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REVIEW

Advances in smart textiles for personal thermal management

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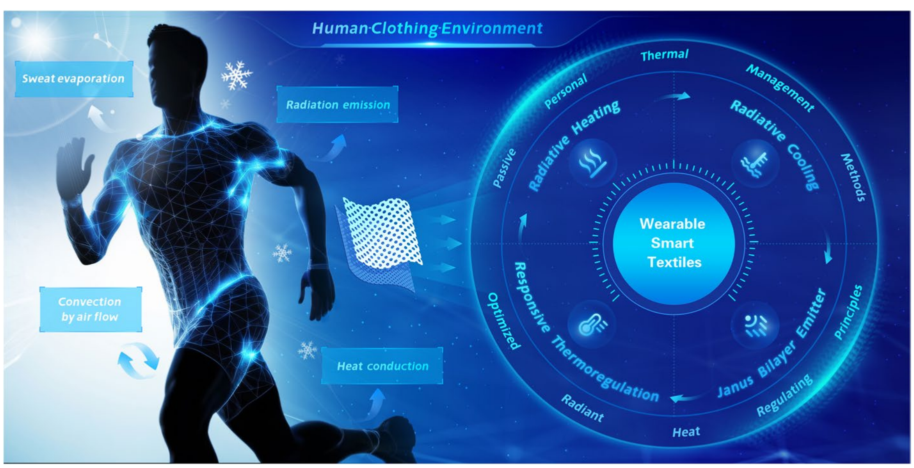
Abstract

Personal thermal management (PTM) is an important topic that holds great potential for enhancing human thermal comfort and optimizing energy efficiency, that typically relies on clothing and textiles. However, traditional textiles fail to adjust human thermal loss at low and high temperatures, no longer satisfy the soaring needs of dynamic heat dissipation due to diversified environmental operation. Recent research has seen significant advancements in smart thermal radiative textiles, which are driven by the booming progress in material-oriented and energy-oriented science and technology. These textiles endow the PTM systems with the efficient modulation of human body temperature and wearable comfortability, demonstrating considerable promise due to their rapid conversion efficiency of radiant heat. Here, we primarily introduce the fundamental concepts of heat transfer as well as the radiant heat regulating principles based on smart textiles. Subsequently, different regulation functionalities of smart textiles, consisting of radiative cooling, radiative heating, and smart textile systems for radiative heating and cooling are demonstrated in detail. Finally, the current obstacles and prospective solutions for smart radiation-controlled textiles are proposed to enhance future thermal management technologies, giving prominence to functional innovations and commercial incubation.

Graphical Abstract



Highlights

• The intricate interplay between thermal models and design principles on functionality for smart textiles are discussed.
• The in-depth approaches for wearable smart textiles of radiative cooling, heating, and thermoregulatory systems are presented.
• The prospects and obstacles of smart textiles are summarized, paving a promising road to personal thermal management.

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Keywords Wearable smart textiles · Personal thermal management · Radiative heating and cooling · Thermoregulatory system

Introduction

Thermal comfort as a state of physical ease free from the drive to correct one's environment through behavior, is critical to human fitness and well-being [1, 2]. With the global environmental issue aggravated, an increased concern is underlined to regulate the ambient surroundings to enhance human comfort [3, 4]. In the case of high or low temperatures with adverse effects on human health, it is always emphasized to maintain normal metabolic activity at a stable body temperature of around 37 °C [5, 6]. Typically, a series of fixed bulk sets such as air conditioners can adjust temperature to achieve personal comfort conditions. However, the high energy consumption and unavailability of outdoor temperature hinder their application in daily use [7–10]. Recently, as a tailored solution for individual needs, personal thermal management (PTM) technique can prevent the unnecessary use of electricity for warming or cooling the human body, offering the additional benefit of convenience [11–13]. Unlike electrically driven cooling or heating devices, state-of-the-art smart textile materials designed for PTM leverage their intrinsic thermal and optical properties to maintain the heat balance of individuals [14, 15]. These innovative designs are crafted to selectively minimize or enhance heat dissipation from the body, ensuring thermal comfort across various settings, whether indoors or outdoors, in high or low-temperature environments.

Textiles already become an essential part for human life and can be traced back to ancient times, which are gradually evolving because of their high portability and wearability [16, 17]. However, traditional textiles fail to prevent human thermal loss at low temperature and does not effectively release the accumulated heat at high temperature. It is worth noting that smart textiles play a vital role in thermoregulatory comfort under varied environmental conditions, even in harsh environments [18–22]. For example, the strategy of enhancing the smart textile's absorptance of solar energy is suitable for human thermal preservation in storms [23]; the strategy of increasing the smart textile's thermal infrared emissivity is conducive to cool feeling under strong sunlight [24]. Therefore, advanced PTM textiles that offer appealing thermal modulation are possible to be preferred [25, 26]. Thereinto, fundamental properties of smart fabrics for PTM are in need such as aesthetics and softness, while the significance of wearable comfortability, dynamic functionality, breathability, and optical performances should not be also ignored [27–29].

The human body exchanges heat with its external surroundings by textiles in the following modes: heat conduction, convection, heat radiation, and evaporation. Particularly, heat radiation emits infrared radiation from the surface of wearable textiles with specific optical performances, as well as solar influence in regulating heat. As a major working principle, the radiative mechanism plays a vital role in alleviating PTM overheating or overcooling [30, 31]. By controlling these cooling and heating strategies, such as topological route [32] and microstructural design [33], wearable smart devices can maintain the optimal operating temperature and ensure the long-term service performance of textile electronics [34, 35]. Recently, tremendous advancements toward radiative PTM technologies have been also witnessed, which realized ambient cooling and heating under solar light with no energy consumption or greenhouse gas release [36]. Therefore, the efficient regulation of thermal radiation from PTM textiles is beneficial to the user comfort and energy saving of the human body, enabling the applicational potential for wearable smart textiles in fashion, medicine, health and entertainment, and other fields [37].

To date, a large number of studies on PTM have been focused on the progress of impressive advanced composites and other single-mode portable devices, but there is something lacking in radiative thermal synergetic effects and in-depth understanding of advanced textile materials by optimized radiant heat regulating strategies to improve thermal comfort in use [38, 39]. Here, we will discuss the state-of-the-art advancement of PTM smart textiles while highlighting the most important achievements as shown in Fig. 1. Firstly, the fundamental concept of heat comfort and thermal transmission routes among human body, environment, and textiles are introduced, followed by modulating principles of thermal radiation. Subsequently, systematic and integrated strategies concerning emerging radiative PTM textiles were proposed, including smart textiles of radiative cooling/heating and smart textile systems with dynamic infrared regulation. Finally, the paper summarizes smart textiles and looks forward to the development of smart textiles from laboratory-scale technologies to practical applications.

Strategies toward wearable thermal management

To understand the innovative strategies of smart fabrics for PTM, the fundamental concepts of thermal comfort are discussed. Additionally, the main design principles are provided to introduce modulating models of radiative heat

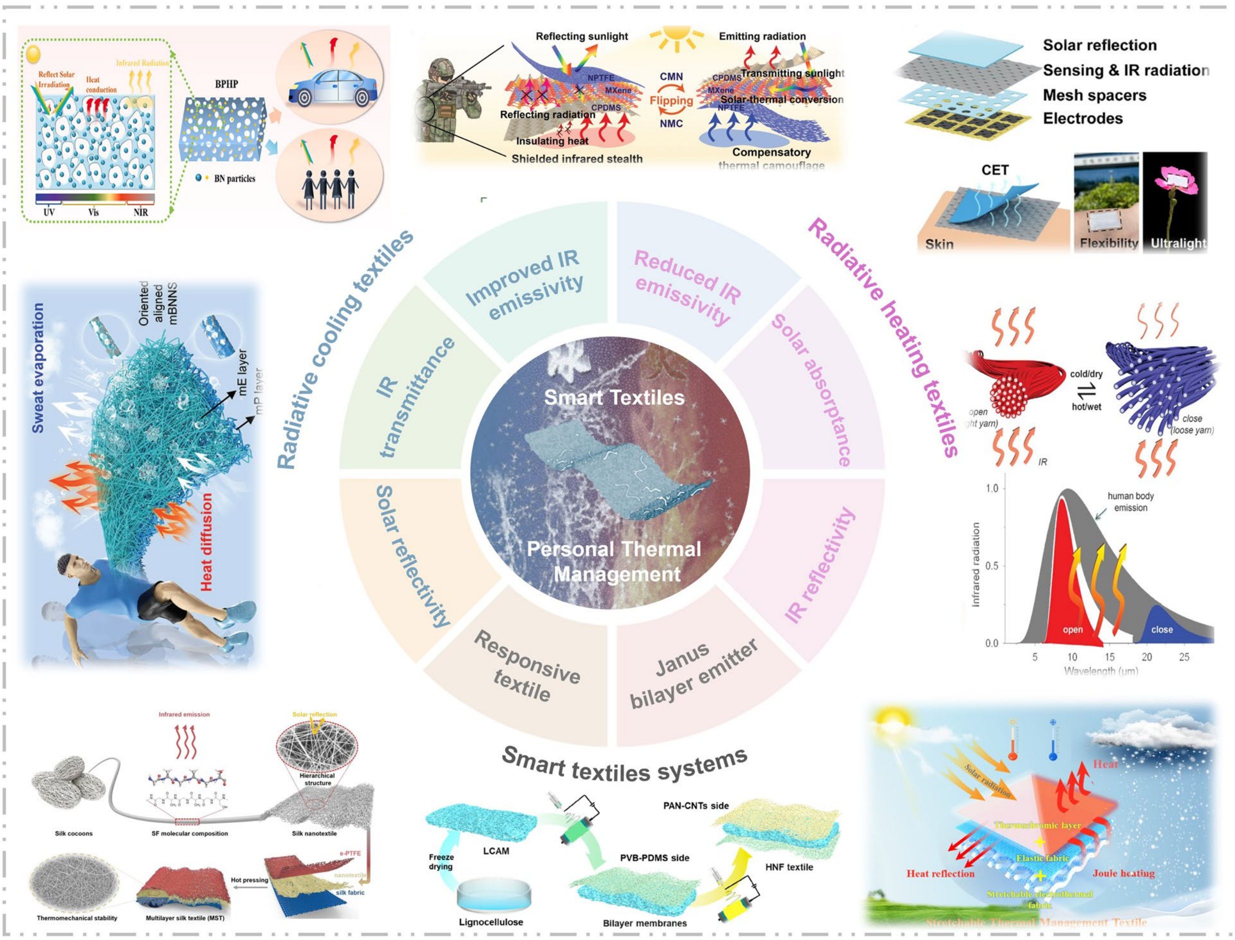

Fig. 1 Categories of the recent advances in smart textiles for PTM strategies. Ternary-channel porous textiles [40]. Metafabric [41]. Cooling electronic textile [42]. Multilayer silk textiles [43]. Dual-functional PTM textiles [44]. Self-cleaning textiles [45]. IR gating [46]. Sweat response [47]

transport, which serve as guidelines for further research of various smart textiles for PTM.

Basic concepts of thermal comfort

Thermal comfort is mainly a person's psychological state in a specific surrounding, and it depends on heat balance between the surroundings and human skin. In varying environments, the human body can dynamically maintain thermal equilibrium to ensure comfort. Currently, the thermal sensory scale (hot, warm, slightly warm, moderate, slightly cold, and cold) is the widely used in thermal comfort evaluation method [48]. Neutral sensation is a satisfactory state under various temperature scenarios, in a dynamic equilibrium to keep human heat comfort. Specifically, the process of heat transfer can be described by conduction, convention, evaporation, and radiation. For a human body, the body keeps a stable temperature by well-balanced process of thermal intake and loss [49]. This balance is expressed by the human body thermal equilibrated formula [50]:

$$Q_{sun} + Q_{gen} = Q_{cd} + Q_{cv} + Q_e + Q_r + Q_s \quad (1)$$

where Q_{sun} is the total heat absorbed by the sun, Q_{gen} is the metabolic heat rate produced by the body, which largely depends on the body's condition. Generally, metabolic heat increases with body activity. Q_{cd}, Q_{cv}, Q_e, and Q_r are the thermal loss rates by conduction, convection, evaporation, and radiation, respectively. Q_s is the heat stored by the body.

Although Eq. (1) does not work in the same way, they all involve the production, transport, and human thermal storage. Heat radiation, conduction, convection, and evaporation are all mechanisms through which the human body releases heat to its surroundings. Metabolic substitutes are used to maintain the daily life of human body. Dietary oxidants, including carbohydrates, fats and proteins, affect different metabolic temperature rates. Specifically, Q_{gen} is the primary source of heat for the individuals, produced through various mechanisms. The Q_{gen} value can be grouped according to different levels of activity.

