications because clothing functions as a barrier between the interior microclimate and the surroundings, and should be specifically tailored for efficient PTMSs.[23,42] Consequently, it is worth mentioning that the optical characteristics (α, ρ, and τ) of textiles in the IR region determine radiative heat transmission between objects and the atmosphere. Traditional fabrics, on the other hand, rarely utilize solar and heat radiation to enhance thermal comfort of the human body. Herein, we mainly focus on the effect of radiation- and conductance-controlled mechanisms on PTMSs since they account for the majority of the total heat energy dissipation. Convection and evaporation transfer heat energy in a parasitic way that is largely impacted by ambient conditions (e.g., temperature).

Principle of Thermal Radiation. Thermal radiation is the electromagnetic waves induced by temperature. Any item with a temperature above 0 K can emit thermal radiation, and thermal radiation is temperature-dependent (the higher the temperature, the higher the thermal radiation).[84] Theoretically, the continuous wavelength range of heat radiation can span from zero to infinity. In principle, the primary carriers of thermal radiation propagate in the IR region and longer visible wavelengths. The temperature dependence of the propagation law is as follows: (1) the IR wavelength is the predominant form of heat radiation at low temperatures; (2) the strongest wavelengths are found in the IR region when the temperature is greater than 300 °C; and (3) the strongest wavelength

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component of thermal radiation occurs in the visible spectrum when the temperature of the object is between 500 and 800 °C.[85]

The radiation source emits and/or absorbs energy per unit time area, associated with the characteristics of the exterior surface and its temperature. Briefly, the darker and more irregular the surface, the greater the ability of the object to emit (absorb) energy.[23,39] Any item releases energy into the surrounding space in the form of electromagnetic radiation. When a radiative electromagnetic wave collides with an object along its path, this interaction accelerates the thermal movement of the microparticles inside the object, resulting in the object heating up. In addition to radiating energy, an object simultaneously receives energy from other objects. If, at any point, the energy absorbed and the energy radiated by an object are identical, the object is referred to as a blackbody. When an object is maintained at a constant temperature, the radiation pathway approaches an equilibrated state, where this phenomenon is termed as equilibrium radiation.[23,86] Thermal radiation transfers heat energy from one object to another across a vacuum at the speed of light. The only approach to transfer heat energy in a vacuum is using thermal radiation since electromagnetic waves travel across the interstellar space in the form of thermal radiation.[87] Basically, these four principles of thermal radiation can be categorized as follows: (1) Kirchhoff's law of radiation,[88] (2) Planck's law of radiation distribution,[89] (3) the Stephan−Boltzmann law,[90] and (4) Wien's law of displacement.[91]

Specifically, thermal radiation is a subset of electromagnetic radiation based on the energy transmission mechanism. Radiation is caused by an alteration in the electronic, vibrational, and rotational states of atomic molecules, while the uneven parachuting of charged particles (electrons or ions) in the medium causes radiative energy output.[83,92] For instance, the opposite process takes place (absorption), when the radiative energy strikes a solid surface and triggers a rise in temperature. The radiation energy can be usually absorbed, transmitted (pass through), or reflected (or any combination thereof) when it impinges a surface. The amount of energy transmitted is equivalent to the total of these three components, with the following variables describing these three phenomena:[93]

$$\alpha(T) + \rho(T) + \tau(T) = 1 \quad (5)$$

where α, ρ, and τ are the spectrum absorption factor, spectral reflection factor, and spectral transmission factor, respectively. In a majority of investigations on human thermal regulation, Fourier transform IR (FTIR) spectrophotometers were utilized to assess the IR reflectance and transmittance. On the basis of the internal absorption of materials, it is possible to directly attain the emissivity according to Kirchhoff's law.[83]

Mechanism of Thermal Conduction. Heat conduction is the heat transfer phenomenon caused by the thermal movement of microscopic particles such as molecules, atoms, and free electrons inside or between the surfaces of objects in contact with each other. Also, it is the process of transferring thermal energy from a high-temperature region to low-temperature region as well as the transfer of vibrational energy from one molecule to another.[94−96] Different materials have different thermal conductivities; materials with high thermal conductivities, like metal, allow for the movement of free electrons, resulting in quick heat transfer and enabling their use as a heat exchanger material; materials with poor thermal conductivities, like asbestos, can be used as thermal insulators.[97−99]

The migration of electrons or lattice vibrations within an item (from high temperature to low temperature) and the tiny collision of particles between two neighboring materials are examples of thermal conduction, a form of internal energy transmission (Figure 3).[100] Basically, atoms of warmer objects

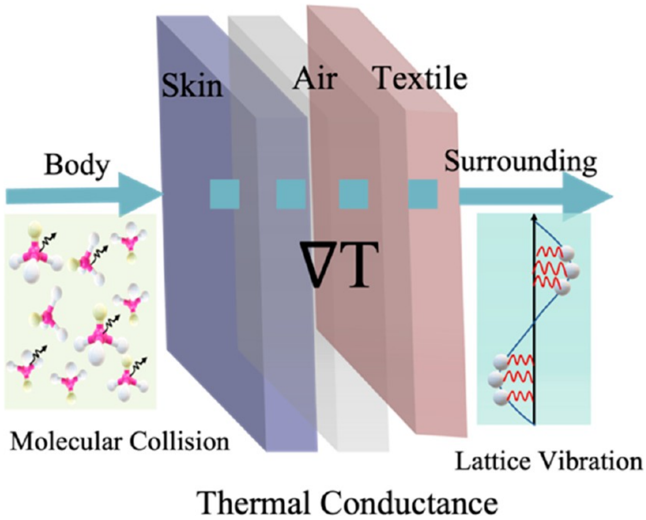

Figure 3. Schematic of thermal conductance models of heat transfer from the human body to its surroundings, including molecular collision and lattice vibration.

have a greater kinetic energy. This dynamic energy is disseminated by molecular collisions until the entire surface of the object has a consistent temperature. Thermal conduction is the most common method of heat exchange between or within solid materials.[90,101] Heat conduction accounts for most of the heat lost by a building. However, air cavities in the insulation (i.e., areas with low thermal conductivity) mitigate this loss by halting conduction. Four variables (κ, A, ∇T, and d) influence the rate at which heat travels through a material, as indicated in eq 6:[102]

$$Q = \frac{\kappa A \nabla T}{d} \quad (6)$$

where Q is the quantity of heat that has passed through the object (W), κ is the thermal conductivity ($W{\cdot}m^{-1}K^{-1}$), A is the area of the conductive surface of the material (m^2), ∇T is the change in temperature (K), and d is the displacement between the two isothermal regions (m).

RADIATION CONTROLLED TEXTILES

Since the human skin is an excellent IR emitter (emissivity = 0.98), the body emits most of its heat in the MIR wavelength range of 7−14 μm, with a diffraction peak at 9.5 μm. Radiation significantly contributes to the heat dissipation of the human body, accounting for more than 50% of the total heat exchange in normal indoor scenarios.[57,102,103] As described in the section of basic concept, controlling human radiation using sophisticated textiles can be achieved by first controlling the optical properties of textiles and then the radiation heat transfer between the human body and textiles.[104] For a cooling effect, it is preferable to dissipate as much human radiation as possible; hence, a fabric with high-MIR transmittance is indispensable.

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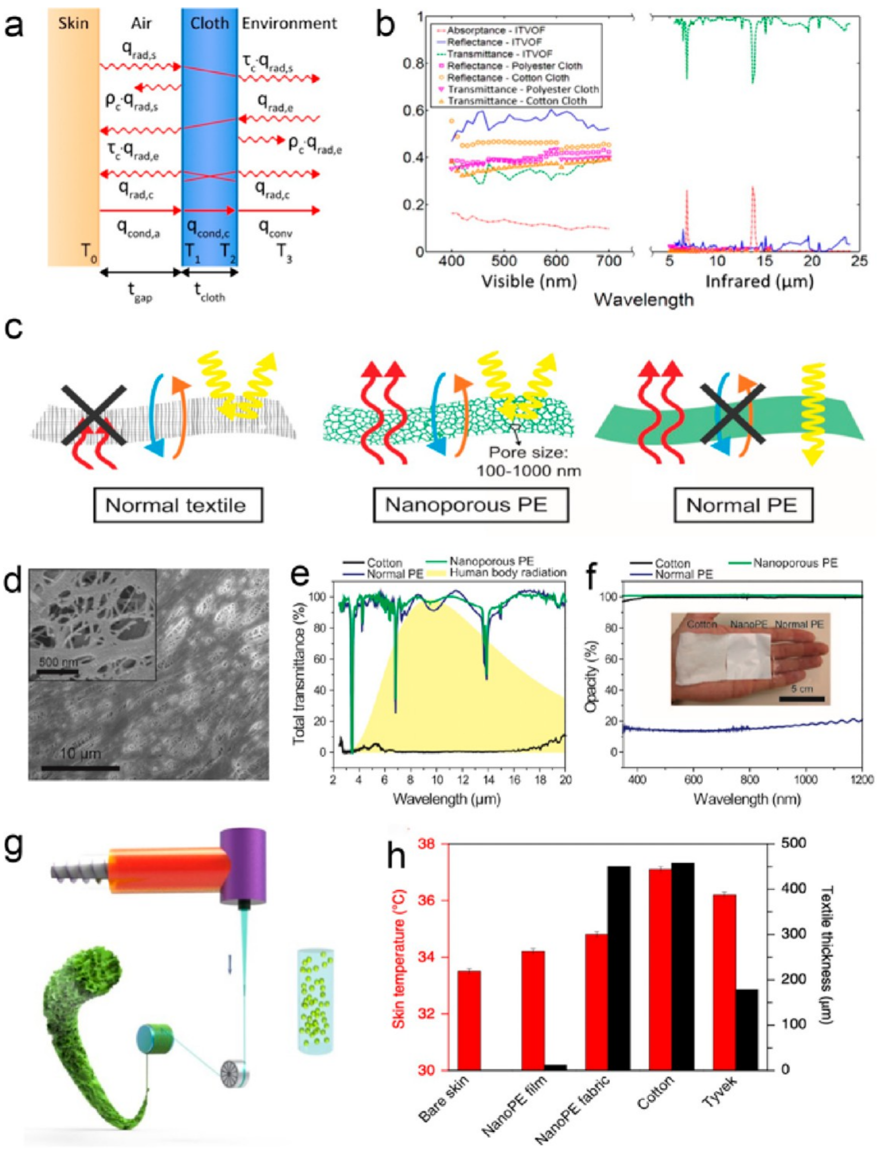

Figure 4. Various MIR-transparent radiative cooling textiles. (a) Schematic of the heat transfer model between the human body and environment. (b) MIR and visible wavelength spectra for an ITVOF. Reprinted with permission from ref 105. Copyright 2015, American Chemical Society. (c) Schematics of cotton, regular PE, and nanoPE. (d) SEM images of nanoPE. (e) Total FTIR transmittance of cotton, normal PE, nanoPE, and human body radiation. (f) Demonstration of quantitative measurements of visible opacity of nanoPE, normal PE, and cotton. Reprinted with permission from ref 107. Copyright 2016, American Association for the Advancement of Science. (g) Schematic representation of the nanoPE microfiber production process. (h) Artificial skin temperature measurement on different samples. Reprinted with permission from ref 106. Copyright 2018, Springer Nature.

Another option is to implement efficiently emissive clothing that emits a considerable amount of human radiation. Both strategies can significantly expedite the rate of heat lost by radiation. In contrast, high-MIR reflection is beneficial for warming. Textiles must be opaque in the visible wavelength region to have cooling and heating effect for applications.

MIR-Transparent Radiative Cooling Textiles. Textiles can inhibit excessive radiation of heat from the body, according to the basic concept of human body heat transfer pathway. Traditional textiles (e.g., cotton and polyester) are permeable to MIR thermal radiation owing to strong vibration of chemical bonds, especially carbon-based bonds. Indeed, the advancement of MIR-transparent textiles will be the optimum alternative as a superb emitter on the human body for heat dissipation.