The human body absorbs sunlight outdoors, while solar absorption can be neglected indoors. Q_{sun} is the energy that the body radiates under the sun, and has the following formula [20, 51]:

$$Q_{sun} = \int_{0.3}^{4} I_{am1.5}(\lambda)\alpha(\lambda)d(\lambda) \quad (2)$$

where $I_{am1.5}(\lambda)$ is the air mass 1.5 global solar radiation spectrum, λ is the radiative wavelength, and $\alpha(\lambda)$ is the solar energy absorbance of the textiles.

Q_{cd} refers to the energy loss of thermal conduction, relying on the temperature difference and heat conductive coefficient [52]. The body can transfer heat from the skin fat, and subsequently distribute it to the textiles. Interestingly, relatively little heat loss occurs through thermal conduction because of the low heat conductivity of traditional clothing [53]. Hence, the thermal conductivity of textiles markedly influences heat transport between the skin and the fabrics, suggesting that thermal conductivity could be a manipulable factor in future PTM research.

Air convection (Q_{cv}) demonstrates variable effects on the heat distribution among human body, textiles, and surroundings, relying on movements of individuals, textile properties, and the environmental conditions [54]. Usually, external convection including electric fans and Chinese fans always enhances the heat transfer coefficient, with the obvious drawbacks of energy and manpower waste. Regulating the level of convection also holds promise for PTM, although it may be not effective in a tranquil environment.

Sweat evaporation (Q_e) is a remarkable cooling method for human skin, affected by personal humid conditions [55]. Generally, sweat is evaporated from the skin surface to release heat, which contributes to the capillarity of fabrics. The sweat on fabric surface can be carried away by the heat transferred across the skin, significantly enhancing the body's heat dissipation owing to the considerable residual heat from sweat sublimation [56, 57].

Thermal radiation (Q_r) is an electromagnetic wave, which successfully transfer the body heat into the surrounding space. Radiant heat dissipation by the human body consumes over 50% of the total heat loss [58, 59]. However, the effectiveness of body heat transfer through thermal radiation is influenced by various factors, including the effective radiative surface area of the skin, the emissivity of the textiles, and the temperature gradient between the skin and ambiance. The radiative heat loss value of human body is shown in the following formula [31]:

$$Q_r = \int_{0}^{\infty} I_{bb}(T, \lambda)\varepsilon(\lambda)d(\lambda) \quad (3)$$

where $I_{bb}(T, \lambda)$ is a blackbody radiance at the temperature of T, $\varepsilon(\lambda)$ represents the spectral emissivity of the human body or textiles. The infrared emissivity is about 0.98 for human skin, which is close to a blackbody emissivity.

Considering the aforementioned facts, adjusting the textile emissivity can be seen as an efficient strategy for PTM, as it significantly influences the overall heat transfer. In the following section, we will focus primarily on the radiative modulating principles on smart textiles.

Modulating principles of radiant heat transport

Thermal radiation is a temperature-dependent electromagnetic wave. In principle, it is mainly found in the infrared (IR) and visible light. After radiative wave strikes the interface of a textile, these three phenomena including transmission (T), absorption (A), and reflectivity (R) will happen. The relationship exists as follows [60]:

$$\alpha(T) + \beta(T) + \gamma(T) = 1 \quad (4)$$

where α, ρ, and τ are the spectrum absorption factor, spectral reflection factor, and spectral transmission factor, respectively.

The use of radiant thermal transfer to regulate human thermal comfort shows great potential because of its passive and efficient characteristics. In particular, the optical performances of the textile surface, including IR reflectivity, emissivity, and solar absorptance, should be customized to regulate the body temperature. The guiding principles and structure strategies can be found in Fig. 2.

According to the guideline, radiation parameters such as infrared transmittance/emittance and solar reflectance/absorbance should be considered when designing radiative heating or cooling smart textiles. The purpose of radiative cooling is to accelerate heat dissipation and make the human body feel cool [61]. Therefore, functional textiles can transmit human infrared emissive wave to the inside surface of the textile while improving the infrared emission of the textile outside is highly desired. As a result, high emissive smart textiles offer remarkable infrared emissivity, which is equal to that of the skin, acting as an almost perfect emitter, making the heat transfer process more efficient. Textiles with high transmittance can effectively transfer human radiation from the skin to the environment, achieving skin cooling to avoid thermal discomfort. In addition, in outdoor environments, the high solar reflectivity can avoid overheating of the human body from the perspective of minimizing the absorption of external solar heat, resulting in a pleasant cooling sensation. In contrast, the purpose of radiative heating is to

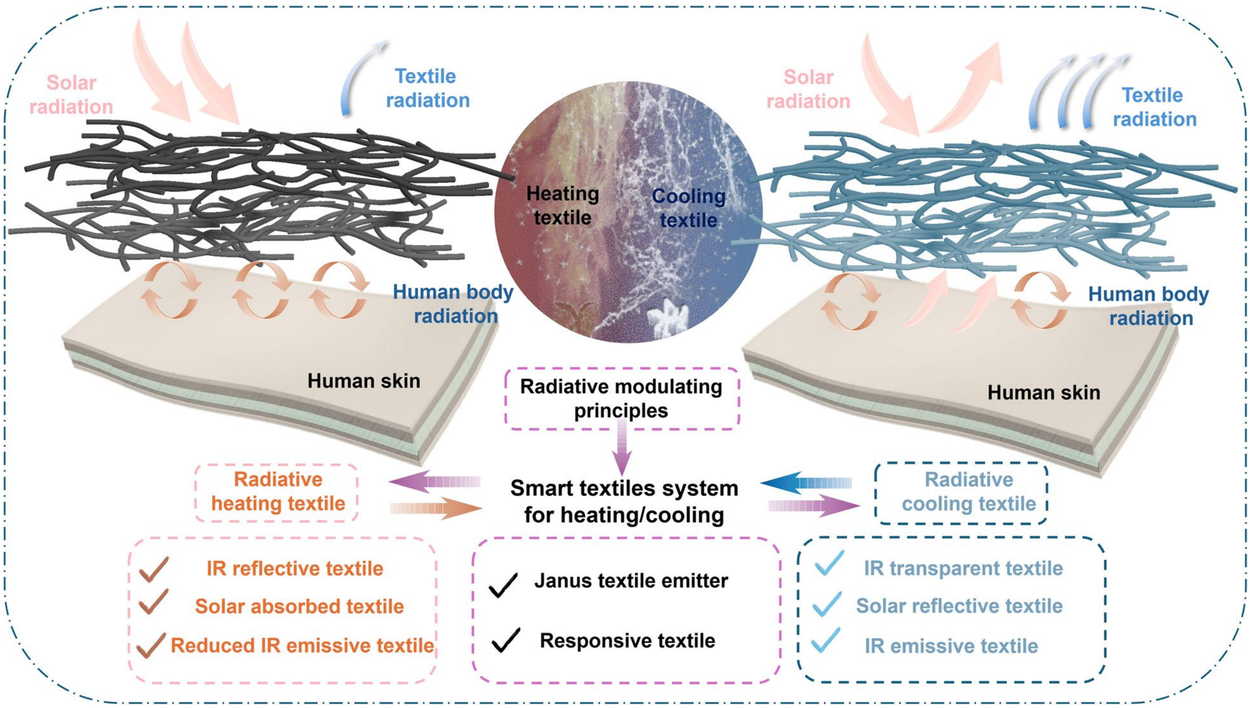

Fig. 2 Design principles of radiative heating/cooling textiles and textile systems on the basis of modulating thermal radiation among smart textiles, human skin and external environment

decelerate human radiative heat to achieve efficient warming effect on PTM. Therefore, it is expected that the IR reflectivity of the inside surface of the radiative heating functional textile is ideally equal to 100%, or the infrared emissivity is minimized to preserve heat, and has a high solar absorptivity. Additionally, by optimizing different wavelengths of light in thermal radiation, it is important to improve energy efficiency and enhance thermal comfort. Infrared radiation primarily facilitates heat transfer in most low-temperature objects, whereas visible and ultraviolet radiation prevail in high-temperature objects. By comprehending how various wavelengths of radiation influence heat transfer, thermal management systems that take advantage of radiative cooling/heating can be effectively designed and enhanced, which minimizes unwanted heat gain or loss. The above results indicate that appropriate infrared modulation strategies are beneficial to radiative cooling/heating for smart textiles.

With the rapid development of materials science and nanotechnology, more and more innovative smart textile systems are able to achieve heating and cooling functions and realize self-temperature regulation [60]. Smart textile systems integrate advanced materials and technologies to adjust thermal sensations in various environments, simultaneously improving the functionality of textiles [62]. According to the surrounding environment, Janus double-layer smart textiles with varied IR emissivities are reasonably combined to realize cooling and warming dual function. In other words, in a hot environment, the higher emissive textile side is optimized to face the outside to dissipate the body's heat as much as possible. Conversely, when people are in a cold environment, the low emissive side can hinder the loss of heat. In addition, responsive smart textiles have made rapid and significant progress in recent years, showing great potential in dynamic thermal regulation. Responsive smart textiles can be designed by integrating fibers or yarns that change geometry with changes, which have a significant effect on the radiant thermal regulation. Thus, traditional fabrics can be translated into environmentally relevant responsive textiles with dual heating and cooling functions, responding to environmental stimuli in ambient temperature or humidity.

Smart textiles for radiative cooling

Significant advancements in wearable textile technology have been witnessed, particularly in the domain of cooling strategies, a topic that has garnered extensive exploration and proposals from a variety of researchers. Among these strategies, radiation plays an important role of dissipating heat from the human body [63]. Through the manipulation of the radiation transparency of textiles, it is feasible to present the attainment of cooling effects in specific environments, whether indoors or outdoors, in high or low temperature conditions [64, 65]. Various proposed designs have demonstrated notable potential and efficacy in their intended applications, employing diverse cooling strategies. In the subsequent sections, we will classify these designs into three cooling principles: enhanced IR transmittance, emissivity, and solar reflectance. Each category will be thoroughly examined, discussed, and compared, encompassing their cooling principles, attributes, manufacturing methodologies, and performance metrics.

Smart textile with improved IR transmittance

The human body inherently emits heat radiation, predominantly within the mid-IR scope, which accounts for over half of total thermal dissipation in indoor settings characterized by ambient temperatures lower than body temperature [66]. Researchers and scientists recognize the importance of fine-tuning the optical characteristics of textiles to selectively amplify the transmission of mid-IR radiation [64, 67–70]. This optimization facilitates the efficient dissipation of body heat through the textiles, thereby inducing a cooling effect.

From this perspective, IR-transparent visible-opaque fabrics (ITVOF) were proposed utilizing polyethylene (PE) nanofibers as the materials by Tong, et al. [64]. The exceptional IR transmission properties of PE nanofibers during mid-IR wave range can be attributed to their simple molecular structure, which consists of C–H and C–C bonds, resulting in low absorption within IR wavelength range. Furthermore, the unique structure of the nanofibers minimizes IR reflection through Rayleigh scattering. Notably, the ITVOF maintains its opaque appearance while capitalizing on an optimized Mie scattering phenomenon. Simulation results indicate that a 300 μm thick ITVOF can achieve approximately 0.97 thermal radiation transmittance. Although the study did not provide experimental results for the ITVOF, it consolidates the direction for the development of textiles with enhanced IR transmittance, an area that has not been extensively explored.

Considering the geometry of IR transmittance fabrics, the pore size of the fabric plays a crucial role in achieving selective spectral control and opacity effects. By carefully controlling the nano-porous PE to a diameter range of 50 to 1000 nm, the fabric effectively increases its IR transmittance while visually maintaining its opacity through strong Mie scattering of visible light within the mid-IR scope [69]. The high IR transmittance is attributed to Rayleigh scattering, which occurs due to the smaller pore sizes compared to the IR wavelength. In addition, the existence of pores in the fabric provides exceptional permeability and facilitates efficient water wicking, making it highly suitable for wearable applications. These properties are particularly advantageous for face masks, as they contribute to enhanced thermal comfort for the wearer [71]. The utilization of nano-porous PE in face masks (as shown in Fig. 3a) developed by Yang, et al. [71] ensures excellent wearability and promotes a more comfortable experience. In addition to adjusting pore size, the shape of the fibers themselves can be modified to improve solar scattering. Researchers have explored the employment of nanofibers with ellipsoidal beads, which can create additive dielectric resonances with the cylindrical and ellipsoidal geometries, as demonstrated by Kim, et al. [72]. This innovative approach has led to the development of Nano PAN fibers with an ellipsoidal bead structure (Fig. 3b), which exhibit remarkable scattering properties. The proposed Nano PAN fibers with ellipsoidal bead structure have shown the ability to achieve high solar reflectance of 95% while keeping high IR transmittance of over 70% simultaneously. By capitalizing on the additive dielectric resonances resulting from the specific fiber shape, these fibers maximize solar scattering, effectively reflecting sunlight away from the fabric surface. This helps in reducing thermal absorption and contributes to the fabric's entire cooling performance. The utilization of nanofibers with ellipsoidal beads represents an exciting advancement in fabric design, allowing for improved solar reflectance and IR transmittance. By optimizing pore size and fiber shape, researchers have demonstrated the potential to enhance the cooling capabilities of textiles, offering a promising avenue for developing innovative cooling wearables.

To further enhance the cooling capabilities and scalability of textiles, scientists have begun exploring the incorporation of functional fillers into the base structure of IR transmittance fabrics. One notable advancement is the embedding of zinc oxide (ZnO) into nanoPE (ZnO-PE), which exhibits effective solar irradiance reflection of over 90% while maintaining high IR transmittance (Fig. 3c) [68]. The inclusion of ZnO in the fabric structure significantly enhances its cooling power, with values exceeding 200W m^{-2}. This high cooling power translates to a considerable reduction in simulated skin temperature, ranging from 5 to 13 ℃. The incorporation of ZnO-PE demonstrates promising results in achieving enhanced cooling efficiency and improved thermal comfort for the wearer.

It is worth highlighting that many of the proposed high IR transmittance fabrics face challenges when it comes to dyeing or coloring without compromising their IR transparency. In the fashion industry, conventional dyes typically consist of organic molecules that absorb IR radiation emitted by the human body, consequently reducing radiative transmission by the fabric. To overcome this dilemma, Cai, et al. [66] introduced the use of inorganic pigments, such as Prussian blue, iron oxide, and silicon, for the coloration of nanoPE fabric (illustrated in Fig. 3d). By employing these inorganic pigments, the colored nanoPE knitted fabric achieved both high IR transmittance (approximately 80%) and excellent colorfastness, enduring

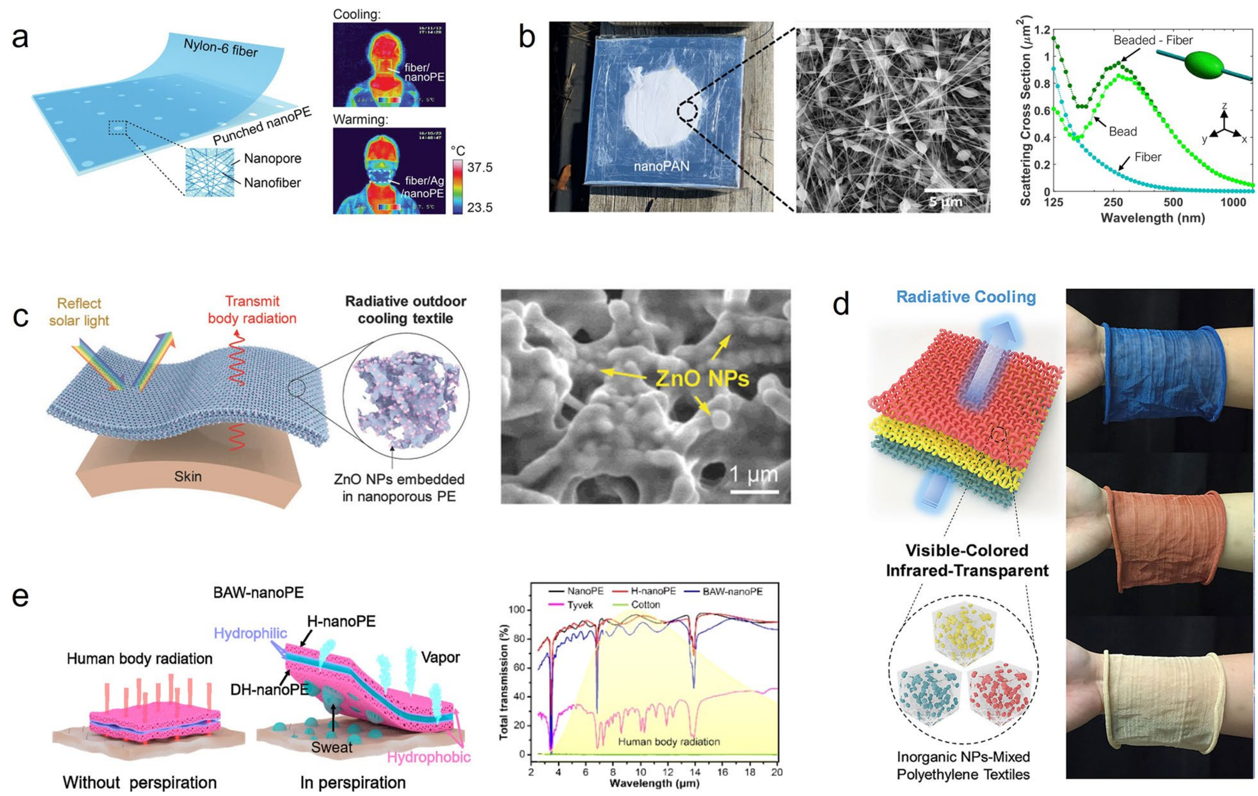

Fig. 3 Recent advancements in textiles with enhanced IR transmittance. **a** Schematic diagram and thermal images presenting nano-porous PE face masks for thermal regulation [71]; **b** Nano PAN textile featuring an ellipsoidal bead fiber structure, alongside the simulated spectral scattering cross-section [72]. **c** Conceptual illustration of ZnO-embedded nanoPE fabric, with an SEM image showcasing the embedment of ZnO within the polymer [68]. **d** Illustration and photograph highlighting colored IR-transparent textiles achieved through the incorporation of inorganic NPs into PE [66]. **e** Bilayer structured nanoporous PE membrane exhibiting anisotropic wettability, with a transmission comparison against commercial textiles [73]

over 100 washing cycles without significant color shifting. This breakthrough demonstrates an effective solution for achieving both desired colors and high IR transparency in fabrics. Additionally, besides incorporating functional fillers into PE fabric, materials with high IR transparency, such as PE, polyamide, and polyvinylidene fluoride (PVDF) [74], can be blended with conventional fibers to create composite fabrics with tunable photonic properties. The integration of conventional fibers offers a balance between wearability and cooling performance, ensuring that the resulting fabric maintains both comfort and efficient cooling capabilities.

One of the challenges faced by cooling wearables is the issue of sweat accumulation on the fabric surface. While the fabric itself may possess acceptable air permeability due to its porous structure, it can still experience poor sweat drainage, particularly when the sweat rate is high. This can occur when the pores of the fabric become blocked by sweat, impeding air exchange and resulting in sweat accumulation. Continuous accumulation of sweat can lead to discomfort, such as skin itchiness, redness, and potentially even allergies. To address this issue, Hu, et al. [73] proposed a bilayer-structured nanoporous PE membrane with anisotropic wettability. This innovative design enhances the rate of water transportation from the surface of the human body to the outermost side of the membrane, enabling efficient sweat drainage (Fig. 3e). Importantly, this optimized water transportation capability does not compromise the fabric's radiative transmittance, allowing for the maintenance of its cooling properties.

Smart textile with improved IR emissivity

An alternative method for crafting radiative cooling textiles involves augmenting the infrared (IR) emissivity of the textile itself. By heightening the rate at which thermal radiation is discharged from the textile surface to outer space through atmospheric windows (8–13 μm), a cooling effect can be realized. The concept of enhancing emissivity for cooling purposes is not a recent innovation. Many years ago, scholars utilized materials with elevated IR emission to fabricate paints and thin films primarily for architectural daylight

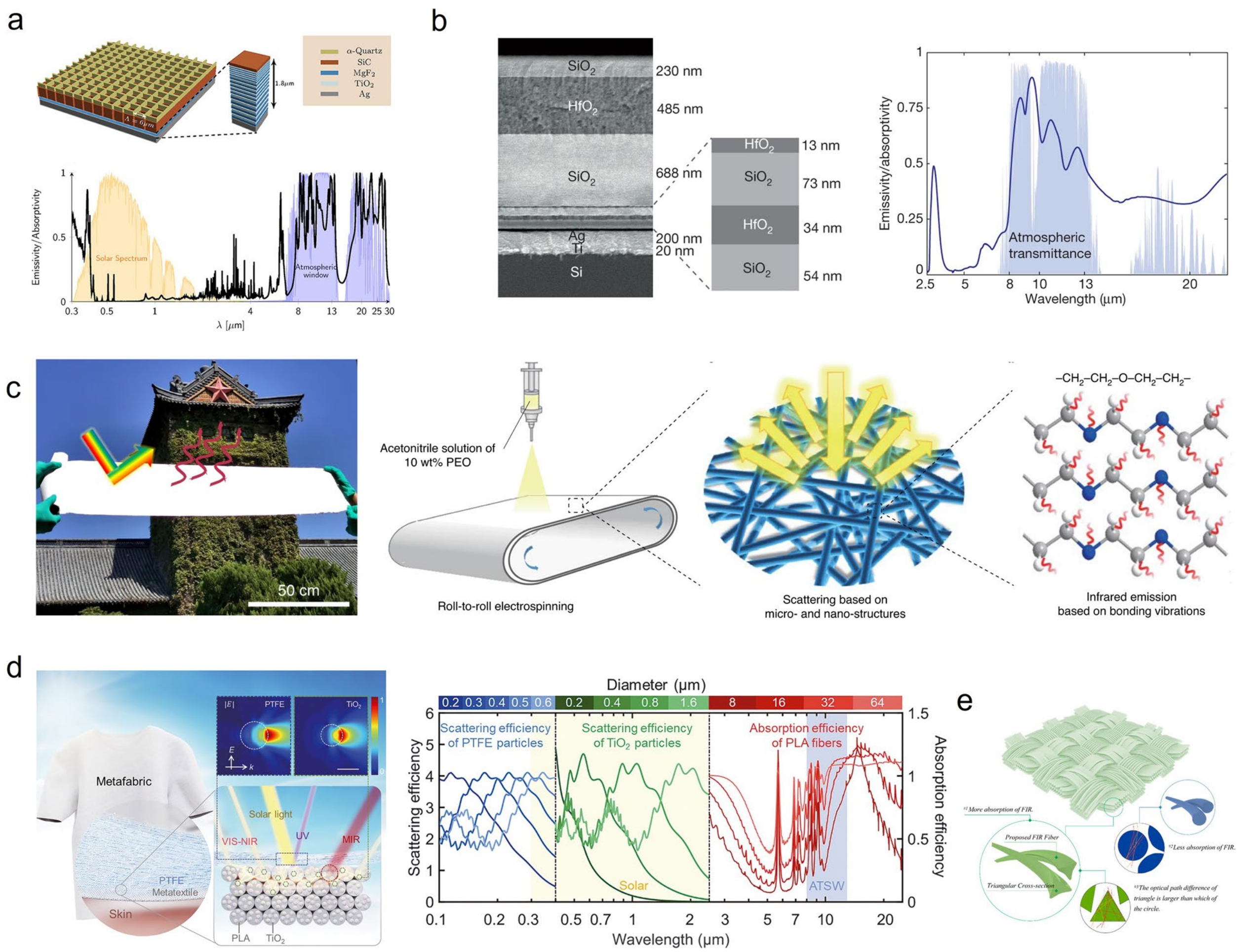

Fig. 4 Strategies for enhancing IR emissivity across various designs. **a** A tailored photonic structure optimized for radiative cooling in daytime outdoor settings [78]. **b** SEM image of a radiative cooler composed of SiO_2, HfO_2, Ag, Ti, and Si [76]. **c** Photograph and schematics illustrating the hierarchically designed all-day radiative cooling POE film [79]. **d** Schematic of a metafabric comprising PTFE, PLA, and TiO_2; showcasing the calculated scattering and absorption efficiencies of varying sizes of PTFE particles, TiO_2 particles, and PLA fibers [80]. **e** Illustration of a woven fabric utilizing triangular PA fibers to enhance emissivity [81]

radiation cooling [75, 76]. In contemporary times, amidst mounting concerns about global warming and a burgeoning quest for enhanced quality of life, researchers have repurposed and modernized this technology into wearable textiles for individual cooling applications [77]. Unlike coatings intended for buildings, radiative cooling textiles must exhibit a specific level of air and vapor permeability to ensure comfort when worn and to prevent the accumulation of sweat, which can provoke skin discomfort.