Tong et al.[105] reported an IR-transparent visible-opaque fabric (ITVOF) that delivers passive cooling by directly dissipating the radiant energy released from the human body to the atmosphere (Figure 4a). A theoretical foundation for thermally and optically creating the ITVOF with poor reflectance in the MIR band and good visible light opacity is described using the heat transfer pathway.[105] The ITVOF extends the thermal comfort range by providing an optimum IR transmittance of 0.644 and a minimal IR reflectance of 0.2, rendering thermal comfort at atmospheric temperatures of up to 26.1 °C (Figure 4b). Mathematical parameter estimation simulations predict that merging 1 μm diameter fibers into a 30 μm yarn can accomplish a total hemispheric IR transmittance of 0.972, which is close to perfect transparence for MIR fabrics comprising parallel-aligned polyethylene (PE) fibers.[105] Another material, PE, is innately MIR-transparent textiles for

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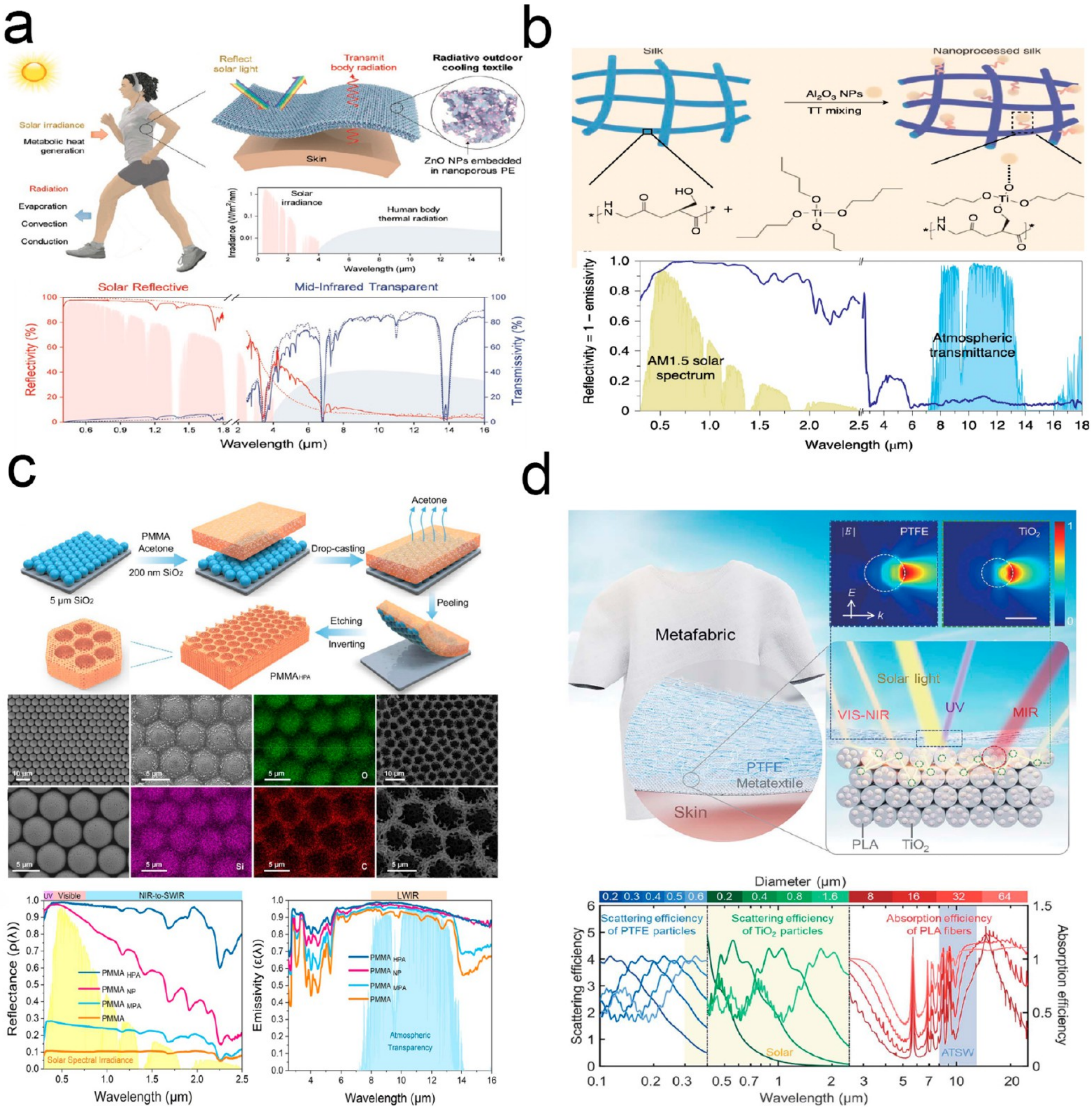

Figure 5. Daytime passive radiative cooling textiles. (a) Schematic of a nanoPE cloth with integrated ZnO NPs and ZnO-PE reflectivity and transmissivity spectra from measurements and simulation in the UV and MIR regions (0.3−16 μm). Reprinted with permission from ref 75. Copyright 2018, John Wiley and Sons/Wiley-VCH. (b) Schematic for the preparation of nanoprocessed silk. Al_2O_3 NPs are incorporated into silk fibers via a coupling reaction, and the reflectivity spectrum of as-fabricated nanoprocessed silk is in the range of 0.3−18 μm. Reprinted with permission from ref 141. Copyright 2021, Springer Nature. (c) Schematic diagram of the synthesis of PMMA with a hierarchically porous array, SEM images and elemental mappings (EDS) of the PMMA/SiO_2 composite, and reflectance and IR emissivity spectra of various types of PMMA films in the solar wavelength range. Reprinted with permission from ref 142. Copyright 2021, Springer Nature. (d) Schematic of a metafabric for daytime radiative cooling and scattering, and absorption efficiencies for particles with different sizes encapsulated in the metafabric, exhibiting high reflectance in the UV−vis spectrum and high emissivity in the MIR spectrum. Reprinted with permission from ref 149. Copyright 2021, Science.

PTMSs since its absorption peak (only aliphatic C−C and C−H bonds) is narrow and wavelength-centered.[20,106] Cui et al.[107] revealed that nanoporous polyethylene (nanoPE) was transparent to MIR but opaque to visible light, probably because the pore size distribution ranges from 50 to 1000 nm as shown in Figure 4(c,e,f). This porous material was characterized by scanning electron microscopy (SEM; Figure 4d) and used to create a textile that had effective radiative cooling and excellent wearability properties, that is, breathability, water permeability, and mechanical strength.[107]

Owing to its outstanding MIR-transparent and superior visible-opaque properties, nonwoven nanoPE has been used to achieve the efficient passive cooling effect. However, the stability and processability of the nonwoven PE film are erratic and challenging, and the drilling method is time-consuming, resulting in a substandard application for widespread usage.[106,108] Developing practical and applicable textiles with cotton-like properties using knitted/woven fibers can effectively alleviate these issues. There have been some investigations to study the potential of these fabrics in PTMSs. For example, Ding et al.[109] proposed a gel extrusion approach that proved the viability of producing digitally continuous thermoelectric textiles with great scalability and process efficiency. Also, Song et al.[110] developed a material comprising proper hybrid fibers and used it to construct a textile with a porous-wrinkled structure for passive cooling effects.

Specifically, Peng et al.[106] determined that extensive extrusion of uniform, progressive nanoPE microfibers with conventional textile properties was beneficial for industrialized fabric production from a practical and applicable standpoint (Figure 4g). Incorporating nanopores into the fibers effectively scatters visible light, rendering the material opaque while maintaining its MIR transparency. The nanoPE fabric outperformed industrial cotton fabrics of almost the same thickness in terms of the cooling efficiency, reducing the human skin temperature by 2.3 °C and conserving over 20% of the indoor cooling capacity (Figure 4h).[106] Therefore, nanoPE microfibers are a crucial component in the development of human-body-cooling materials owing to their abrasion resistance, durability, and effective cooling performance.

Additionally, composite materials based on intrinsic MIR transparency without overlapping absorption peaks have also been designed to achieve passive cooling, and these materials simultaneously have superior wearability.[53,111] Incorporating IR-transparent materials into the structure of traditional textiles and engineering their orientation is one strategy for enhancing heat dissipation from the human body.[54,111] Specifically, Catrysse et al.[112] reported that a combination of IR-transparent nylon and cotton (17%) dissipated body heat more efficiently than that of the cotton (100%) counterpart. In this design, the net total radiative heat flux of the nano-engineered cotton/nylon blend was 2 °C higher than that of cotton alone, resulting in an effective cooling performance.[112]

Daytime Passive Radiative Cooling Textiles. Due to the scarcity of alternatives to radiation heat, it is essential for residential buildings to regulate MIR thermal radiation from the human body. In addition to using MIR-transparent textiles for preserving the passive radiation cooling performance, it has been observed that controlling surface emissivity of textiles is an effective approach for temperature regulation.[107] In outdoor circumstances, however, limiting solar radiation becomes crucial for passive cooling effect.[113] The portions of visible light (400−700 nm) and NIR (700−2500 nm) involved in nanoscale wavelengths account for roughly 95% of solar radiation (1000 W m^{-2}) in this spectral region. By preventing the penetration of visible light into clothing, solar radiation exposure to the human body can be minimized to an optimum level.[114] Hence, nanoengineered structures exhibit effective thermoregulation properties that are dissimilar from those of traditional thermal emitters, facilitating wide use in the field of PTMSs.[115,116]

One-way passive daytime radiative cooling (PDRC) below an ambient temperature under direct sunlight, on the other hand, is challenging since a vast majority of readily accessible radiative cooling materials absorb impinged solar radiation.[117−120] Therefore, designing and fabricating high-efficiency PDRC materials with high solar reflectivity in the range of 0.3−2.5 μm, which restrict solar radiation while retaining superior MIR thermal radiation in order to optimize thermal radiation escape, are indeed indispensable.[117,121,122] While progressive strides have been made, developing cost-effective and energy-efficient radiative cooling materials for year-round and all-climate use remains a significant challenge. Alloying elements (e.g., Ag, Ti, and Al)[123−126] and inorganic or organic chemicals (e.g., TiO_2, ZnO, and Al_2O_3)[82,127,128] have been employed to promote solar reflectance. Furthermore, radiative cooling for PTMSs is achieved using an integrated random metamaterial or hierarchical structure, both of which enable the design and construction of textiles that reject solar energy while emitting robustly in the MIR range, according to the Mie scattering theory in the region of the solar spectrum and strong vibrations in the MIR region.[129−132]

Controlling the entire solar spectrum and MIR radiation is essential for delivering exceptional cooling performance.[133−136] MIR-transparent textile materials with the potential to reflect solar radiation have been proposed. By incorporating zinc oxide nanoparticles (NPs) into nanostructured PE, called ZnO-PE, Cai et al.[75] integrated intrinsic material properties with optical-structure engineering to create a textile material with specific spectral responsiveness. Owing to its ability to reflect more than 90% of solar radiation while selectively transmitting human body thermal radiation, ZnO-PE allowed the mimicked skin to avoid overheating by 5−13 °C in comparison to typical textiles (Figure 5a). Such PDRC clothing provided an innovative way to social sustainability due to its high passive thermal radiation efficiency and production scalability.[75]

An additional particle of inorganic alloyed Al_2O_3 was introduced into a natural silk material used for PTMSs. Silk is a glossy natural protein fabric that is created by moth caterpillars and is renowned for its cooling properties and skin comfort.[137−140] Zhu et al.[141] created a fabric with significant net cooling potential in sunlight by treating silk via a scalable coupling-reagent-assisted dip coating technique, based on the mechanism of high-refractive-index Al_2O_3 for blocking ultraviolet (UV) light and intrinsic high emissivity of silk in the MIR wavelength range (Figure 5b). Under direct sunlight, the superb nanostructured silk could effectively reduce the temperature of the skin to 3.5 °C below the ambient temperature. In addition, monolithically integrated silk enabled to achieve subambient daytime radiative cooling without sacrificing wear resistance or thermal comfort of the human body.[141] For optimal daytime and nighttime passive radiative cooling, Wang et al.[142] fabricated a hierarchically organized poly(methyl methacrylate) (PMMA) film with an arrangement of micropores mixed with randomized nanopores, aligned geometrical micropores (average diameter = 4.6 μm), and randomly assigned nanopores (average diameter = 250 nm), as depicted in Figure 5c. This metal-free multilayer PMMA film had an adequate solar irradiation reflectivity of 0.95 and a superb MIR emissivity of 0.98, achieving subambient cooling efficiency of 8.2 °C at night and 6.0−8.9 °C during the daytime owing to its periodically scattered micropores integrated with random nanopores and merits of inherent properties. By eradicating the impact of moisture at various relative humidity, the superhydrophobic PMMA coating could ensure the cooling performance.[142]

The ultimate objective is to design thermoregulatory textiles that can be manufactured industrially and are cost-effective, energy-efficient, versatile, and sustainable.[143] From the beginning to the end of the life of a textile, it consumes large amounts of water, power, labor, and chemicals while producing detrimental environmental byproduct and tons of trash, gas emissions, and wastewater. These wastes and contaminants from the garment manufacturing process may pose high-level risks to the survival of animals, plants, and humans across the ecological systems.[108,144] In terms of

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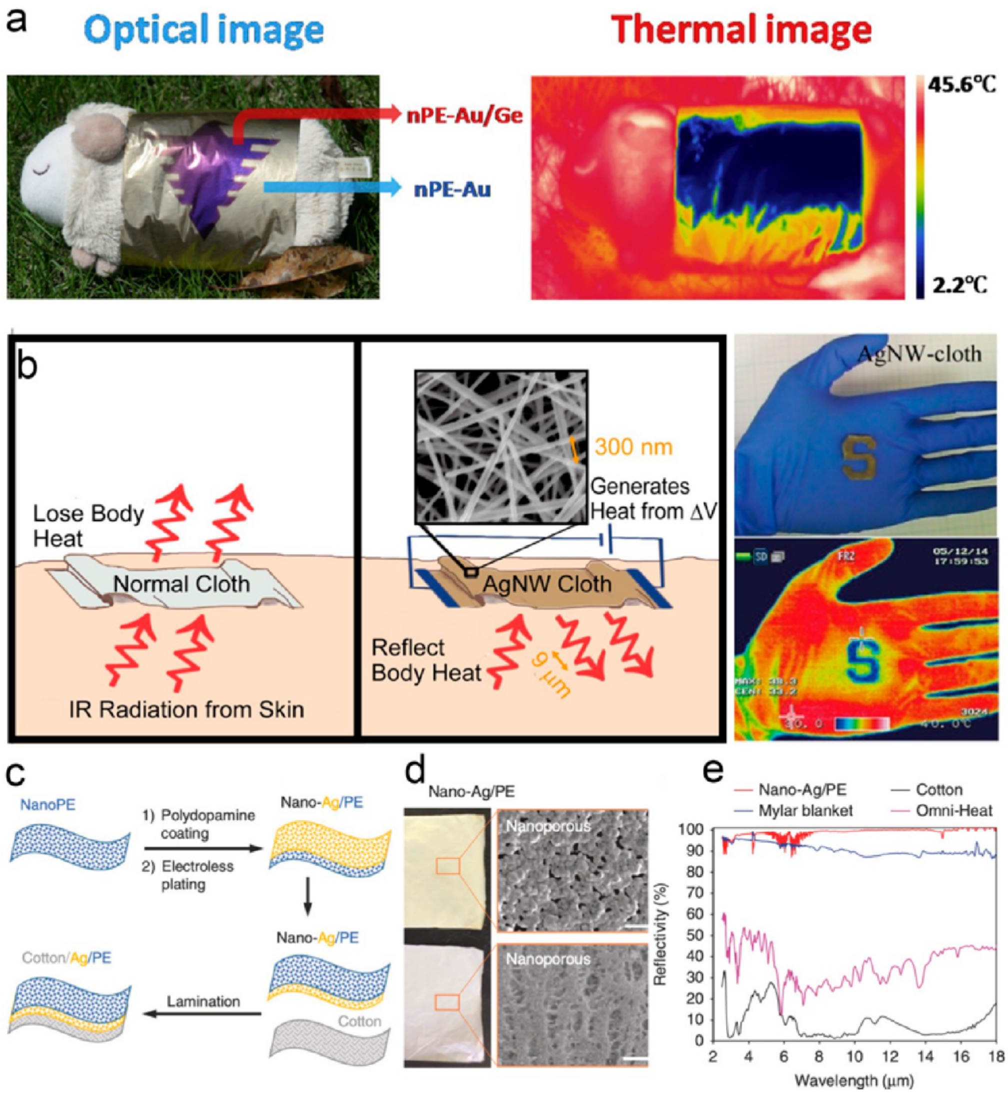

Figure 6. MIR emissivity of radiative warming textiles. (a) Optical and thermal images of a toy sheep wearing a colored garment with simultaneous solar and passive heating capabilities. Reprinted with permission from ref 152. Copyright 2019, Elsevier. (b) Nanowire cloth concept with active heating and thermal radiation insulation (left); the regular photos (top) and thermal images (down) of a AgNW cloth with an S shape (right). Reprinted with permission from ref 153. Copyright 2014, American Chemical Society. (c) Schematic illustration of the preparation of the laminated nano-Ag/PE textile on the outer surface of cotton. (d) Photograph (left) and SEM images (right) of nano-Ag/PE and Ag sides. (e) IR spectra, including the total FTIR reflectance of nanometal-coated nano-Ag/PE, cotton, Mylar blankets, and Omni-Heat. Reprinted with permission from ref 154. Copyright 2017, Springer Nature.

environmental factors ranging from raw material shortlisting, chemical consumption, and end-of-life procedures to the innovation of temperature-regulating clothing as sustainable textiles, ecofriendly chemistry has become progressively significant. Sustainable fibers are produced from ecofriendly raw materials (such as cellulose) with minimum hazardous emissions (e.g., CO_2) and water consumption. Additionally, sustainable consumption focuses on easily washable and recyclable textiles rather than disposal and landfilling of polymers and metal fittings, therefore alleviating the issue of contamination by hazardous gases and heavy metals.[51,144]

The PDRC textiles with superior properties, such as effective passive cooling, distinct optical scattering, and outstanding wearability, have been manufactured via three primary techniques:[145−147] (1) coating and lamination of functional NPs on the surface of textiles; (2) electrospinning of embedded fillers into thermoregulatory textiles; and (3) knitting or weaving technology to construct sustainable and large-scale temperature-regulating textiles.[148] All techniques are affected by environmental conditions, especially humidity and temperature. The environmental temperature and humidity affect the surface tension of the preused solution and the solvent diffusion process.[143,146] Lowering the relative humidity of the surroundings during electrospinning, for example, will boost the solvent diffusion process, resulting in a more uniform fiber distribution and a decrease in fiber diameter. Conversely, an increase in ambient temperature will decrease the concentration of the polymer solution during electrospinning procedures. Thus, in order to reduce the influence of environmental conditions, it is essential to manufacture engineered textiles in an enclosed room with an automated control system.

To better balance the passive cooling effect and wearability in a sustainable and applicable way, Zeng et al.[149] proposed that massive interwoven metafabrics potentially had a high emissivity of 94.5% in the MIR region and a high reflectivity of

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Table 1. Summary of Materials, Achievements, and Thermal Modes of Various Textiles Fabricated Using the Radiation-Controlled Technique

textile types	achievements	limitations	thermal modes	ref
Al_2O_3−Cellulose Acetate	Solar reflectance of 0.8, MIR transmittance of 0.97	Poor wearability	Cooling	159
es-PEO	High reflectivity of 96.3%, 5 °C subambient cooling	N/A	Cooling	137
MXene−PE	Passive heating and Joule heating, 4.9 °C increase, MIR emissivity of 0.176	Complicated process and poor resistance to washing	Warming	156
PA/Al_2O_3/PA6	High solar reflectivity (0.99), good moisture permeability, sweat release	N/A	Cooling	160
PU/Si_3N_4	Solar reflectance (91%), MIR emittance (93%), 2.8 °C drop than commercial textile	Complicated fabrication process	Cooling	161
Cu/SEBS	On/off switching ratio of ∼25 (transmittance), dynamic set point temperature window (8 °C)	Complicated process, not scalable, uneven cracks	Cooling/warming	162
Nafion-based textiles	Humidity-based quick and reversibly changeable porosity or thermal insulation	Poor wearability	Cooling/warming	163
Glass-polymer hybrid metamaterial	Fully transparent in the solar spectrum, emissivity greater than 0.93 in the atmospheric window	Poor air permeability and moisture-wicking	Cooling	81
PVDF/cellulose acetate (CA)	High solar reflection (≈96.6%), high solar transmission (≈86.6%), switchable in various humidities	Poor wearability, not scalable	Cooling/warming	164

92.4% in the solar spectrum wavelength. This was attributed to the hierarchical construction of randomly distributed scatterers across the metafabric (Figure 5d). Typically, the term "metafabric" refers to engineered textiles possessing outstanding properties, that is, effective passive cooling effect, superior mechanical strength, or wettability, which are difficult to find in conventional fabrics. Based on this mechanism, fabrics containing TiO_2 NPs as scatterers could overlap the whole visible−NIR (vis−NIR) region with high reflectivity according to the Mie resonance theory.[149] Poly(lactic acid) (PLA) microfibers with inherent emissivity function in the MIR region owing to strong vibrations of numerous carbonized bonds.[149] Specifically, a person who was wrapped in this layered-structure fabric could achieve a temperature reduction of 4.8 °C in comparison to traditional cotton textiles. Also, the metafabrics had appropriate mechanical properties, waterproofing performance, and breathability and effective radiative cooling capabilities when used as industrial garments, and their manufacturing had the scalability of traditional textile manufacturing techniques.[149] Actually, humans can be effectively shielded from the effects of escalating anthropogenic global warming by integrating passive radiative cooling designs into PTMSs.

Typically, sustainably designed textiles begin with a systematic life cycle assessment, which may modify the entire manufacturing process due to theoretical, technological, and practical factors.[23,150] However, some textiles are manufactured using challenging and costly materials (e.g., boron nitride, graphene, and laboratory-scale materials). These nanomaterials extensively used in temperature-regulating textiles possess serious health and environmental hazards, which necessitate a comprehensive evaluation.[144,151] Therefore, sustainable development and practical applications of thermoregulatory fabrics are severely restricted. Except the aforementioned thermoregulatory clothing (nanoPE and metafabric), along the practical and sustainable path, Alberghini et al.[108] demonstrated that sustainable nanoPE-based fabrics could outperform conventional textiles in terms of their radiative passive cooling efficiency. The sustainable clothing was constructed using melt-spinning and weaving techniques common in the international textile industry. In addition, the as-synthesized textiles were incredibly lightweight, recyclable, and cost-effective, as well as generally acknowledged assessment tools, such as the industrial materials sustainability (Higg) index for sustainable textile manufacturing.[108] In summary, sustainable materials and technologies can facilitate the transition of temperature-regulating textiles toward energy preservation and the harboring of individualized thermal comfort.

MIR Emissivity of Radiative Warming Textiles. Passive heating is made possible by successfully inhibiting the heat dissipation channel of MIR emissivity, as opposed to personal cooling management, which maximizes thermal radiation emissions. Coating the inner surface of garments with metallic fiber sheets is an effective approach.[112,143] Additionally, core-spun technology and hybrid metal−polymer composite fabrics have been investigated for high-MIR reflective textiles with increased flexibility to coating-metal textiles from releasing hefty and rigid restrictions. To further the development of low-radiation-emissivity materials, the proposed smart textiles can efficiently achieve superior heat retention in the human body, out of the contradiction between high breathability and effective heat radiation properties.

Maintaining the body temperature has become one of the most fundamental demands for human survival; however, maintaining air temperatures requires a great deal of energy. Radiant heating uses textiles with tailored effective MIR reflectivity or emissivity. Specifically, Luo et al.[152] reported that localized heat retention was feasible in a colored nanophotonic-structured textile, principally by reducing radiative heat dissipation from outer surfaces with a low IR emissivity of approximately 10% for energy-free heating management, as shown in Figure 6a. This fabric provided superior aesthetics, abrasion resistance, and manufacturability and permitted an artificial skin temperature rise of 3.8 °C when compared to a black sweatshirt.[152] However, the mismatched connection between the coated metal-element surface and clothing affected the intrinsic wearability of textiles, possibly due to the roughness of the textile and its insufficient flexibility. To address aforementioned issue, Hsu et al.[153] fabricated a silver nanowire-pre-embedded cloth (AgNW cloth) for PTMSs. Based on that, further evolution of the passive heating effect and MIR reflection was achieved by using nanostructured metals (Figure 6b). Cai et al.[154] demonstrated that a nanostructured fabric with specific MIR properties boosted PTM heating capabilities without compromising breathability. In this design of nanoporous metallized PE textile (nano-Ag/PE), the implanted nanopores were of a precise diameter, smaller than IR wavelengths but larger than water molecules,

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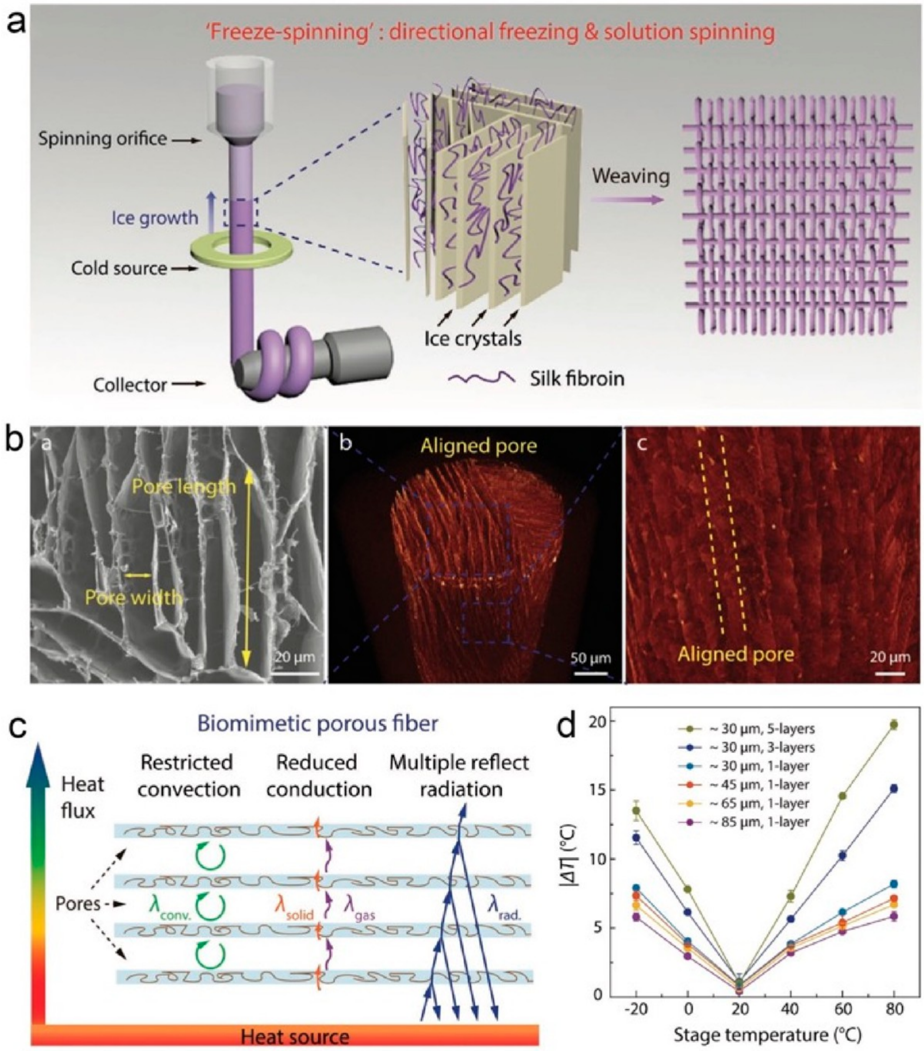