To enhance the IR emissivity of materials, a combination of factors such as optical nanostructures, molecular composition, and metamaterial morphology can be strategically adjusted. One effective method involves creating a photonic crystal structure with a periodically varying refractive index to facilitate radiative cooling in daytime outdoor settings. For example, Rephaeli, et al. [78] have engineered a metal-dielectric photonic structure tailored for optimal radiative cooling (as illustrated in Fig. 4a), with a remarkable cooling power exceeding 100W/m2. This innovative structure employs quartz and silicon carbide (SiC) to enhance selective emission within atmospheric windows, capitalizing on phonon-polariton resonances in the range of 8–13 µm. The resonances of SiC and quartz at 9.3 µm and 12.5 µm, respectively, amplify radiation emission specifically within the atmospheric windows. Furthermore, Raman, et al. [76] have devised an integrated photonic system (Fig. 4b) comprising a solar reflector and heat emitter including 7 layers of hafnium oxide (HfO_2) and silicon dioxide (SiO_2). This design facilitates a cooling effect of 4.9 °C with solar exposure exceeding 850 W/m2. The photonic radiative cooler is formed by depositing 7 alternating layers of HfO_2 and SiO_2, each with changing thicknesses, onto a silicon wafer. SiO_2 exhibits a pronounced absorptivity peak at 9 µm attributed to phonon-polariton resonance, contributing significantly to the cooling mechanism.

While photonic crystal structures have proven effective in achieving radiative cooling, their complex production processes and high costs hinder their widespread application in wearable textiles. Additionally, many of these structures tend to be rigid and challenging to integrate into traditional textile forms for wearable technology. Current research endeavors are increasingly focused on combining soft polymers with functional nano-sized particles, employing metamaterial morphology to create flexible, soft, and stretchable radiative coolers that hold significant promise in the realm of wearable textiles and personal thermal regulation [82–84]. These innovative designs are typically fabricated in fiber form using conventional spinning techniques, enabling enhanced air and water vapor permeability to enhance wearing comfort. Li, et al. [79] introduced a scalable and hierarchically designed fiber film tailored for all-day radiative cooling applications (Fig. 4c). Polyethylene oxide (PEO) was chosen as the primary material due to its optimal selective absorption band, arising from C = C, C–O, and C–H bonds that align with the atmospheric window [85]. This design achieved a remarkable 78% selective emissivity, and the controlled diameter of the nanofibers contributed to a high reflectivity of 96.3%.

A notable advancement proposed by Zeng, et al. [80] has successfully enhanced the emissivity of fabric by controlling the diameter of polylactic acid (PLA) fibers to approximately 30 μm, facilitating multiple scattering to augment emissivity (Fig. 4d). The fiber diameter also contributes to the creation of a textured textile surface for gradient refractive index antireflection. Their proposed multilayer metafabric incorporates a titanium oxide (TiO_2)-PLA layer laminated with a polytetrafluoroethylene (PTFE) layer. Leveraging a hierarchical morphology design that disperses scatterers randomly throughout the metafabric, an emissivity of 94.5% and a reflectance of 92.4% have been achieved. Practical application tests demonstrate that the metafabric exhibits approximately a 4.8 °C lower temperature compared to the commercial cotton textiles when worn on the body. Notably, the metafabric design is based on a scalable weaving technique that imparts exceptional mechanical strength, breathability, and comfort. From a geometric perspective of fiber morphology, Tao, et al. [81] have posited that triangular cross-sectional polyamide (PA) fibers exhibit significantly higher infrared (IR) emissivity compared to circular reference PA fibers (Fig. 4e). Fabrics woven from the optimized PA fibers had an impressive emissivity of 91.85%. This enhancement can be attributed to the varying orientations of triangular fibers within a single yarn, which effectively amplifies the absorptive and emissive properties of IR radiation from diverse directions with heightened efficiency.

Smart textile with improved solar reflectivity

The solar reflectivity of textiles holds considerable importance within the domain of radiative materials, particularly in outdoor environments [86]. In such settings, the impact of intense solar radiation on textile temperatures is pronounced. Unlike the previous radiation emissive approaches, the solar reflectivity of textiles becomes a critical factor when subjected to high levels of sunlight. Solar radiation encompasses ultraviolet (UV), visible (VIS), and IR wavelengths. Notably, the VIS light spectrum (400–700 nm) and near-infrared (NIR) wavelengths (700–2500 nm) collectively represent over 90% of the total sunlight irradiance, typically measuring around 1000 W/m^2 [87]. A prevalent method of enhancing the solar reflectivity of textiles involves the integration of high solar reflective materials using various techniques. These materials can be applied as coatings or laminates on textiles, spun into yarn, or utilized as fillers within fibers [68, 80].

The selection of a polymer matrix plays a pivotal role in achieving optimal solar reflectivity. For example, polymer molecules containing pi (π) bonds or conjugated π bonds, such as C–N, N = N, and C = S bonds, exhibit a tendency towards high solar absorption, thereby adversely impacting radiative cooling. This propensity stems from the excitation of electrons within π bonds to the π* orbital by sunlight, facilitated by the presence of weakly bound electrons. Consequently, these electrons absorb light energy, transitioning from the ground state to a higher energy orbital when exposed to light energy that aligns with the electronic transitions within the molecules [88, 89]. Additionally, the extent of electromagnetic wave attenuation in a medium is a critical consideration when selecting an appropriate polymer for radiative cooling materials. Polymers characterized by lower k values (extinction coefficients) in the solar spectrum exhibit a reduced rate of light amplitude attenuation, leading to diminished light absorption [90].

In addition to the selection of a polymer matrix, the choice of fillers is crucial in developing effective textiles for radiative cooling. Fillers with high solar reflectance, such as barium sulfate ($BaSO_4$), aluminum oxide (Al_2O_3), TiO_2, and SiO_2, have been widely utilized in recent studies [69, 75, 91–93]. TiO_2 stands out as a prominent functional filler renowned for enhancing solar reflectance due to its high refractive index ($n > 2.5$), facilitating effective sunlight scattering [94]. For example, Li, et al. [95] utilized TiO_2 as a filler in the fabrication of a PVDF radiative cooling fiber film via electrospinning, achieving remarkable solar reflectivity values of 99.01% (VIS spectrum) and 97.20% (NIR spectrum) (Fig. 5a). Nonetheless, TiO_2 inherently absorbs UV light and violet light (approximately 7% of sunlight energy) [75].

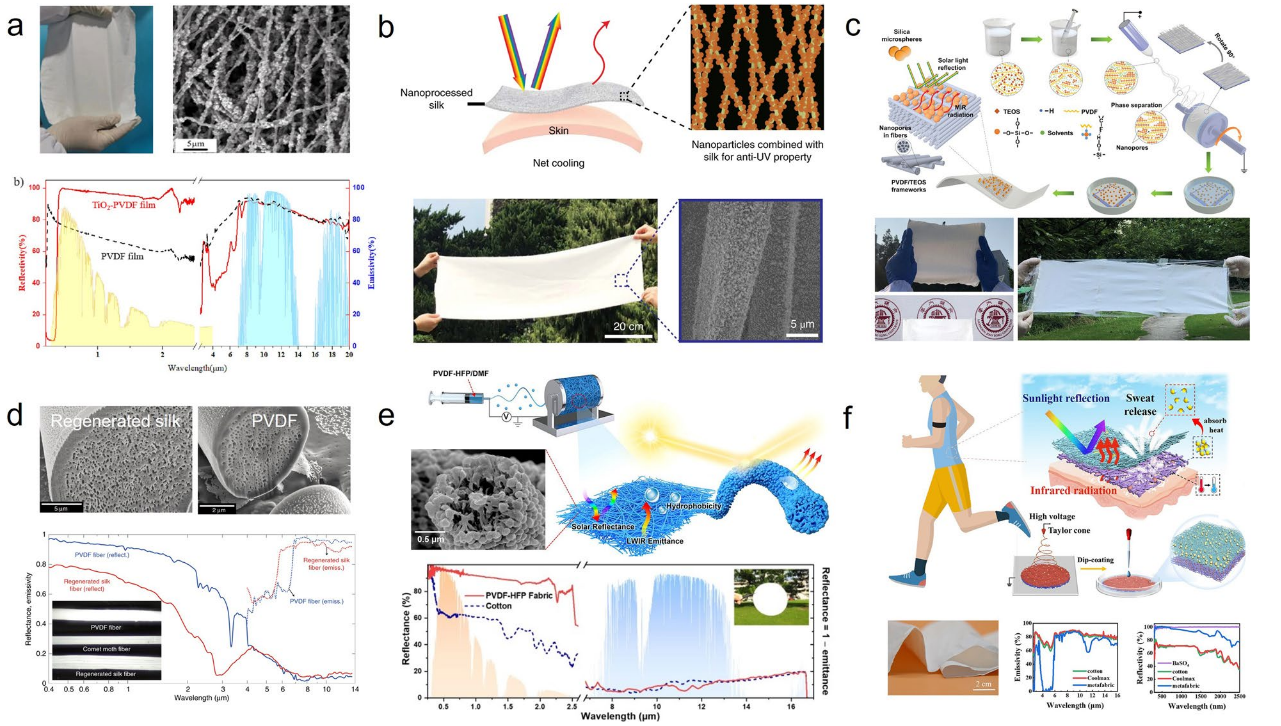

Fig. 5 Advancements in smart textiles for enhanced solar reflectivity and multi-mode cooling regulation. **a** Photograph and SEM image showcasing the TiO_2/PVDF electrospun radiative cooling fiber film and its performance in reflectance and emissivity [95]. **b** Schematic, photograph, and SEM image illustrating the radiative cooling nanoprocessed silk textile with Al_2O_3 [91]. **c** Schematic diagram and photograph presenting the SiO_2/PVDF/TEOS electrospun radiative cooling fiber thin film Wang, et al. [96]. **d** SEM images displaying nanostructured regenerated silk and PVDF fibers with porous structures and their reflectance and emissivity performance [99]. **e** Production schematic and SEM image of the water vapor-induced nano-porous PVDF-HFP fiber thin film; the photograph along with the reflectance and emittance of the design are depicted at the bottom [100]. **f** Schematic and photograph of PTM metafabric; the reflectivity and emissivity metrics of the design are displayed in the lower right corner [101]

To address this issue, researchers have redirected their focus towards metal oxides with broad optical bandgaps, such as Al_2O_3 (7.0 eV, λ ~ 0.177 μm) and $BaSO_4$ (6.0 eV, λ ~ 0.208 μm) [75], as fillers. For example, a radiative cooling nanoprocessed silk textile was proposed by Zhu, et al. [91], enhancing its reflectivity in the UV range by dip-coating the silk fabric with Al_2O_3 and utilizing tetra-n-butyl titanate as a coupling reagent to improve adherence (as illustrated in Fig. 5b). This modification led to an increase in the silk fabric's reflectivity in the UV range from 70 to 85%, and in the VIS and NIR ranges from 86 to 95%, enabling a cooling effect of approximately 3.5 °C during daytime. Furthermore, in a study by Wang, et al. [96], SiO_2 microspheres were integrated into an electrospun PVDF/tetraethyl orthosilicate (TEOS) thin film, enhancing solar reflectivity by randomly dispersing the SiO_2 microspheres across its surface (Fig. 5c). The combined scattering effect of nanopores and fibers with SiO_2 enabled the thin film to reflect approximately 97% of solar irradiance while maintaining excellent mechanical strength and flexibility. Efforts have also been directed towards incorporating high solar reflectivity particles into conventional textiles like cotton and polyester. Miao, et al. [97] experimentally deposited a 200 nm layer of copper on cotton and titanium on polyester to enhance their solar reflectivity, resulting in a 20% enhancement in the infrared reflection rate by contrast with non-coated fabrics. Moreover, Panwar, et al. [98] proposed a TiO_2–SiO_2 Janus particles modified cotton textile for heat modulation. The above hybrid particles were treated by the Pickering emulsion way and coated on cotton textile. The NIR reflection highly improved (79% reflectivity at 1000 nm) after coating the TiO_2–SiO_2 Janus particles. These approaches not only offer a straightforward process but also retain the advantageous properties of conventional fabrics, including moisture absorption, processability, and a soft and flexible hand feel.