Figure 7. (a) Diagram of the "freeze-spinning" technique. (b) Radial cross-sectional SEM and X-ray computed microtomography images illustrating the aligned porosity. (c) Schematic depiction of thermal conductivity of the biomimetic fiber with oriented pores. (d) Temperature difference (|ΔT|) between the textile surface and the stage is shown against the stage temperature for different mimicking textiles. Reprinted with permission from ref 169. Copyright 2018, John Wiley and Sons/Wiley-VCH.

addressing the drawbacks of existing radiation-heated textiles, where the distribution of the coating-metal element was balanced between the impermeable density and underperformed reflectivity density (Figure 6c,d).[154] Figure 6e shows that nano-Ag/PE had the lowest IR emissivity of 0.101 on the exterior surface, significantly minimizing radiative thermal dissipation without compromising comfort, leading to a set point lower temperature of 7.1 °C compared to that of traditional textiles.[154] As a result, metal-decorated PE textiles with minimal emissivity can effectively inhibit the dissipation of thermal radiation from the human body to its surroundings without obstructing the movement of water vapor.

PE textiles in conjunction with a nanostructured metallic layer guarantee optimal reflectivity and breathability. Additionally, carbon-based substances (e.g., graphene/graphene derivatives) or carbon-like materials (such as MXene) have been added to polymers to enhance the performance and wearability of personal heating management systems.[155,156] Hazarika et al.[157] synthesized composite vertically oriented metal-decorated nanowire arrays on the surface of woven Kevlar fiber sheets and further coated them with reduced graphene oxide/polydimethylsiloxane films. These nanowire arrays exhibited superb thermal insulation and outperformed electricity. Furthermore, carbon-based materials can be utilized as personal heating devices. Wang et al.[158] synthesized a graphene fiber-based heater with the capacity to reach high temperatures for PTMSs owing to its the tremendous stretchability, extraordinarily rapid electrically heated reaction, and incredibly low operating voltage.

In addition to these advanced clothing materials, Table 1 highlights the thermal performances and limitations of other radiation-controlled textiles. As shown in the table, most textiles could achieve high emissivity or transmittance in the MIR region and high reflectance in the range of the solar spectrum to provide a cooling performance. Meanwhile, an excellent warming performance is primarily ascribed to the high reflectance in the MIR region. Unfortunately, these functional thermal clothing might still be hampered by numerous restrictions, including poor wearability, a complicated fabrication process, underperformed antiwashability, and practicable commercialization.

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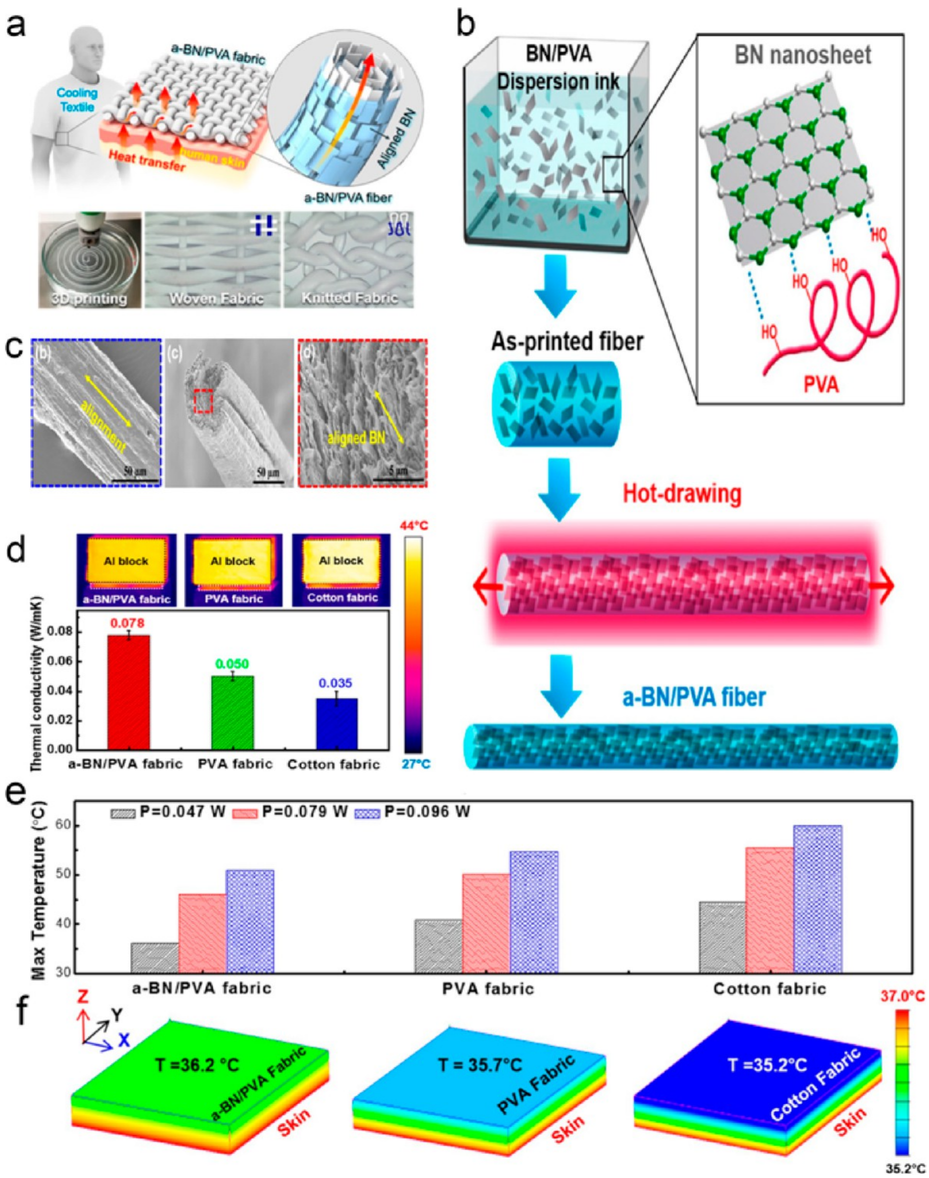

Figure 8. (a) Schematic of the thermal regulating textile and (b) the fabrication process of a-BN/PVA composite fibers. (c) SEM images of the a-BN/PVA fiber, exhibiting aligned BNNS along the composite fibers. (d) Thermal conductivities of different fibers. (e) Maximum surface temperature of cotton, PVA, and a-BN/PVA fabrics in a sandwich construction. (f) Modeling and calculation of the maximum temperature of various fabrics above the human skin. Reprinted with permission from ref 179. Copyright 2017, American Chemical Society.

CONDUCTANCE CONTROLLED TEXTILES

As one of the primary methods of thermal energy dissipation from the human body, heat conduction regulation merits investigation in terms of enhancing or mitigating human body heat transfer for effective PTMSs.[51,52,165] At the interface between the human skin and inner side of the garment, thermal conduction, rather than IR radiation, is the major method of heat transmission. Additionally, thermal conduction is the only approach that dissipates heat when heat is confined within textiles.[23] As a result, various innovative nanocomposites and metastructured design have been incorporated into PTMSs to achieve thermally conductive materials for textiles or clothing with enhanced thermal transfer between the human body and its surroundings. It is imperative to design textiles with high heat conductivity to ensure conductive cooling and warming and thermal insulation.

Thermally Insulating Warming Textiles. Bioinspired fibers encourage the use of engineered textiles for efficient PTMSs by conserving roughly 47% of the total of energy consumption used to maintain the thermal comfort for occupants.[51,52,166−168] It is necessary to build a smart textile and/or fabric that can provide insulation from the environment and prevent body heat dissipation by releasing heat to the human body, and furthermore, it should be worn as a commercial garment. Recently, Cui et al.[169] developed a "freeze-spinning" technique that allows the large-scale production of fibers with aligned porosity that resemble polar bear hair. This knitted textile provided superb thermal insulation, breathability, and abrasion resistance.

A basic "freeze-spinning" process that combined "directional freezing" with "solution spinning" was shown in Figure 7a. Specifically, a computer-controlled pump permits the extrusion of the viscous solution from a syringe at a constant speed,

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which was intended to generate a steady liquid flow. The obtained fibers were further freeze-dried to maintain their porous microstructure. Subsequently, the biomimetic fiber roll could be knitted into a textile similar to that used for fabricating normal clothing.[169] As shown in Figure 7b, SEM characterizations and X-ray computed microtomography images revealed a highly porous and axially oriented microstructure within the fiber. Theoretically, the sum of thermal convection (λ_{conv}), solid (λ_{solid}), and air (λ_{air}) heat conduction, and thermal radiation (λ_{rad}) were used to determine the thermal conductivity of porous fibers (λ_{fiber}), as shown in Figure 7c. Since air was entrapped within individual micropores, thermal convection (λ_{conv}) of biomimetic fibers is severely constrained.[169] In addition, the thermal conductivity of air was far lower than that of solid fibers, and the thermal conductivity of biomimetic fibers was considerably reduced due to the high fraction of air-filled pores. With its enormous solid−air contacts, frozen textiles could significantly enhance IR reflectance in terms of IR radiation.[169]

Basically, the size of the aligned pores was determined by synthesis factors including solution concentration/viscosity, injection rate, and freezing temperature. To demonstrate the relationship between the pore size and thermal performance, textiles composed of oriented fibers with different porous microstructures had been synthesized. As seen in Figure 7d, woven textiles with a pore size of 30 μm had the best thermal insulation efficiency among one-layer conditions due to their smallest porosity. At −20 and 80 °C, increasing the temperature to 7.9 and 8.2 °C, respectively, resulted in a high $|\Delta T|$ or superior thermal insulation performance. When enlarged to five-layer ones, $|\Delta T|$ could reach temperatures between 14 and 20 °C, implying that the biomimetic textiles had outstanding thermal insulation even better than that of commercial textiles.[169] Based on the preceding discussion, it can be concluded that the aligned porous structure of biomimetic textiles facilitated thermal convection, conduction, and radiation, affording thermally insulating fibers for PTMSs, and their thermal performances could be superior to those of traditional textiles.

"Freeze-spinning", one of the practicable and scalable spinning techniques via ice templating, has been extensively employed to produce biomimetic porous textiles with well-oriented structure (e.g., ceramics, metals, polymers, and carbon-based materials). The technique of "freeze-spinning" has enabled these materials to be endowed with distinctive properties and greatly expanded its applicability and practicability.[170] By using "freeze-spinning" technology, it is feasible to attain high mechanical and thermal performance, outstripping brittleness of the conventional aerogel.[171,172] Similar to the aforementioned thermal insulation textiles, Wang et al.[173] synthesized the fibers with a porous structure using polyimide and the freeze-spinning method. The woven textiles made from polyimide fibers had excellent thermal insulation and were flame retardant and super stretchable. Also, Wu et al.[174] described an energy-free and skin-friendly method to synthesize insulating fabrics with passive heating and cooling effects on the human body. Due to their excellent thermal resistance, low MIR emissivity, and superior dyeability, these bioengineered textiles were widely implemented in thermoregulatory systems. The proposed thermoregulatory textiles with slow rates of temperature-changing and enhanced thermal comfort were viable and adaptable alternatives for localized cooling/heating systems.[174] Due to its practicability and applicability, the freeze-spinning technique is an approach for manufacturing multifunctional thermoregulatory textiles with well-oriented microstructures inspired by wild species. This is crucial for the innovation of better insulating materials for clothing, vehicles, and spacecrafts.

Thermally Conductive Cooling Textiles. The capacity of personal cooling systems to directly manage body temperature to deliver thermal comfort in a cost-effective and energy-efficient approach has drawn considerable attention.[151,175] Due to their localized cooling properties, abrasion-resistant textiles can offer increased thermal comfort to building residents under hot conditions while simultaneously decreasing the temperature settings on the air-conditioning systems indoors, thereby effectively minimizing the total construction cost.[112,176] Recently, numerous commercially available materials have been used to synthesize systems with varying degrees of PTM; however, their cooling effect is dependent on the presence of high humidity, precluding their practical applications in environments with fluctuating humidity levels.[177,178] To conquer this constriction, Gao et al.[179] synthesized a textile with well-aligned, high-thermal-conductance boron nitride (BN)/poly(vinyl alcohol) (PVA) composite fibers (labeled as a-BN/PVA) for personal cooling management via 3D printing technology (Figure 8a).

The thermally regulated textiles were constructed from well-oriented, interconnected BN nanosheets (BNNSs) embedded in a thermally conductive PVA matrix. BN/PVA textiles could conduct body-generated excessive heat along the fibers and further dissipate it into the surrounding air. The main procedures were shown in Figure 8b. A homogeneous BN/PVA suspension was fabricated, and then the liquid-phase-exfoliated BNNS was dispersed into a PVA/dimethyl sulfoxide (DMSO) solution and sonicated to ensure adequate dispersion. The printed fibers were fabricated via a 3D printing technique (using the precursor homogeneous solution) under coagulation bath.[179] Printed fibers were then subjected to a high-temperature heat drawing. Thermal drawing allowed the BNNS to compress into a well-aligned arrangement, compared to their pristine state where they were haphazardly distributed inside the fibers. It is worth noting that a more regular spacing in BNNS fibers can be achieved if the BNNS precursor solution is well dispersed during the 3D printing process. Further confirming the well-aligned BNNSs in fibers, the morphology of the fibers revealed that the diameter of a-BN/PVA composite fibers was three times smaller than that of original fibers before heat treatment. Heat treatment significantly reduces the BN/PVA fiber diameter from 300 to 95 μm, hence producing more tightly aligned structures than stretched free-printed fibers, as shown in Figure 8c. The thermal properties (including thermal conductivity and heat dissipation) of a-BN/PVA, PVA, and cotton fabrics were evaluated. The thermal conductivity of a-BN/PVA fabrics with a sandwich construction (Al block/fabric/Al block) were tested under the same laser power. Figure 8d shows that the a-BN/PVA fabric had the highest thermal conductivity (0.078 W/(m·K)) owing to the presence of thermally conductive BNNSs, surpassing the thermal conductivity of cotton (0.035 W/(m·K)) and PVA fabrics (0.050 W/(m·K)).[179] Additionally, a laser IR camera was used to evaluate the heat dissipation of fabrics. At varied laser power inputs, the a-BN/PVA composite fabric continuously maintained the lowest temperature, indicating that well-oriented BNNSs dissipate heat efficiently (Figure 8e).[179] In order to illustrate the cooling

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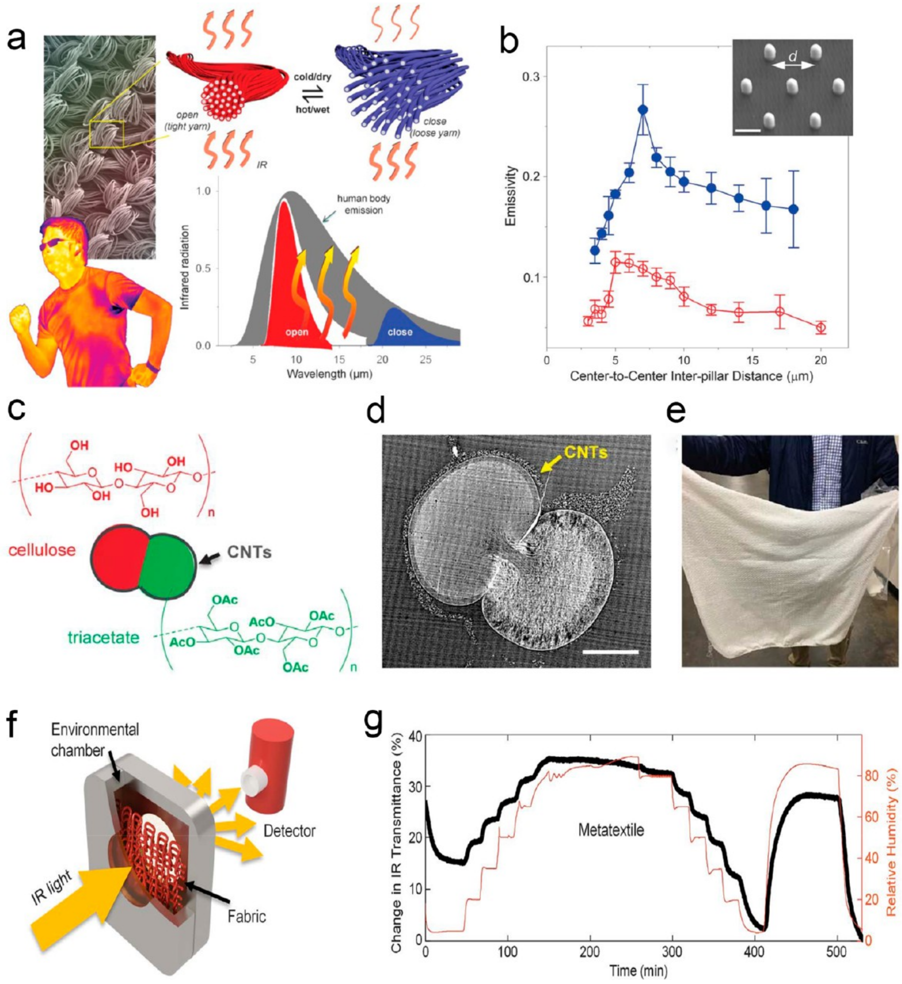

Figure 9. (a) An IR gating design concept for a textile. (b) Distance dependence of the emissivity of carbon- (blue solid circles) and gold-coated (red circles) pillar arrays. (c) A metafiber made by CNT-coated triacetate-cellulose bimorph fibers placed side by side. (d) TEM image of the metafiber. (e) Photograph of a knitted fabric. (f) Schematic setup for experimental measurements. (g) Change in IR gating (black curve) and relative humidity (orange curve) of the metatextile with time. Reprinted with permission from ref 192. Copyright 2019, Science.

effect of three fabrics with various thermal properties in PTMSs, a simulation model was created in ANSYS (Figure 8f). The highest outer temperature of the a-BN/PVA composite textile was 36.2 °C with a heat flow of 58.4 W/m^2, demonstrating its superior cooling performance compared to that of pure PVA and cotton fabrics, which had outer temperatures and heat flows of 35.7 °C and 55.99 W/m^2 and 35.2 °C and 53.35 W/m^2, respectively.[179]

Basically, applying a thermally conductive material to decorate fibers is a conventional method for achieving an efficient cooling effect by conduction in textiles.[180−182] In addition to the development of cost-effective, streamlined, and large-scale 3D printing techniques (a-BN/PVA composite fibers), thermally conductive and uniform heat dissipation properties in textiles for PTMSs have been developed.[179] Carbon-based compounds, including graphene and carbon nanotubes (CNTs), have been embedded into thermally conductive fabrics.[183−185] Chen et al.[183] proposed that a graphene-based composite, phenylphosphonic acid@graphene nanoplatelets (PPA@GNPs), was extremely thermally conductive and could exhibit an ultrahigh thermal conductivity of 82.4 W m^{-1} K^{-1} (in-plane), hence enabling efficient passive cooling. This optimized nanocomposite material demonstrated a lower temperature of 3.0 °C than that of a bare smartphone. Additionally, the surface temperature of illuminated LED chips was essentially lower than the temperature of an unlit LED chip (52.6 °C).[183]

DUAL-MODE TEXTILES

Beyond the typical PTM strategies, radiation heat regulation has proven to be an effective alternative. Different controls of heat transfer can be performed by adjusting emissivity, transmittance, and reflectivity. IR radiation (wavelengths from 7 to 14 μm) accounts for 40−60% of heat dissipated by a resting human body.[115] It has been reported that metal-decorated conventional textiles reflect IR energy back to, rather than away from, the body for personal heating.[121] Cooling clothing necessitates directing as much IR radiation away from the body as possible using transparent PE materials.[130] As of now, contradictory IR radiation management requirements for heating and cooling have hampered the ability of textiles to manage heat. The production of a single clothing with both heating and cooling performances remains a major challenge.

Flipped Bilayer Emitter Textiles. Maintaining an ambient temperature in a constant state costs a great deal of energy, despite the fact that preserving the body temperature is

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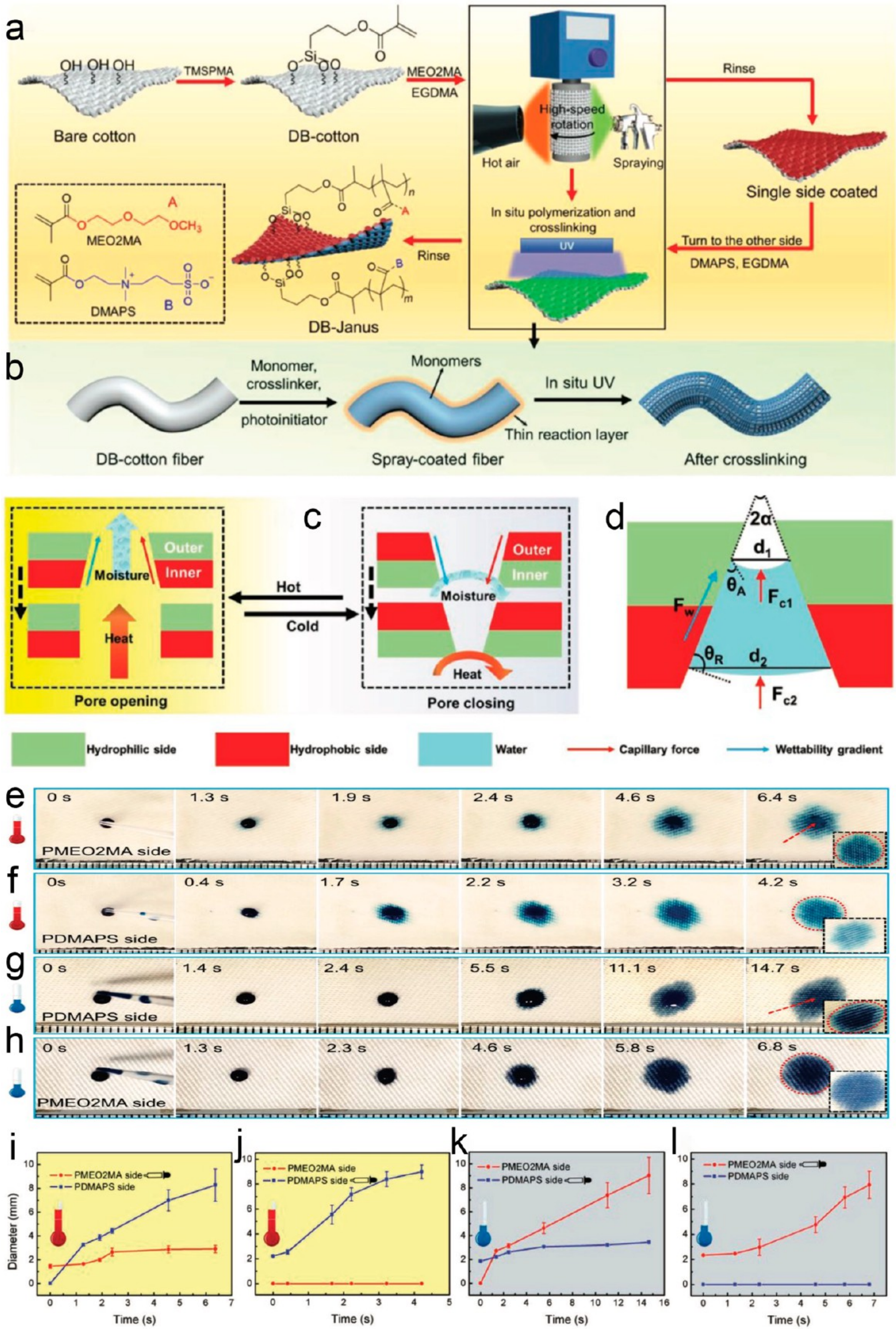

Figure 10. (a) Schematic of the smart DB-Janus fabric fabrication process. (b) Demonstration of the in situ polymerization and cross-linking reaction around a single cotton fiber. (c) Mechanism of moisture and heat management based on the reversible wetting gradient and pore size modification and (d) Demonstration of water transportation behavior. Images of the (e) PMEO2MA side at 40 °C, (f) PDMAPS side at 40 °C, (g) PDMAPS side at 10 °C, and (h) PMEO2MA side at 10 °C, with 1 mm scale bar, and (i–l) the wetting diameter changes corresponding to (e–h), respectively. Reprinted with permission from ref 194. Copyright 2020, John Wiley and Sons/Wiley-VCH.