Instead of incorporating reflective materials within or onto textiles, the engineering of micro-structured fibers represents an alternative approach for enhancing the solar reflectance of materials. Shi, et al. [99] explored the sponge-like internal structure of silk fibers, demonstrating that a single silk fiber (50 μm in diameter) could reflect 66% of incident sunlight radiation (demonstrated in Fig. 5d). Building upon this internal structure observed in silk fibers, the researchers developed biomimetic composite fibers using PVDF and regenerated silk fibroin through a wet spinning technique, resulting in a significant enhancement in solar reflectivity. The nanostructured silk fibers and PVDF fibers achieved solar reflectivity values of 0.73 and 0.93, respectively. Their spectroscopic analyses indicated that intense backscattering of the nanoscale voids in the VIS and NIR bands contributed to the enhanced solar reflectance.

A similar method was utilized by Cheng, et al. [100], who induced a nano-porous structure on electrospun poly(vinylidene fluoride-co-hexafluoropropylene) fibers through regulating the humidity levels in the environment (Fig. 5e). The existence of aqueous vapor in the electrospinning chamber environment facilitated the solvent exchange process, accelerating solvent volatilization and the diffusion of nonsolvent molecules within the substrate, leading to the formation of a rougher and more porous fibrous structure. Textiles fabricated under optimized electrospinning chamber humidity conditions achieved a superior solar reflectance of approximately 93.7%. Experimental results indicated that these textiles could induce temperature reductions of around 19.8 °C and 13.2 °C under a sunlight intensity of approximately 950 W/m^2.

Smart textile with multi-mode cooling regulation

To optimize the efficiency of radiative cooling textiles across diverse practical scenarios, designs often integrate multiple cooling mechanisms to achieve the desired cooling regulation [102–104]. For instance, in the pursuit of creating a versatile cooling textile suitable for both indoor and outdoor settings for personalized thermal management, Song, et al. [105] engineered a tri-layered cooling textile comprising PA, PVDF, and PE. This innovative design yielded cooling capabilities of 72.78 W/m^2 indoors and 118.18 W/m^2 outdoors. The PVDF layer was specifically employed as a potent emitter in the mid-IR band, while the PA and PE layers facilitated the transmission of human heat radiation and the PVDF layer. Moreover, meticulous control over the fiber diameter and pore size of all three layers ensured effective solar reflectance (300–800 nm, 90.22%) through Mie and Rayleigh scattering phenomena. In outdoor testing, this textile exhibited significant cooling proficiency, reducing human body temperature by 4.5–6.5 °C with direct solar exposure.

Similarly, Wu, et al. [106] developed a spectrally engineered radiative cooling textile to combat the urban heat island effect. Conventional radiative cooling textiles often absorb radiation from the ground and nearby structures, limiting their effectiveness in real-world applications. In contrast, the spectrally selective hierarchical fabric (SSHF) comprised an electrospun silver nanowires (AgNWs), polymethylpentene (PMP) nano-micro hybrid fibrous layer, and wool textile [106]. This design boasted a high sunlight reflectivity of 0.97, attributed to robust Mie scattering by fibrous structured engineering. The inclusion of PMP was strategically aimed at achieving outward-facing emissivity within the atmospheric window, while AgNWs were instrumental in suppressing non-atmospheric window emissivity. Furthermore, the wool fabric was incorporated to guarantee the remarkable emissivity, facilitating heat exchange between the human body and textile, and minimizing the direct reflectance of heat radiation at AgNWs layer. Leveraging a multi-faceted cooling regulation approach, the SSHF demonstrated superiority by maintaining temperatures 2.3 °C cooler than a broadband emitter in vertical positioning and 6.2 °C cooler than environment temperature in horizontal positioning.

The design of radiative cooling technologies in textiles transcends mere emphasis on achieving optimal cooling performance [107, 108]. Considerations extending to wearability factors, such as incorporating a moisture-wicking effect, are crucial. Scientists have recognized the importance of ensuring that radiative cooling textiles are not only efficient in cooling but also comfortable for wearers. An exemplary illustration of this holistic approach is evident in the hierarchical metafabric devised by Zhang, et al. [101]. This innovative fabric not only exhibited exceptional solar reflectivity of 99.16% in the 0.3–0.76 μm region and 88.60% in the 0.76–2.5 μm region, and selective IR emissivity of 78.13% in the 8–13 μm region, but also showcased remarkable capabilities in ultrafast water transport and evaporation (Fig. 5f). Achieved through the modulation of water hydrophilicity across different fabric layers, this metafabric demonstrated efficient moisture management properties. By leveraging differential water hydrophilicity accomplished through the application of commercial hydrophilic reagent surface treatment, the hierarchical metafabric displayed an impressive antigravity directional water-transport performance. This integration of advanced functionalities not only enhances the cooling efficiency of the textile but also prioritizes wearer comfort and usability, marking a significant advancement in the realm of radiative cooling textiles. Additionally, Ma et al. [109] introduced a biomass-derived aerogel with appealing radiative cooling characteristics attributed to its fluorescence and phosphorescence. The novel biomass-based intrinsic photoluminescent approach for radiative cooling was presented with high solar reflectivity, which could be prepared on a large scale and recycled. The materials exhibited excellent radiative cooling performance and showed potential for PTM applications in smart textile technology, emphasizing environmental friendliness and sustainability.

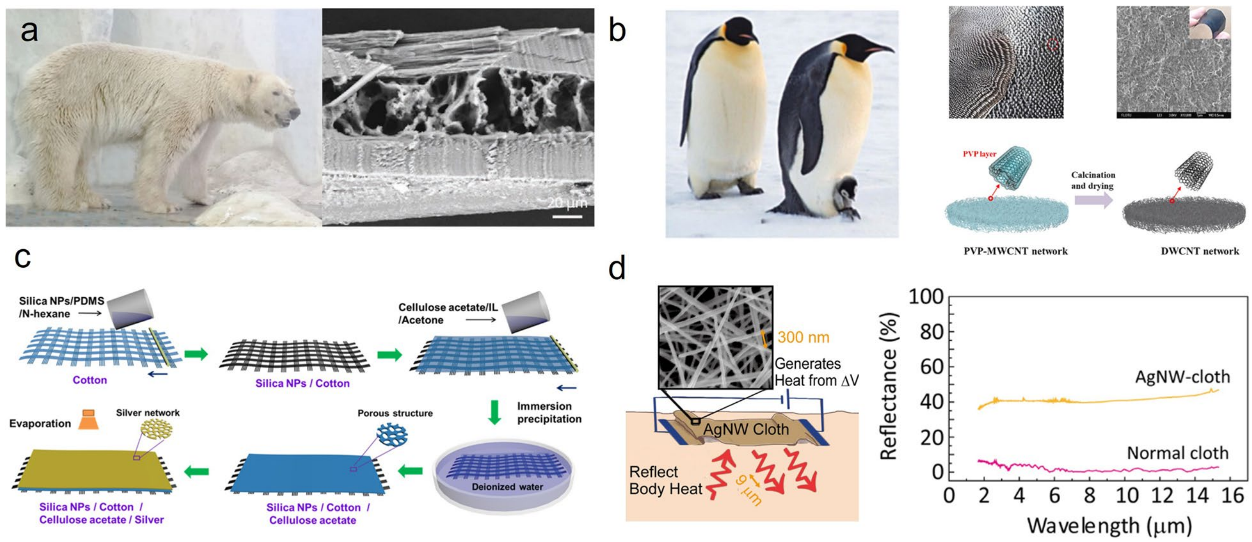

Fig. 6 Advancements in smart textiles with improved IR reflectivity. **a** A biomimetic wire with a hollow core from Polar bear hair [114]. **b** A biomimetic non-woven textile and schematic diagram of the fabrication process with thermal insulation from Penguin hair [116]. **c** Schematic of thermal and waterproof fabrics [117]. **d** Concept of AgNW cloth with high thermal reflectance [118]

Smart textiles for radiative heating

Maintaining body temperature has become one of the most essential requirements for human survival. However, regulating ambient temperature consumes a significant amount of energy [110]. Radiant heating, as an effective human-warming strategy, has attracted much attention utilizing textiles with minimized body thermal radiation outwards and high solar absorptance in the outdoor environment [111]. The radiative heating categories will be organized and discussed as presented as follows.

Smart textile with improved IR reflectivity

For radiative warming, the key to smart fabrics lies in minimizing heat loss from the human body, which is achieved by using materials that have improved IR reflectivity [112]. IR reflective textiles are those that prevent human mid-IR radiation at 7–14 μm emitted from the human body to pass through the textiles with total obstruction. Combining the aligned microstructure with smart textiles can enable the warming function for the human body. Some natural organisms, like the hairs of polar bears, possess a distinctive hollow core and aligned outer layers that can efficiently reflect infrared radiation from their skins, exhibiting an amazing ability to keep warm [113]. The hollow hair of polar bears can trap air within the hollow structures of the hairs, preventing heat radiation from passing through. This effectively controls heat transfer and prevents heat loss. Inspired by the natural radiative warming fibers in hollow structures, Cui et al. [114] developed fibers with arranged porous structure by employing a continuous freeze-spinning technology in Fig. 6a. The porosity of these biomimetic porous fibers was as high as 87%, and their unique porous structure endows them with excellent thermal insulation properties. In addition, the large air–solid interfaces in the fibers significantly enhance their reflectivity for infrared light. In the region of 15–25 μm, the IR reflectivity of textiles can reach 70–80%. Additionally, Yu et al. [115] fabricated a series of thermoplastic polyurethane (TPU) fibers with a stretchable hollow porous structures by wet spinning. Due to the large amount of air contained in the fibers, textiles woven from these hollow porous TPU fibers have excellent thermal insulation properties, maintaining an absolute temperature difference of 68.5 °C and 44°C at harsh temperatures of 115 °C and -40 °C, respectively. Considering the geometry of the infrared reflection, the pore manipulation of the fabric plays a crucial role in achieving effective thermoregulation. Lin et al. [116] developed a double-walled carbon nanotube nonwoven fabric (CNF) with a controlled gradient pore structure that initiates multiple infrared reflection mechanisms Fig. 6b. CNFs had interconnected network structures with no obvious agglomeration and featured a highly porous nanostructure with high porosity (over 90%).

In addition to the structural design methods previously mentioned, combining metal-based materials with various functions also helps maintain body warmth [119]. Metals are known to be excellent IR reflectors and have been widely utilized in everyday life. The free electrons in metals reflect incoming photons, resulting in high IR reflection on the metal surface [120]. Coating textiles with metals is a common strategy for thermal insulation through metallic coatings. For example, a multifunctional cotton textile was fabricated, with one side modified with a nanoporous silver layer, and the other side with superhydrophobic silica/PDMS layer in Fig. 6c [117]. In the fabric composite, the porosity allows the fabric to be breathable, while the silver layer has an average transmittance of about 0% in the 2.5 – 16 μm region, making it an excellent infrared reflector. Embedding metal nanowires in fabrics is also a splendid strategy. Among them, silver has become the first choice due to its excellent infrared reflection efficiency, resistance to acid and alkali, and antioxidation properties [121]. Gao et al. [122] prepared double-sided nonwovens composed of AgNW mesh and PI electrospun nonwoven, where a higher concentration of AgNW tends to form dense networks with over 80% IR reflectance. For example, Hsu et al. [118] developed a AgNW-based cotton textile using the dip-coating way in Fig. 6d. The metal nanowires constructed a conductive network that could reflected human infrared radiation and enabled Joule heating to enhance passive warming. Additionally, Gu et al. [123] demonstrated cellulose fiber-based hybrids by orderly vacuum filtration of boron nitride nanosheets, nickel-silver nanowires, and cattail stick cellulose. Among these, silver nanoparticles are beneficial in enhancing the optical performance with a high reflectance of about 0.85, which suppresses human radiation loss for radiative warming application.

Smart textile with reduced IR emissivity

The IR emissivity of the outer surface of textiles is crucial for their warming properties. In a typical indoor environment, the radiation plays a more substantial role than the convective heat transfer. Thus, lowering the emissivity of the outer surface can effectively reduce human radiative thermal dissipation. For example, a cotton-based textile containing nanoporous silver and nanoporous polyethylene had a suppressed thermal emissivity of 10.1% [119]. Smart textiles significantly minimized radiative thermal dissipation without compromising comfort, with a temperature decrease of 7.1 °C in contrast with traditional textiles. Similarly, the robust silver paste/cotton fabric (AgPA/CF) was designed by integrating electrical, radiative, and solar heating and other functions [124]. The average mid-IR emissivity of AgPA/CF at 7–17 μm was 46.2%, which was much lower than that of the virgin cotton (93.6%), indicating that AgPA/CF had a stronger ability to intercept human thermal radiation. Additionally, a multi-scale porous structure to coat silver on an aerogel textile could be used to achieve personal warming [125]. The fabric had a low IR emissivity of 22.2% as well as a low thermal conductivity through silver layer coating, indicating that the silver acts as a mid-IR barrier, thus obstructing thermal energy and preventing thermal transfer between the human body and the surroundings.