one of the most basic demands in daily life.[186,187] Recently, PTMSs comprised of fabrics that can control heating and cooling and independently implement human IR radiation to widen the ambient temperature range while retaining thermal comfort for the human body have been reported.[106,154] The achievement of these two contradictory properties in the same clothing would be a fascinating academic challenge and a technological triumph.[188] To achieve these conflicting performances on the surface of one textile, Hsu et al.[189] synthesized a dual-mode and energy-free textile that could achieve passive radiation performance (both cooling and heating), ascribed to a MIR-transparent nanoPE material with a bilayer thermal emitter inserted inside. This dual-mode emitter arrangement was obtained via juxtaposing the two emitters on both nanoPE surfaces.[189] To generate an asymmetric layer, one piece of nanoPE (24 μm thick) was placed onto the high-emissivity carbon side, while another piece (12 μm thick) was placed on the low-emissivity copper side. As shown by FTIR spectra, the emissivity of the carbon side was roughly 0.8−1.0 between 2 and 18 μm, which was extremely close to that of a blackbody. In contrast, the

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weighted average emissivity of the copper emitter was only 0.303.[189]

Since heat conduction and convection are often well-balanced and immutable, conventional fabrics only have one constant heat transfer coefficient. In this design, the layer with high emissivity was exposed in the cooling mode, and the nanoPE thickness between the emitter and the skin was moderate.[189] On the other hand, when the textile was inverted, it was in the heating mode because of the increased distance between the two layers, which decreased thermal conductivity and impedes thermal dispassion. Moreover, the artificial skin temperature as a control was 31.0 °C under the conditions of bare skin, resulting in a reduction of 5.9 °C than that of conventional textiles. By switching the same piece of dual-mode fabric with the same thickness and bulk, a 6.5 °C variation (thermal comfort zone) in the temperature of the artificial skin was achieved.[189] Further, the thermal comfort zone enlargement of the dual-mode textile in comparison to traditional fabrics was exhibited. It demonstrated that conventional fabrics could only react to thermal fluctuations in the environment and deliver thermal comfort over a narrow range of temperatures, whereas the designed dual-mode textile could switch between cooling and heating modes and had tenability over a wide temperature range.[189]

IR Gating Textiles. Importantly, for on-demand PTMSs, Yue et al.[190] reported a multifunctional Janus Cu/MnO_2 cellulose@layered double hydroxide fiber (CMCFL) membrane with a sandwich construction based on the same principle as bilayer emitter textiles. Numerous creatures have sophisticated strategies for heating and cooling based on MIR thermal radiation. These developed methods, however, are not responsive to climatic stimuli and do not have appropriate mechanisms for dual-mode (heating and cooling) management.[84,191] Zhang et al.[192] synthesized a dynamic gating textile (Figure 9a) integrated a thin layer of carbon nanotubes into cellulose triacetate bimorph fibers. Employing 3D laser irradiation technology, ordered arrays of carbon-imbedded polymer pillars with various interhole intervals were fabricated, and their IR responses were studied to demonstrate distance-dependent electromagnetic coupling, as shown in Figure 9b. Briefly, the scalable elliptical-shape fabric was composed of hydrophobic triacetate (~14.5 μm by 9.4 μm) and hydrophilic cellulose (~13.6 μm by 9.9 μm), further incorporated carbon materials with high conductivity, as shown in Figure 9c−e.[192]

Based on the fundamental concepts, the nanoengineered IR-responsive textiles could explicitly manage thermal radiation for PTMSs. Each textile yarn was made of a package of metafibers that served as carbon (typically a metal-like conductivity), and were attached to polymer fabrics in proper proportions. Furthermore, the principle required a precise response to alterations in temperature and/or relative humidity.[192] Owing to metaelements threaded tightly together on neighboring strands, the yarn shrunk when it was exposed to heat or humidity, resulting in resonant electromagnetic coupling. The connection modified the emissivity of the metatextile to better match the thermal radiation of the human body, and this caused the IR emissivity spectrum to coincide with that of the skin, leading to an enhancement in heat exchange. In contrast, when the metayarn was cold and/or dry, it had an opposite response; thus, the radiation spectrum shifted far away from that of the human body, diminishing heat dissipation. This allowed the efficient regulation (i.e., "on" and "off") of heat radiation across fabrics in response to environmental variations.[192] Au had also been investigated as a metaelement candidate, and its performance had been compared with that of its carbon-based counterparts. Even though the tunable emissivity of Au-coated pillar arrays was equivalent to that of carbon-coated arrays, their resonant emissivity and tenability range were significantly lower. As shown in Figure 9b, most notably, the radiation of the small-pitch array was lower, attaining a peak pitch of 6 μm, and subsequently decreasing as the pitch decreases, as displayed by both metaelements.[192]Figure 9g showed that the metafabric had a relative IR transmittance shift of 35.4% under rapid (less than 1 min) and reversible IR reaction conditions. Also, an FTIR spectrometer with an ambient chamber was used to study the IR radiation response of knitted materials at regulated relative humidity levels (Figure 9f).[192] This work provided a method for enhancing the observed gating effect in terms of cost-effectiveness, safety, and human requirements to make the system more acceptable for commercial applications.

Temperature-Adaptive Smart Janus Textiles. Thermally regulating textiles that are worn adjacent to the human skin and can flexibly manage the microclimate are emerging as a feasible alternative for personal thermal comfort.[22] Several reported textiles have demonstrated self-cooling or thermal insulating performances. Contrarily, managing heat alone is typically insufficient.[159,193] Wang et al.[194] proposed that in order to design textiles that are ecologically sensitive and capable of dynamic thermal/moisture control, both sides of synergistic Janus textiles should feature bidirectional diode-like water transport and temperature-dependent tunable thermal dissipation.

This smart Janus cotton was created using a technique employing double bond (DB) monolithic decoration, single-sided spraying, and in situ UV-triggered polymerization/cross-linking. The synthesis process was composed of two steps: changing hydrophilicity and enhancing solvent evaporation to impede the monomer solution from penetrating (Figure 10a).[194] Rapid solvent extraction facilitated subsequent polymer grafting to an ultrathin layer of enclosing cotton fibers (Figure 10b), therefore preventing fiber-to-fiber adhesions. Water was carried from the interior poly[2-(2-methoxyethoxy) ethoxy-ethyl methacrylate] (PMEO2MA) side to the outermost poly[*N*,*N*-dimethyl (methacryloyl ethyl) ammonium propanesulfonate] (PDMAPS) side at high temperatures, promptly swelling due to moisture absorption, which led to a reduction in pore distribution from the inner to outer side. This arrangement, which changed from bigger to smaller holes, created a capillary force that pumped water molecules from the inside to the outside, as seen in Figure 10c,d.[194]

The behavior of unidirectional water delivery was investigated by releasing 5 μL of water on each side of the synthesized Janus fabric at various temperatures. After being placed on the PMEO2MA surface, the droplet could maintain its spherical form for several seconds before collapsing. Concurrently, the wetting diameter of the backside expanded progressively (light blue area), implying that water could penetrate and propagate in Figure 10e,g.[194] At the same temperature, however, once the droplet was placed on the PDMAPS side, it collapsed and spread on the droplet side, resulting in a visible dark blue region on the droplet side and a considerably lighter blue region on the backside (Figure 10f,h), illustrating that there was no penetration from the PDMAPS side to the PMEO2MA side.[194] Also, the corresponding

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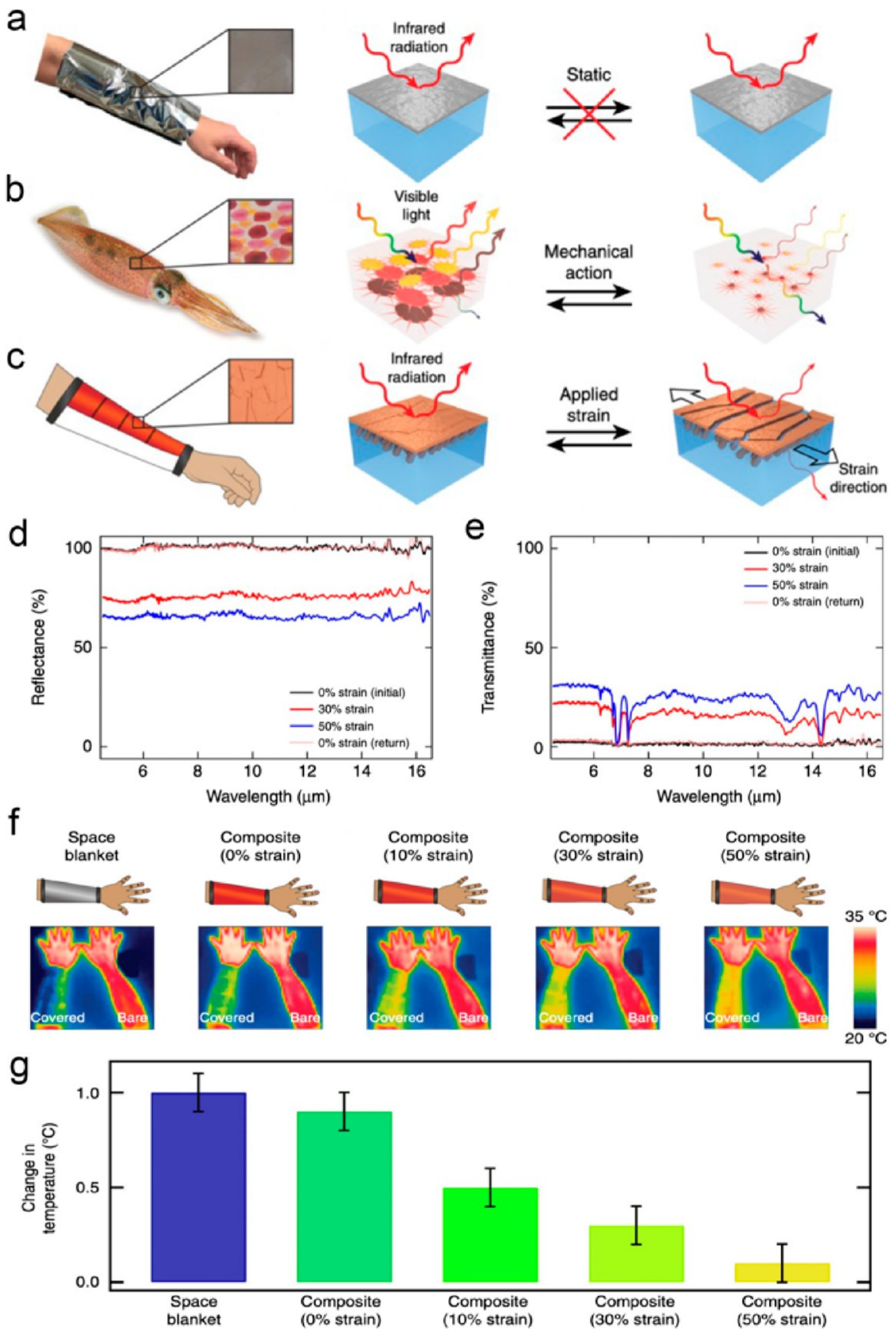

Figure 11. Biomimetic design of a thermal management composite material. (a) Photograph of a space blanket draped across a human arm, and the outer surface of the space blanket is an uninterrupted metal film (e.g., aluminum). (b) Image of a squid using a camera, and a schematic of the squid layer consisting of arranged chromatophore organs embedded inside a visibly transparent dermal matrix. (c) Schematic of the composite on a human arm with a wearable (sleeve), and a fragmented multidomain metal (e.g., copper) coating covers the composite's exterior. Schematic of an IR-transparent polymer matrix coated with IR-reflecting nanostructure-anchored metal domains. (d) Total IR reflectance spectra for a representative composite material and (e) total IR transmittance spectra for a representative composite material under strains of 0% (black), 30% (red), and 50% (blue). (f) IR images and (g) plot of temperature change of a forearm covered with a space blanket-based sleeve at different strains. Reprinted with permission from ref 162. Copyright 2020, Springer Nature.

quantitative study of the variations in diameter demonstrated a similar tendency at 40 and 10 °C as shown in Figure 10i,j and k,l, respectively. This result was most likely attributed to the surface energy gradients of hydrophobic PMEO2MA and hydrophilic PDMAPS.

As a result, an adhesive-adaptive polymer matrix undergoing reversible transition promoted drying and cooling effects in a hot environment by delivering synergistic surface energy gradients and capillary gradients. Compared to commercial cotton textiles, this designed Janus fabric had a 50% faster moisture evaporation, 1.2−2.3 °C lower temperature with cooling performance, while retaining thermal comfort in cold conditions, a 2 min longer cooling duration and 3.3 °C higher temperature.[194] This strategy could lead to the development of more flexible textiles and clothing that achieved optimal personal comfort in high-stress situations.