Apart from Ag particles, various metallic particles, carbon-based materials (such as graphene and its derivatives), or carbon-like substances (such as MXene) have been incorporated into polymers to improve the efficiency and comfort of PTM systems. These materials can also demonstrate a low infrared emissivity, contributing to better thermal insulation [126–128]. For example, Tavakkol et al. [129] also developed passively radiative personal heating fabrics by melt-spinning Polypropylene(PP)/Aluminum(Al) composites. The optimal amount of Al particles was decided by numerical full-wave analysis to minimize thermal radiation transmittance. The most effective fabric samples demonstrated a total mid-infrared transmittance of 0.20% and an average emissivity of 16%. This fabric serves as outdoor winter clothing, enhancing skin temperature by 3.8 °C. Dong et al. [130] constructed a wearable heating system using MXene@polyester polyurethane blend fabrics (MP textile) for PTM by a spraying method. Remarkably, the MP textile with an MXene concentration of 28 mg/mL exhibited a low mid-infrared emissivity of 19.53% at 7–14 μm. Notably, the temperature of these MP textiles increased by more than 6.83 °C, indicating promising indoor passive radiative heating properties. While these advanced nanofillers can be woven into fabrics, they tend to be stiff, and brittle, usually leading to uncomfortable wear. Thus, it remains a challenge to reconcile optimal heat transfer properties with remarkable wearability by designing state-of-the-art photonic structures.

Smart textile with improved solar absorptance

In the outdoor environment, apart from the use of atmospheric transparent windows for radiative thermoregulation, the solar radiation energy during the day can also be used as a clean heat source for thermal management, whose wavelength is mainly visible light and near infrared bands. Wearable textiles with enhanced solar absorption have been proposed as a device that utilizes solar absorption for high-performance smart heating [131]. Typically, the sunlight radiation that reaches the surface of the Earth through the ozone layer is composed of NIR, VIS, and UV light [132, 133]. Moreover, far-infrared (FIR) rays can penetrate a variety of biological materials and induce strong molecular-level vibrations, thereby improving the metabolism of the human body [134]. The human epidermal layers can absorb FIR rays, resulting in a pleasant warmth sensation. The progress of materials that emit FIR has attracted much attention, mainly including MgO, TiO_2, SiO_2, ZnO, CNTs, and,ZrC, ZrO_2 [135, 136]. At present, there are two mechanisms of UV–VIS-NIR heating mechanism by increasing the UV–VIS-NIR absorbance and FIR radiative warming mechanism by using function particles to emit the

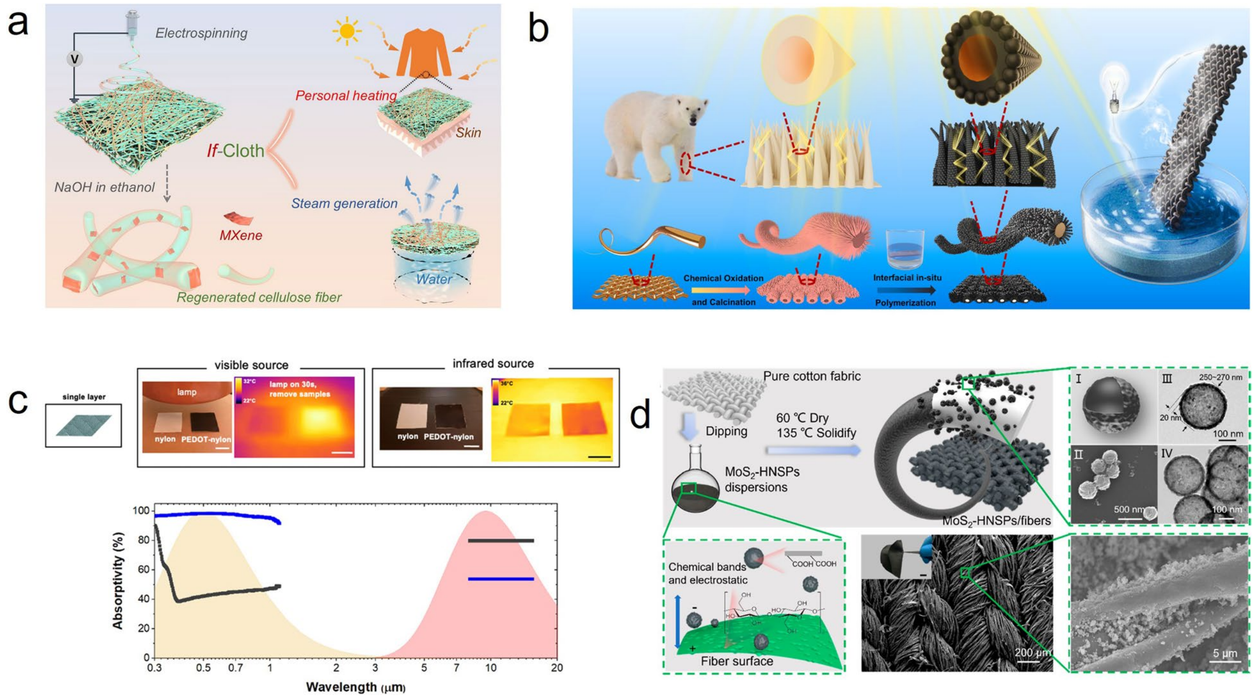

Fig. 7 Advancements in smart textiles with improved solar absorptance. **a** Schematic of the integrated functional cloth (if-Cloth) in personal heating by electrospinning method [139]. **b** Schematic illustration of fabricating PPy@CuO NAs coated Cu mesh [141]. **c** Characterizing the optical properties of PEDOT-nylon fabrics and sun absorptivity of PEDOT-coated nylon [142]. **d** Schematic diagram for MoS_2-HNSPs photothermal textiles [143]

FIR rays. Therefore, advanced design principles can be used to develop smart fabrics by applying structure and material engineering, converting the sunlight into the satisfied heat energy to a certain extent [137, 138].

For example, Chang et al. [139] prepared an ultrathin cellulose/MXene composite cloth through electrospinning as shown in Fig. 7a. Compared to commercially available cotton fabrics, the composite cloth enhanced the temperature of 5.6 °C for the simulated skin, demonstrating high solar light capture instead of a dry state. Similarly, carbonized waste fabrics were used as raw materials and modified by dopamine and dodecylamine to obtain a modified carbonized fibers (MCF) [140]. Due to the photothermal synergy between polydopamine and the carbonized fabrics, the MCF coating exhibited a high light absorptivity of over 95% in the VIS wavelength range and can be rapidly heated to 95.3 °C in 120 s. In addition, porous or topological structures were explored for photothermal conversion applications. Li et al. [141] introduced a hair-inspired 3D photothermal mesh with a novel cone-shaped 3D topology to enhance light absorption in Fig. 7b. Under the solar exposure, the polypyrrole (PPy)@CuO-3 NAs exhibited high evaporation rates and energy efficiency. Viola et al. [142] designed a double-layer textile, which maximized sunlight absorption of VIS–NIR in Fig. 7c. Under moderate lighting conditions, the textile produced a heating effect of 10 °C compared to a standard heavy cotton T-shirt. Besides, Cao et al. [143] prepared photothermal fibers via a hot-blast dip-drying process for PTM in Fig. 7d. The solar efficiency of MoS_2-HNSPs textile was as high as 36% under the irradiation of an 808 nm NIR laser at 0.5 W/cm^2, which is due to the high light absorption capacity of the hollow structures.

Smart textile with multi-mode heating regulation

When the human body is exposed to the external surroundings with sunlight irradiation, sunlight absorption should be maximized to obtain additional energy for body warmth. Of course, other methods can be devised to make the remarkable sunlight absorption, minimized IR emissivity and maximum IR reflectivity work in synergy to significantly improve the radiative insulation of textiles [144]. Thus, designing multi-mode heating textiles to amplify the radiative heating effect is significant based on the sections from 4.1 to 4.3.

Harnessing the synergistic effect of solar absorption and improved IR reflectivity, a series of smart textiles were purposely dedicated to PTM. For example, by growing PPy and depositing AgNW on cotton fibers, smart AgNWs/Cotton fabric@PPy/PDMS textiles were exploited in Fig. 8a [145]. The above smart textile had good external sunlight absorptivity (98.6%) and inner IR reflectivity (76.3%), ensuring that the textile could be heated to 96 °C under a single sun

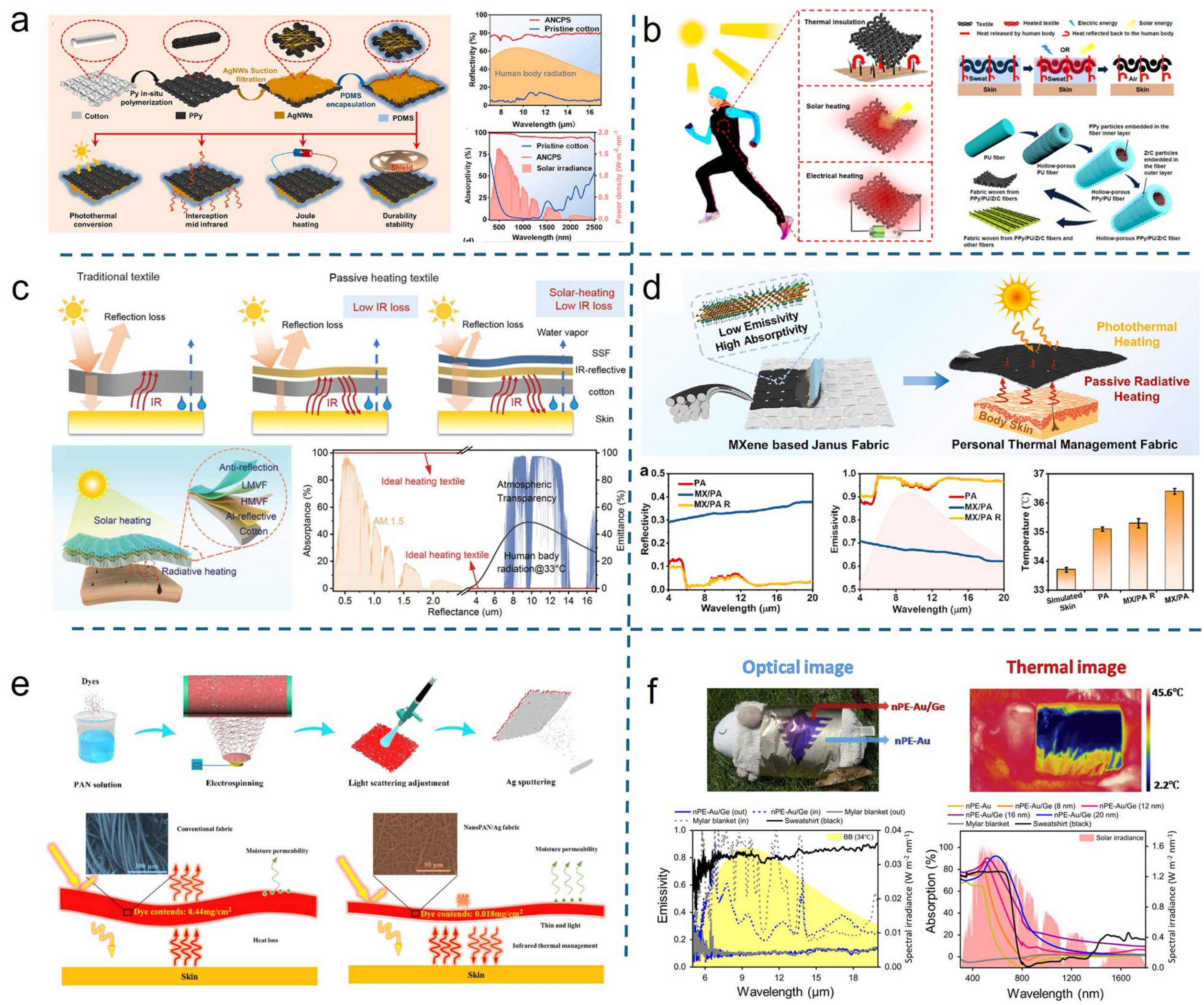

Fig. 8 Advancements in smart textiles with multi-mode heating regulation. **a** Schematic of the preparation AgNWs/Cotton fabric@PPy/PDMS textile with improved solar absorption and IR reflectivity [145]. **b** Illustration of fabricating the PU/PPy/ZrC textiles with improved solar absorption and IR reflectivity [146]. **c** Mechanism and advantage of ZrNbMo-Al-N from heat radiation and solar irradiance [147]. **d** Schematic of MXene/PA Janus fabric for PTM with enhanced IR reflectivity and reduced IR emissivity of MXene/PA-based textiles [148]. **e** Schematic for a radaitive warming textiles with a colored NanoPAN/Ag materials [149]. **f** Optical/thermal images and optical properties of the smart textiles [150]

irradiance and increased the human body's temperature by 2.0 °C without consuming energy. Another example was polypyrrole/polyurethane/zirconium carbide (PU/PPy/ZrC) fiber, created through a straightforward two-step process, which demonstrated excellent electrothermal/photothermal conversion in Fig. 8b [146]. Because of the porous structures of the PU/PPy/ZrC fibers, they exhibited enhanced thermal reflection and high photothermal properties with outstanding thermal stability. The composite fibers could be used for personal protection against the cold and reached 51.7 °C with an infrared lamp and 55.8 °C at 2 V through the triple effect of radiative, electrical and solar-driven heating.