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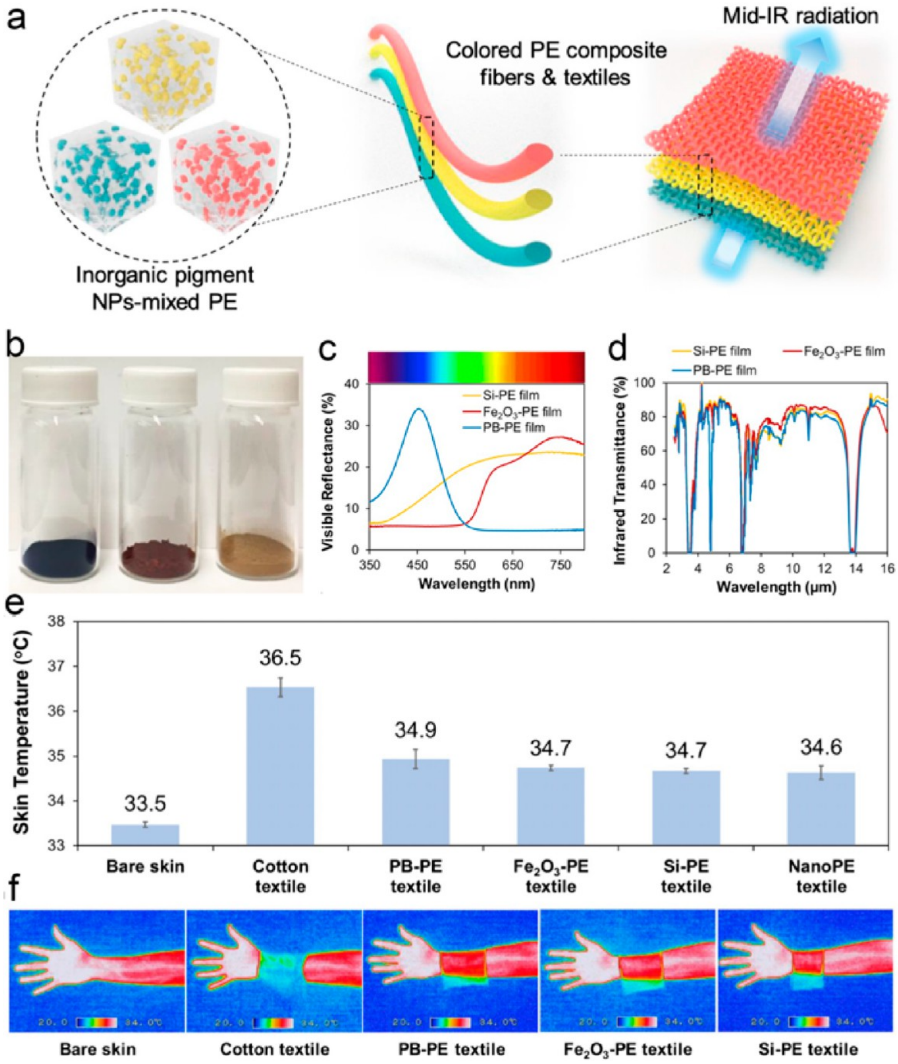

Figure 12. Color response for radiative cooling of PE-based textiles. (a) Design for coloration of radiative cooling textiles by combining MIR-transparent inorganic pigment NPs with PE. (b) Photograph of the inorganic pigment powders. (c) UV−vis and (d) FTIR spectra of the pigment NP-mixed PE composite films. (e) Temperatures of with bare and textile-covered skin-simulating heaters and (f) IR images of the bare skin and textile-sample-covered skin (cotton, PB−PE, Fe_2O_3−PE, Si−PE, and nanoPE). Reprinted with permission from ref 211. Copyright 2019, Elsevier.

RESPONSIVE THERMOREGULATORY TEXTILES

To manage human physiological and thermal comfort, multifunctional textiles and wearable materials are becoming increasingly popular.[23] Recent studies have demonstrated that tuning the IR optical characteristics of clothing has a significant impact on specific PTMSs (cooling and heating) of the human body.[159,195,196] Radiation energy is crucial to the thermal transfer from the human body, accounting for more than half of all thermal dissipation in indoor environments due to the high emissivity (ε = 0.98) of the human skin.[197,198] Technologies for indoor thermal management are currently diverse and have been categorized as "passive" or "active" based on the fundamental concept.[116,199,200] Basically, conductive textiles, MIR fillers, and coatings are examples of passive temperature regulating strategies that hamper heat transfer. In recent years, it has been demonstrated that MIR-transparent nanoPE[172] passively cools the body by 2 °C, and metal-decorated nanoPE[153] with low MIR transmittance higher than 7 °C to the human body for heat retention, hierarchically porous poly(vinylidene fluoride-*co*-hexafluoropropene)[201] coatings for subambient temperature decrease of 6 °C. In addition, other materials such as the Coolmax fabric[202] composed of profiled fibers and the directional water transfer fabric[194] with asymmetric wettability have been reported. These progressive technologies are cost-effective, sustainable, and facile to manufacture; however, they are immobile and unresponsive to the dynamic surroundings. As a result, there is an urgent need for a "perfect" thermal management platform that combines the advantages of passive systems (low cost, practical implementation, and energy efficiency) with the capabilities of dynamic control.

Strain Response. A space blanket made of a plastic sheet covered with a continuous and thin layer of metal with a highly effective IR-reflectivity architecture has been illustrated.[203] Also, the skin of coleopteran cephalopods (squid, octopus, and cuttlefish) dynamically shifts in a way that may inspire the next generation of PTMs.[204−206] Based on these theories, Leung et al.[162] combined the static IR-reflecting architecture of the space blanket (Figure 11a) with the dynamic color-changing

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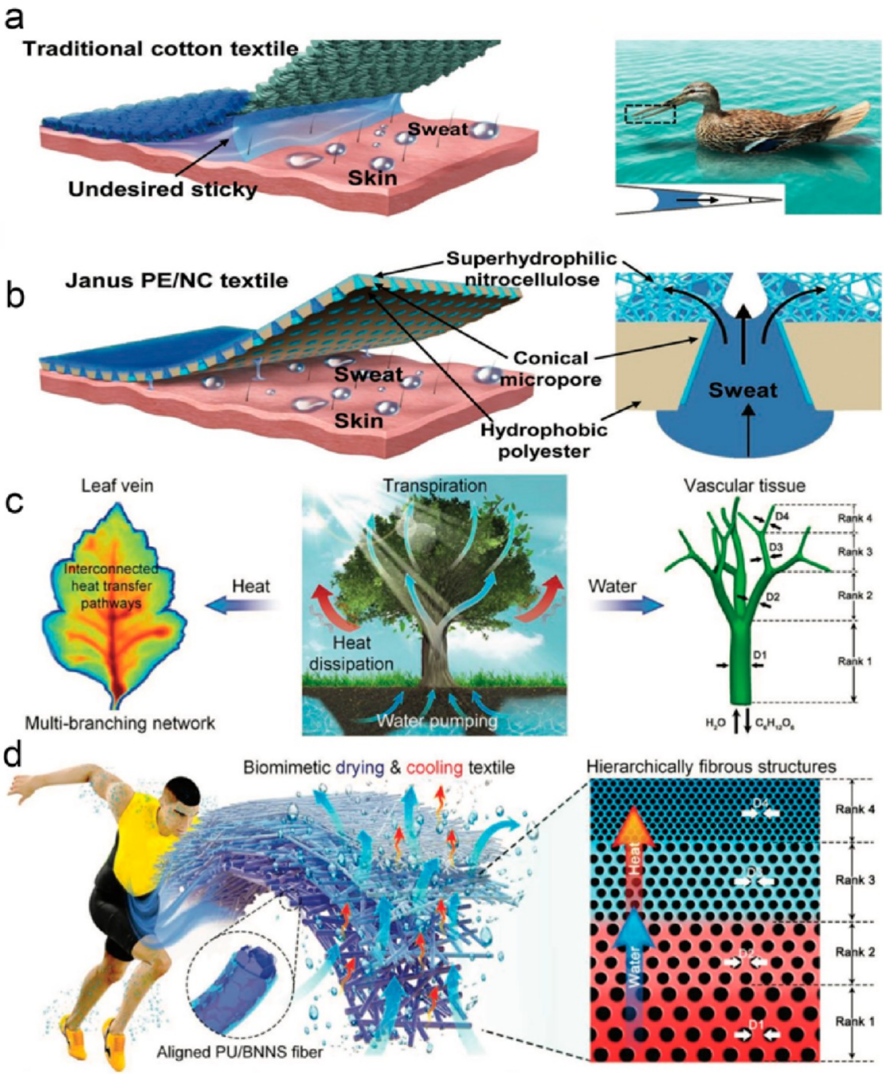

Figure 13. Sweat response textiles for thermal regulation with cooling and moisture-removal performance. (a) Schematics of the capillary force between a conventional cotton cloth and wetted skin and asymmetrical liquid transport in a constrained environment. (b) Diagram of the sweat outflow channels of a human body coated in Janus PE/NC textiles, and conical micropores are asymmetrically curved over the Janus PE/NC textile to transfer perspiration. Reprinted with permission from ref 216. Copyright 2019, John Wiley and Sons/Wiley-VCH. (c) Diagram of the transpiration process in plants. Water evaporation and heat dissipation occurs via vascular tissue and leaf veins; the diagram shows that vascular tissues have four diameters. (d) Schematic of the sweat release and heat dissipation performance of the biomimetic multilayer fibrous membrane as a functional textile for personal drying and cooling; the right inset shows the hierarchical fibrous structure, and the left inset shows the aligned PU/BNNS fiber. Reprinted with permission from ref 217. Copyright 2021, John Wiley and Sons/Wiley-VCH.

capabilities of squid skin (Figure 11b) to create a hybrid fabric with tunable temperature-regulating properties.

The metallic domains mimicked the implanted chromo-organ, whereas the polymer matrix portrayed the transparent dermis of a chromophore-containing squid. Prior to providing the mechanical stimuli seen in Figure 11c, the MIR reflective metal areas were tightly populated and totally enveloped in the supporting matrix.[162] Owing to better access to the underlying polymer substrate, the representative composite exhibited a lower average reflectance of 67% (Figure 11d) and a higher average transmittance of 25% (Figure 11e) under a 50% expanded strain.[162] Sleeves made of composite materials could be modified to control heat transfer from the body to the surroundings. As strain increased to 0%, 10%, 30%, and 50%, the space blanket and composite-based sleeve captured only a fraction of the heat generated by the wrapped forearm (Figure 11f), raising its temperature by 1, 0.9, 0.5, 0.3, and 0.1 °C, respectively (Figure 11g).[162] Furthermore, the biobased composites could accommodate a quarter of the metabolic heat flux observed in sedentary individuals and approximately 10-fold temperature fluctuations in the participating body. Overall, these composite materials combine the characteristics of passive technologies to offer superior energy efficiency and genuine comfort management.[162]

Color Response. By passively modulating thermal radiation dissipation, it has been demonstrated that manufactured textiles with IR characteristics can successfully cool and warm the human body.[101,130,145,192] However, it is challenging to regulate the visible color of textiles while concurrently performing effective IR management.[207,208] As the color combination is one of the prominent factors of the apparel industry, this is a key obstacle to the practical deployment of