Additionally, smart textiles with excellent sunlight absorption and poor IR emissivity also drew remarkable attention for PTM devices. He et al. [147] prepared a novel three-layer high-entropy nitride (ZrNbMo-Al-N) from Al-coated cotton fabric through experiments and calculations, with an excellent solar absorptance (92.8%) and poor thermal emittance (39.2%), contributing to efficient radiative heating in Fig. 8c. Besides, as shown in Fig. 8d, a Janus MXene fabric [148] for radiative heating was fabricated through brushing the MXene on the polyamide (PA) side by taking full advantage of radiated thermal characteristics of superior spectral selectivity (low mid-infrared emission, high reflectivity and solar absorption). The bilayer textile raised the temperature of 3.4 °C for the simulated skin, which suppressed body radiation dissipation.

For developing the smart textiles with warming properties, researchers have strived a lot for high performance. Significantly, the most effective strategy has also been achieved through combining materials with different characteristics of textiles, such as fashion and color. Li et al. [149] fabricated the colored polyacrylonitrile nanofiber/silver textile as shown in Fig. 8e, which had excellent air breathability, mechanical stability, good sunlight energy utilization (50%) and low IR emittance (15%) for excellent heating function. The color intensity of the fabricated textile can be adjusted using a scalable solvent impregnation technique. Besides, in Fig. 8f, the other authors [150] reported a colored nanophotonic structured textile with a maximum sunlight absorbance of 50% and a low infrared emissivity of 10%, while also offering excellent wearability, aesthetics, and manufacturability. In conclusion, these functional materials and techniques can promote the development of temperature-modulating smart textiles, enhancing energy-efficient preservation and personalized thermal comfort.

Smart textile systems for radiative heating and cooling

The above smart textiles for thermal management are gaining increased attention across various thermal surroundings; however, they remain static and unresponsive to changing environment. Traditional materials and structures which offer only singular cooling or warming functions, are falling short in providing thermal comfort in dynamic settings. Consequently, there is a pressing need for individually customized thermal management systems that integrate the benefits of both warming and cooling mechanisms with dynamic control capabilities for dual-mode applications. In the following part, we will introduce two main categories including Janus textile systems for bilayer emitters and responsive thermoregulatory textile systems.

Janus textile systems for bilayer emitters

The term "Janus textile" refers to a fabric type that exhibits dual characteristics. Janus textiles possess different properties or appearances on each side of the fabric, including variations in texture, color, pattern, or functional attributes such as water-resistance on one side and breathability on the other [151]. These fabrics find application in high-performance and technical apparel, as they offer versatile benefits. For instance, one side of the fabric may have moisture-wicking properties while the other side provides insulation, making it suitable for activewear that requires effective perspiration management and warmth. Conventional radiative cooling and radiative heating materials are typically static and not adaptable to the dynamic demands of seasonal and weather changes. Therefore, it is crucial to develop materials that enable all-weather dual-mode textile systems for efficient management of radiant heat [152].

Asymmetrical IR emissivity and solar reflectivity

One approach to achieving this dual functionality is through asymmetrical infrared radiation. These textiles have two sides with different infrared emissivity, a property that enables their use for both cooling and heating purposes. When cooling is required, the side with low IR emissivity is worn against the body, allowing the side with high IR emissivity to actively dissipate heat to the atmosphere. The opposite holds true when warmth is needed.

For instance, Cui et al. [153] reported representative bi-function Janus textiles, by incorporating a carbon coating side as a high-emissivity material and a copper coating side as a low-emissivity material within nanoporous polyethylene layer as shown in Fig. 9a. This textile can achieve passive radiant heating and cooling without external energy inputs and can switch modes by changing the orientation of the emitter. Similarly, Yue et al. [154] developed a special fabric membrane to achieve asymmetrical infrared emissivity in Fig. 9b. This Janus fabric membrane consists of a sandwich structure with MnO_2 and Cu nanowires by vacuum-assisted filtering method on a cellulose fiber@layered double hydroxide basement membrane. Cu nanowire layer exhibits low emissivity, while the other layer has high emissivity, achieving the cooling-heating mode by flipping.

Apart from using coating technologies, Janus textiles with asymmetric emissivity can also be created through asymmetrical stitching treble weave in Fig. 9c [155]. 3-aminopropyl triethoxysilane (APTES) was used as a coupling agent to bond nanoscale TiO_2 and carboxymethyl cellulose sodium (CMCNa) to the PLA, increasing the IR emissivity. These materials are then interwoven with low emissivity silver-plated polyamide (SPPA) to fabricate a Janus textile. Experiments were conducted to compare the temperature of this dual-mode metafabric, which enabled IR emissivity of 94% for cooling and a low emissivity (41.3%) for warming. In the practical application aera, textiles can be made into a variety of commercial products, such as face masks. Xu et al. [156] explored innovative textile-based functional masks made of interlayered PLA fibrous filters could regulate thermal mid-infrared emissivity with a remarkable PM0.3 capturing efficiency of 99.69% in Fig. 9d. Cooling mode of masks with cotton nonwovens exhibited good IR emissivity of 90.7%, whose temperature was 1.1 °C lower compared to the 3M mask; whereas, in heating mode, the perforated Al/PE films had low mid-infrared emissivity of 10.7%, whose temperature was approximately 1.1 °C higher than that of 3M mask for thermal retention.

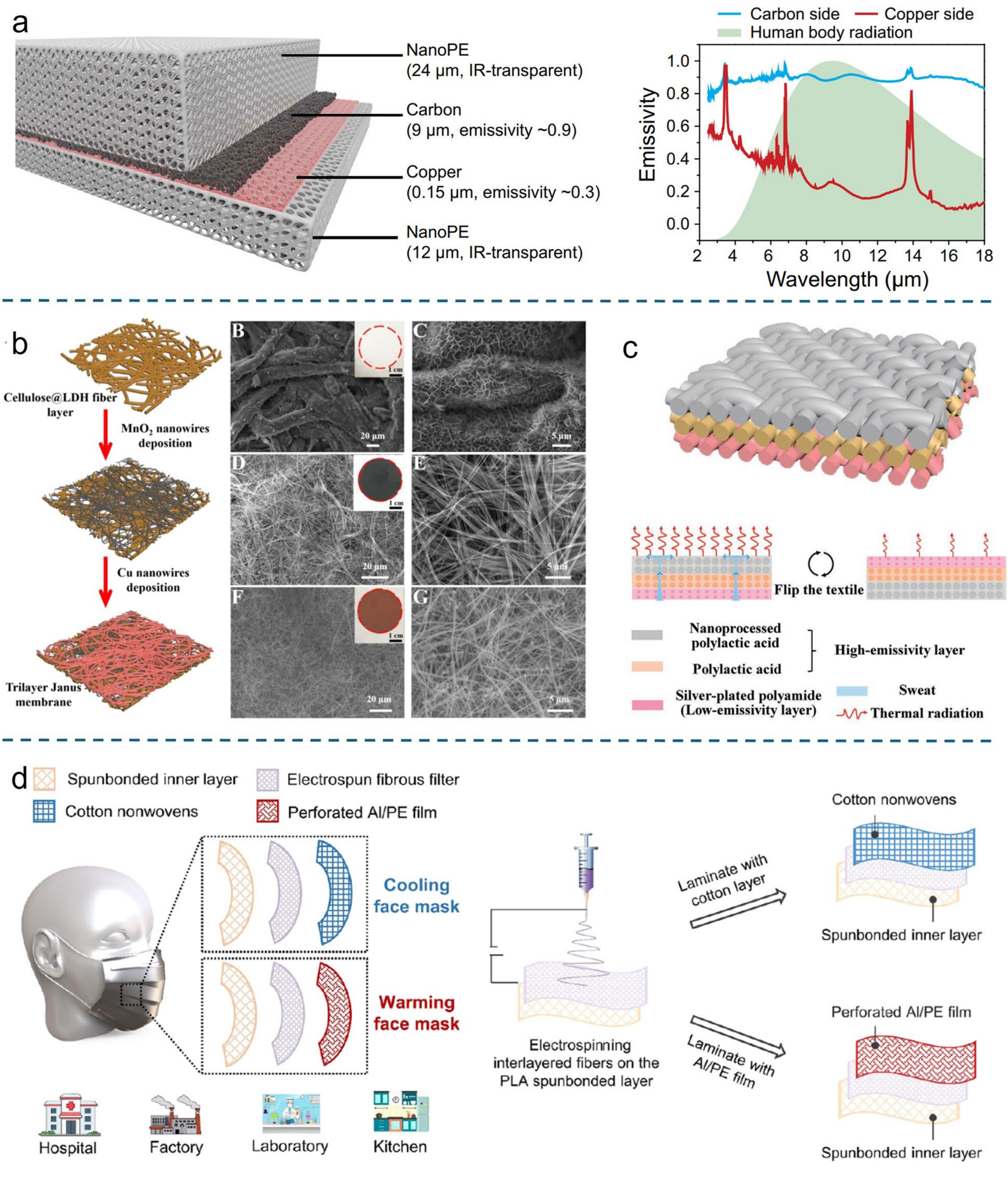

Fig. 9 Advancements in Janus smart textiles for symmetrical IR emissivity. **a** Structure of Janus textile and emissivities of carbon and copper coating by FTIR spectrum [153]. **b** Preparation of trilayer Janus membrane and SEM images of trilayer fibers [154]. **c** Schematic of the metafabric and the cooling-heating mode by flipping [155]. **d** Schematic of face mask and assembly procedure for face masks [156]

In addition to improving infrared emissivity, Janus textiles can be designed with different reflectance of sunlight on each side, allowing for dynamic adjustments for heating and cooling purposes [157, 158]. For instance, a Janus film can be created using an aluminum film as the substrate [159]. SiO_2 microspheres are mixed with a PDMS precursor, and the mixture is cast onto an Al layer, followed by thermal curing to create the cooling layer. The heating layer consists of a PDMS matrix encapsulating carbon nanotubes specially designed for solar heating. Similarly, a comfortable Janus fabric was successfully designed by incorporating boron nitride nanosheets (BNNS) into a porous TPU and integrating MXene into a separate layer of TPU pores [160]. The BNNS exhibited a remarkable solar reflectivity of 94.22% due to optimized pore size distribution, while the MXene/TPU had a high solar absorptivity of 93.57%. By flipping, Janus fabrics could adapt to varied temperatures, switching from cooling side of 7.2 °C to heating side of 46.0 °C.

Synergy effect of IR emissivity and solar reflectivity

In practice, techniques that modify fabric emissivity and utilize sunlight can be combined to achieve better adaptability and enable temperature management throughout the day [161, 162]. On this basis, more and more researchers have attempted to use IR emissivity and solar reflectivity of fabrics in an integrated manner. Turning the coating over to adjust the textile properties was a significant strategy to automatically and dynamically adjust to the changing environment to realize dual mode. For instance, as shown in Fig. 10a, a bilayer leather-like nanotextile (LNT) was successfully developed with breathable, soft, stretchable properties for radiative thermal regulation by electrospinning method, including a heating layer and a cooling layer based on the polyurethane fibers [163]. The heating layer was made by mixing conductive carbon black and a hydrophobic agent, while the cooling layer was electrospun from a solution containing aluminum oxide and a hydrophilic agent. As a result, the cooling side of the LNT showed a sunlight reflectance of approximately 94.8% and infrared emissivity of 95.0%, while the other heating side showed high solar absorption of about 95.3% after flipping. Similarly, flexible layered AgNW/rGO/PVDF-HFP composite nanofiber films were fabricated by a fiber-spinning method for all-weather PTM textiles [164]. Efficient radiative heating and anti-solar cooling could be controlled by regulating heat transfer properties. Because of the difference between radiative and photothermal performances, the two sides including AgNWs and PVDF-HFP layers showed efficient thermoregulating performances, contributing to the potential in smart clothes for varied surroundings.