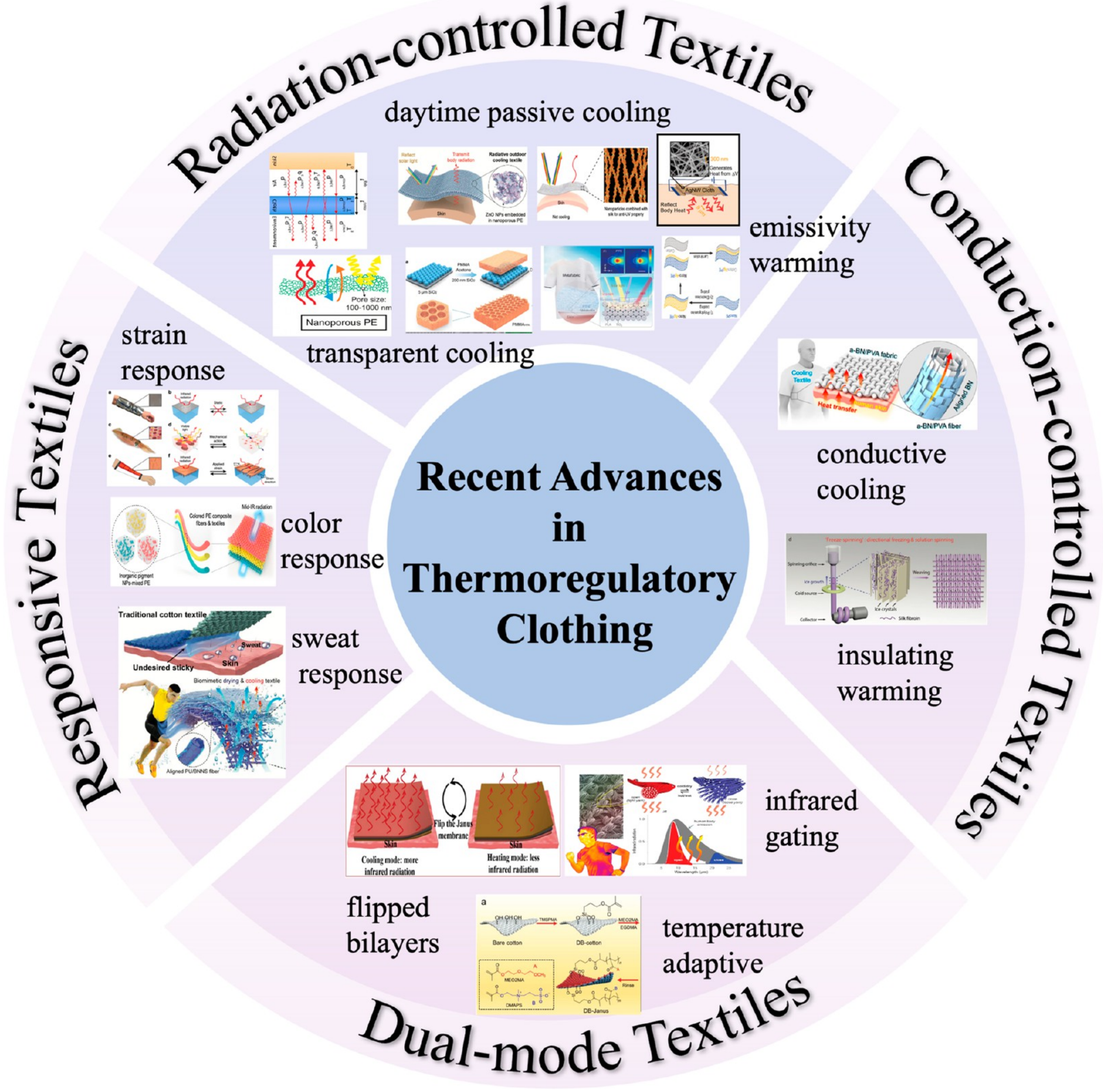

Figure 14. Summary of the recent advancements in thermoregulatory textiles for PTMSs based on their working mechanisms, including radiation controlled, conduction controlled, dual-mode, and responsive textiles. Transparent cooling. ITVOF. Reprinted with permission from ref 105. Copyright 2015, American Chemical Society. NanoPE fabric. Reprinted with permission from ref 107. Copyright 2016, American Association for the Advancement of Science. Daytime passive cooling. ZnO-PE textile. Reprinted with permission from ref 75. Copyright 2018, John Wiley and Sons/Wiley-VCH. Al_2O_3 NP silk. Reprinted with permission from ref 141. Copyright 2021, Springer Nature. PMMA film. Reprinted with permission from ref 142. Copyright 2021, Springer Nature. Metafabric. Reprinted with permission from ref 149. Copyright 2021, Science. AgNW cloth. Reprinted with permission from ref 153. Copyright 2014, American Chemical Society. NanoPE/Ag film. Reprinted with permission from ref 154. Copyright 2017, Springer Nature. A-BN/PVA fabric. Reprinted with permission from ref 179. Copyright 2017, American Chemical Society. Thermal insulation textile. Reprinted with permission from ref 169. Copyright 2018, John Wiley and Sons/Wiley-VCH. Flipped bilayers. Reprinted with permission from ref 190. Copyright 2019, Elsevier. IR gating. Reprinted with permission from ref 192. Copyright 2019, Science. Temperature-adaptive textiles. Reprinted with permission from ref 194. Copyright 2020, John Wiley and Sons/Wiley-VCH. Strain response. Reprinted with permission from ref 162. Copyright 2020, Springer Nature. Color response. Reprinted with permission from ref 211. Copyright 2019, Elsevier. Sweat response. Reprinted with permission from ref 216. Copyright 2019, John Wiley and Sons/Wiley-VCH. Reprinted with permission from ref 217. Copyright 2021, John Wiley and Sons/Wiley-VCH.

IR-tailored textiles.[209,210] Cai et al.[211] illustrated a strategy where inorganic NPs were considered as candidates for highly scalable, brightly colored, IR-transparent fabrics, as shown in Figure 12a. The inorganic nanomaterials (e.g., Prussian blue (PB), iron oxide (Fe_2O_3), and silicon (Si)) served as pigments (Figure 12b), while PE acted as a polymer matrix to evenly blend these two components, which could subsequently be extruded into knitted interlaced fabrics.[211] According to UV–vis spectra, the predominant reflection wavelengths of nanoengineered textiles were around 450, 600, and 750 nm,

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well-matched with the wavelengths of PB, Fe_2O_3, and Si, respectively, as shown in Figure 12c. The as-fabricated tailored textile possessed not only a high IR transparency of 80% in the MIR region (Figure 12d) and a passive cooling effect of 1.6–1.8 °C (Figure 12e,f), but also a strong visible color and excellent antiwashability.[211] Practically, NP-embedded textiles tackle a crucial constraint in radiative cooling of colored textiles that are economically and environmentally effective for PTMSs.

Sweat Response. Creating functional textiles with a cooling effect is essential for human thermal comfort during daily activities.[174,212,213] Although passive fabrics provide an efficient cooling effect, they have several thermal limitations in real-world situations. Especially, excessive perspiration causes clothing to stick to the skin and generate chills, which is detrimental to thermal comfort.[214,215] Therefore, it is imperative to design fabrics that promote comfort and productivity while facilitating effective evaporation of perspiration and heat dissipation.

To exhibit both heat dissipation and sweat release, Dai et al.[216] synthesized a hydrophobic/superhydrophilic Janus polyester/nitrocellulose (PE/NC) textile, which facilitated considerable heat dissipation throughout the sweat transport process. Figure 13a shows that the fabricated Janus textiles with tapered micropore arrays and hydrophilic inner surfaces enabled directional liquid transport, with the value of 1246% for directional water transportation and a body temperature increase of 2–3 °C in comparison to traditional fabrics.[216] Owing to its asymmetric hydrophilic tapering conical micropores, this Janus PE/NC fabric was able to pump surplus sweat from the hydrophobic layer to the superhydrophilic layer in a unidirectional method, preventing undesirable sticking and overwhelming cooling due to perspiration (Figure 13b). Janus PE/NC fabrics with conical micropores rapidly transferred perspiration from the skin to the outside of the fabric, resulting in a drier and warmer experience than that provided by commercial alternatives.[216]

Another clothing with biomimetic transpiration for effective personal drying and cooling was proposed by Miao and co-workers.[217] It was aimed at mitigating the dilemma between water transport and heat transfer capacity. Hierarchical microporous constructions with a decreasing capillary pore size and oriented polyurethane/boron nitride nanosheet (PU/BNNS) fibers were inspired by vascular and mesophyll tissues, as shown in Figure 13c.[217] The inner layer, which had the thickest fibers and the most capillary pores, was utilized as the interface layer of the skin to naturally withdraw perspiration, and the oriented PU/BNNS fibers traversed each other to establish rich heat exchange channels with reduced interfacial thermal impedance (Figure 13d).[217] In order to preserve thermal comfort in a humid environment, these bioinspired transpiration fabrics comprised of stacked and coordinated networks of vascular plants were studied. This nanoengineered textiles with a bioinspired construction achieved a targeted unidirectional water transport coefficient of 1072%, a fast water moisture escape rate of 0.36 g h^{-1}, and an superior through-plane and in-plane thermal conductivity of 0.182 and 1.137 W m^{-1} K, respectively.[217] Furthermore, based on the enhanced performance, logical techniques were also presented and calculated to obtain the current viewpoint on water and heat transport across layered and interconnected networks, which might result in the invention of multifunctional drying and cooling fabrics.[217]

For sophisticated temperature and humidity management, Zhang et al.[160] introduced a membrane-based systemic-layered structure for moisture wicking and passive cooling that incorporated selectively photonic evaporative cooling. Ultimately, the successful fabrication of these moisture-wicking textiles created a comfortable microenvironment for the human body, thereby satisfying the growing need for enhanced productivity and sustainability.

SUMMARY AND OUTLOOK

Personal comfort has become progressively essential since society has developed. Researchers have paid tremendous attention to PTMSs because of their importance for human comfort, health, and productivity as well as energy efficiency. Examples of passive textiles controlled via thermal radiation and conduction properties for both heating and cooling performances were discussed keeping in mind the pathways the human body uses to dissipate heat. Dual-mode textiles mostly based on dynamic radiative emissivity via flipped layers and modified structures (electromagnetic induce), which alter the microstructure of textile according to environmental factors (e.g., humidity), that could be used to regulate thermal comfort for the human body in various environments have been reported. Double-sided Janus textiles with a synergistic effect have also been reported, which displayed reversible diode-like moisture conveyance and temperature regulation. Moreover, smart responsive textiles that can tune the microenvironment of the human body in response to strength, color, and sweat have also been reported. Innovative textiles provide advanced perspectives on energy efficiency and perspective alternatives for managing the thermal comfort of the human body. Compared to advanced building materials, PTMSs based on textiles are more adaptive, cost-effective, and energy-efficient since they can achieve localized temperature regulation by concentrating on the human body and microenvironments. Overall, the concept and strategy of PTMSs have undergone numerous advancements in recent years as a result of these phenomenal advancements (Figure 14).

Despite the rapid development of advanced thermoregulatory clothing, there are still numerous obstacles to overcome and opportunities to investigate. First, it is necessary to close the gap between lab-scale trials and commercialization due to mismatched practical applications. The affordability and availability of developed materials are sufficient for large-scale industrial manufacturing. An example of this mismatch in reported investigations is the inferior connection between functional materials and polymer matrices, resulting in a blocky structure and hence rigid construction of thermoregulatory textiles. Previous studies have indicated that a one-step construction of nanostructured self-supporting flexible textiles with high-performance and excellent mechanical properties is a promising strategy.[23,162] Additionally, designed textiles need to overcome the dilemma of the opposing effects of thermoregulation and wearability. For example, one typically has breathability, or wicking-moisture performance, and rarely both since the higher the breathability, the poorer the wicking-moisture performance. To achieve a balance between breathability and the rate of evaporation of perspiration, a fabric for PTM should be proposed as a prototype, whose hierarchically porous structure might synergistically serve for aspiration and water transportation by harnessing a structure that mimics that of vascular plants (leaf veins, for instance).[160,217] Other

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important approaches include polymer matrixes paired with functionalized materials for PTM applications that have biocompatible and safe properties, a colorful and styled design, and sustainable strategy, all of which will impact the overall thermal performance. We believe that academia, industry, and research institutions should combine their efforts to turn prototypical thermoregulatory clothing into practical applications, bridging the gap between laboratory research and commercialization.

Dynamic PTM techniques may be more advantageous for regulating the thermal heat transfer of the human body to stabilize thermal comfort since external surroundings are in a dynamic state (changes in humidity and temperature).[189] Smart textiles can transition between "cooling" and "warming" modes to provide the thermal comfort zone of the wearer. The potential of intelligent apparel could be explored using additional materials (e.g., metamaterials).[162] An exciting possibility is to fabricate metafabrics with high-MIR-reflective NPs based on a high-emissivity polymer structure, in which the nanostructure changes to automatically adjust its operating window in response to daily or seasonal temperature variations.[162] For example, there is large discrepancy in IR emission between the liquid metal (LM) and eco-flex, where LM is highly reflective and eco-flex is extremely emissive. Therefore, the LM is implemented as a composite material, while the superelastic eco-flex serves as a polymer matrix. Depending on the mismatch that occurs during the stretching process between the highly emissive eco-flex and the high-reflectance LM, this nanoengineered material LM/eco-flex may exhibit both radiative cooling and warming.[218]

Furthermore, many biological species have extraordinary heat regulation capabilities, in which they utilize to survive in harsh environmental conditions. For instance, the porosity of polar bear hair has recently inspired many warming textiles.[169,174] Additionally, several naturally occurring tropical animals, such as silver Saharan ants, *Goliathus goliatus*, and *Neocerambyx gigas*, exhibit outstanding heat regulation behavior due to the peculiar structures of their hairs.[164,202,209] Based on the fascinating dynamic color-changing capability of squid skin, a dual-mode textile that could switch between cooling and heating has also been reported.[162] Also, the biomimicking transpiration fabric based on the layered and connected network enables effective personal cooling and drying.[217] Thus, further study should be undertaken to present innovative insights into the development of advanced thermoregulatory clothing inspired by the special PTMSs of these wildlife species.

In addition to bioinspired textiles with facilitated thermal comfort for PTMs, AI-assisted inversion design may be paired with innovative cloth microstructures.[219−222] Specifically, flexible electronic and energy-harvesting devices can be integrated into modified textiles for PTMSs and connected to data systems on a mobile phone via Bluetooth to develop the next generation of smart clothing, which is capable of performing various tasks, such as thermal comfort, temperature detection, data processing, and self-powered implementation of medicines. This study provided researchers with a comprehensive understanding of the current developments in the field of PTMSs and enabled them to investigate more effective approaches for enhancing the localized temperature regulation of advanced clothing in the future.

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Notes

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VOCABULARY

personal thermal management, a technology that can be used to generate a localized thermal environment around the human body, rather than cooling/heating the entire building; **radiation**, one type of energy that can travel in waves and is accompanied by electric and magnetic fields; **conductance**, the ability of a body or material to conduct heat by changing its temperature; **passive cooling**, a strategy that emphasizes heat transfer and heat gain control to enhance thermal comfort by an energy-free way in a building; **metafabric**, one kind of engineered textile possessing outstanding properties, effective passive cooling effect, superior mechanical strength, or wettability; **thermoregulatory textile**, one kind of functional fabric providing long-lasting warmth protection in cold environments and cool in hot situations to maintain the thermal comfort of the human body.

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