Recently, to develop multi-mode textiles suitable for changing climates with significant temperature variations, a series of advanced materials such as MXene, played a vital role for PTM textiles. Li et al. [165] demonstrated a three-mode textile, achieving radiative cooling, radiative warming as well as Joule heating in Fig. 10b. The cooling layer was formed from an electrospun polyethersulfone-Al_2O_3 composite textile, reflecting a significant portion of solar radiation while efficiently emitting IR radiation. The heating side was created using a MXene coating, exhibiting high a sunlight absorptance of 0.85 and low IR emissivity of 0.22. Due to the electrical conductivity of MXene, the fabrics could generate heat when voltage is applied, providing an additional heating mode. Additionally, Janus PTM textiles for bi-functional cooling and heating were also designed through modulating sunlight and human radiations combined with satisfactory wearability and durability in Fig. 10c [166]. The cooling layer with electrospun porous polyacrylonitrile had high solar reflectivity of 91.42% and an about 14 °C temperature decrease. By flipping the fabric, the MXene-coated heating layer exhibited remarkable heating capability with a photothermal conversion efficiency of 37.5%. At the same time, Dong et al. [167] proposed smart textiles including the white TPU/PDMS layer and the black AgNW/MXene layer, enabling the textiles radiative bilayer thermal regulation. As shown in Fig. 10d, the cooling layer of smart textiles exhibited a high value of 97.5% for IR emissivity and 90% for sunlight reflectivity, thus decreasing the temperature of 4.9 °C. The warming side exhibited a large value of 86.6% for solar absorptivity, thus increasing the skin by 5 °C. Tang et al. [168] exploited a bi-functional smart textile with asymmetric optical properties. In this textile, one side of a cotton fabric was coated with AgNWs for moderate solar absorptivity and IR emissivity, and then MXene was used to the opposite side for excellent solar absorptivity and low emissivity Fig. 10e. This innovative design guaranteed that the MXene side exhibited the photothermal and radiative heating temperatures of 16 °C and 1.7 °C, which were higher than those of AgNWs side, respectively.

Responsive thermoregulatory textile systems

To ensure human physiological and heat comfort, smart textiles designed for adaptive thermoregulation are gaining popularity [169, 170]. The dynamic structural changes in fabrics primarily include the shape memory properties of fiber materials or special textile structure designs, such as the opening and closing of micro-pores, adjustments in fiber alignment, and changes in laminated structures. Based on the anisotropic volume expansion mechanism of fibers, various material designs and actuation strategies have been proposed to exhibit high and rapid dynamic structural changes in response to environmental stimuli, such as carbon nanotube yarns, polymers, shape memory alloys, and their composites. When these stimulus-responsive materials undergo specific shape or color changes due to external environmental changes temperature and humidity. This allows the fabric to provide optimal comfort and energy efficiency for the wearer in different environments, achieving personal thermal and moisture comfort and enabling personal intelligent thermal management [171].

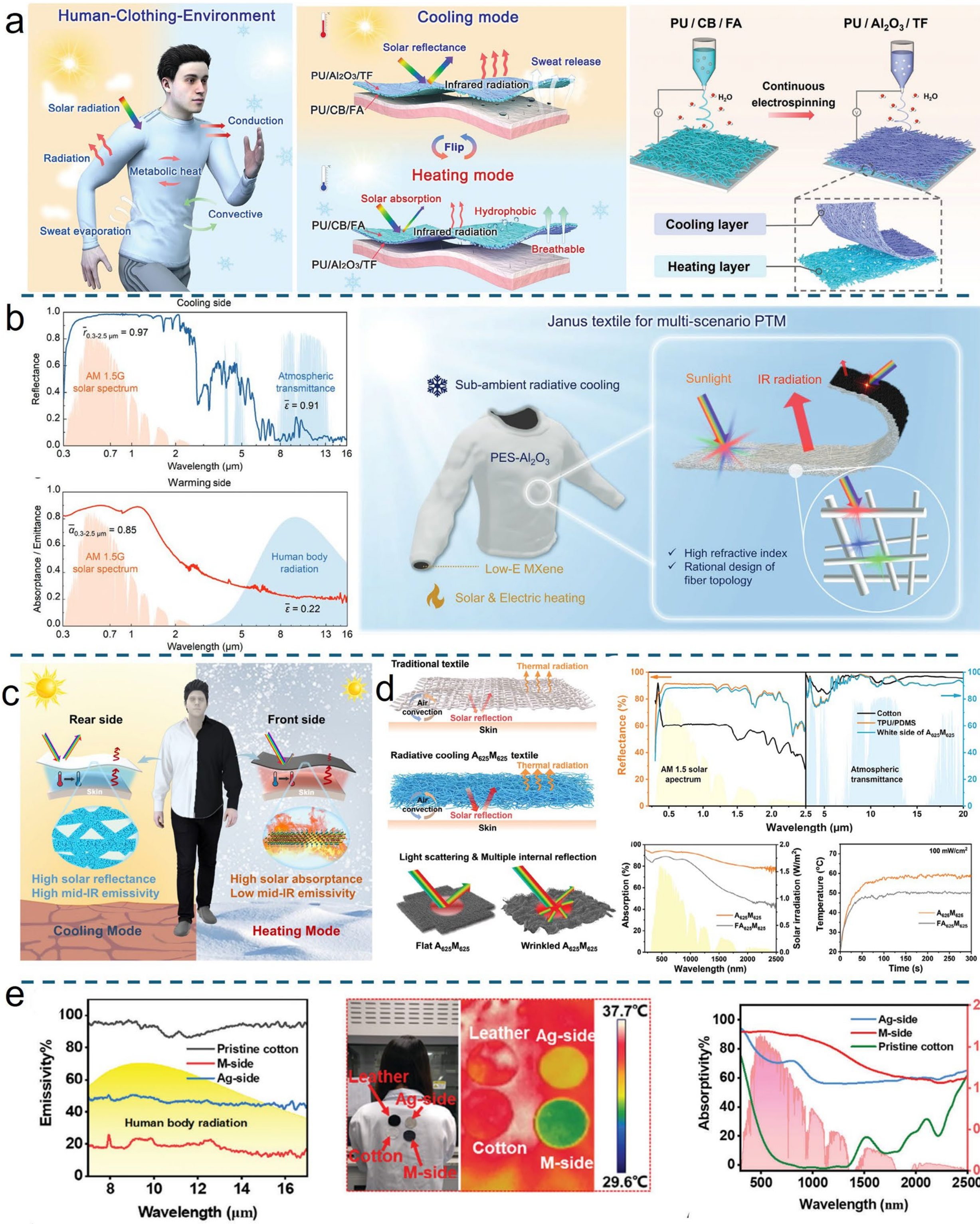

Fig. 10 Advancements in smart textiles for synergy effect of IR emissivity and solar reflectivity. **a** Schematic of the human body-clothing-environment system for thermoregulation and assembly process of bi-functional smart textiles [163]. **b** Schematic of Janus smart textile, the cooling side with reflectance spectrum and the warming side with absorptance/emittance spectrum [165]. **c** Schematic of the dual-mode textile for PTM [166]. **d** Schematic of the traditional and smart fabrics. UV–VIS–NIR reflectivity and emissivity of the cooling side; wrinkled fabrics for enhanced light absorptive performance, UV–VIS–NIR spectra of the warming side and the temperature profiles under one-sun light [167]. **e** The IR emissivity of smart textiles, the IR image covered on the back and the UV–VIS–NIR absorption spectra of both textile sides [168]

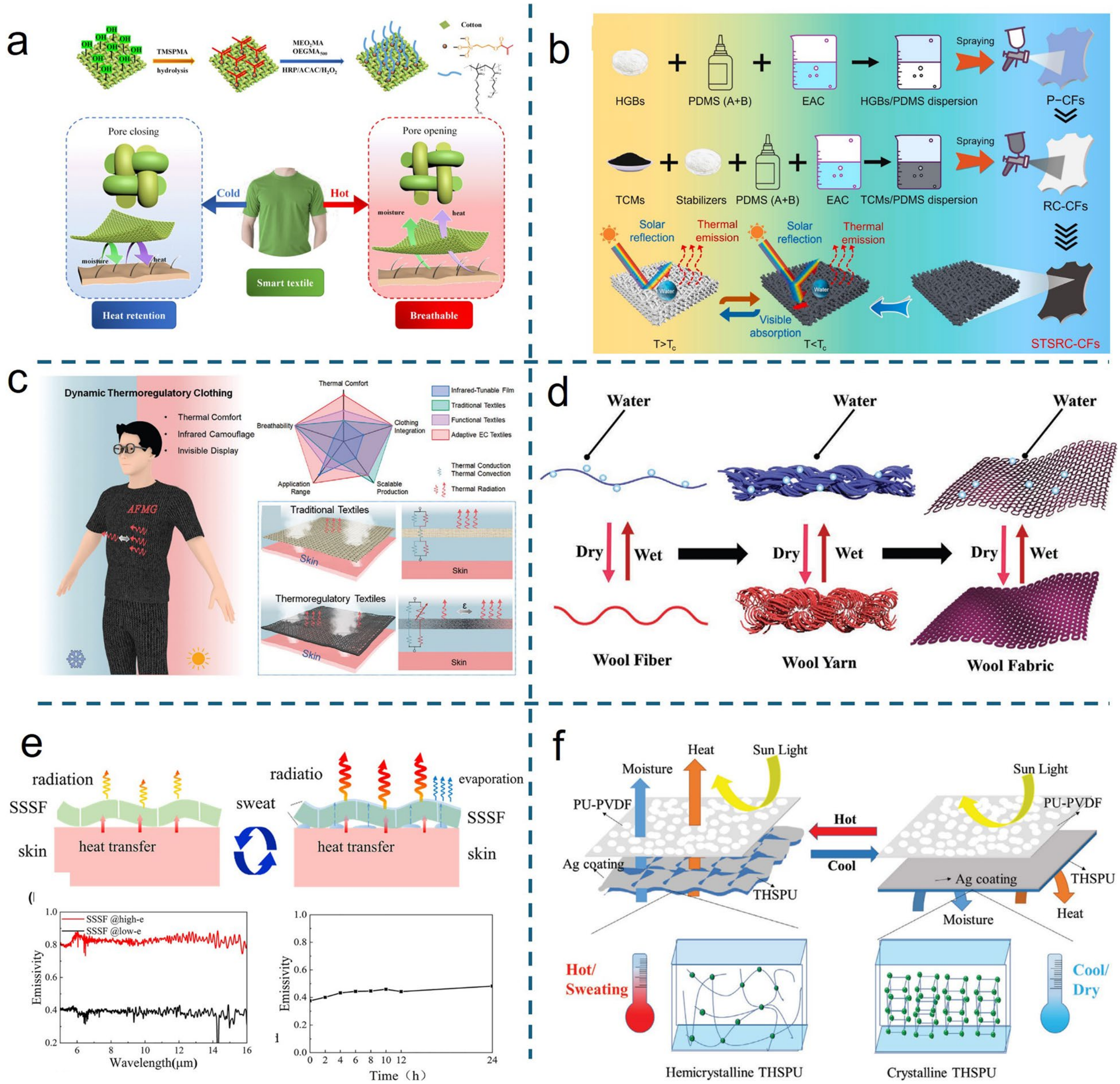

Fig. 11 Advances in responsive thermoregulatory textile systems. **a** Fabrication of TR-cotton fabric, pores closing and opening with temperature change [172]. **b** Schematic of the assembly process of STSRC-CF smart textiles [173]. **c** Dynamic smart textile from electrochromic fibers [174]. **d** Schematic diagram of water responsive process of the smart fiber, yarn, and fabric [175]. **e** Schematic of the smart fabrics for PTM process and fabric emissivity after water washing times [176]. **f** Mechanism of the multimodal smart fabric in moisture and thermal management [177]

Recently, temperature-responsive smart fabrics have attracted much attention in multi-mode integrated textile systems. In low-temperature status, the integrated fabric systems can enhance the retention of body heat through dynamic structural change, thereby reducing thermal dissipation from the user and retaining more body warmth. In high-temperature status, the fabric system can increase the air gaps within the structure to enhance heat dissipation from the body's surface for thermal comfort. For instance, Yang et al. [172] designed thermo-responsive cotton textiles by enzymatic fiber surface graft polymerization in Fig. 11a. At high temperatures, the contraction and breakage of thermos-responsive polymer chains on the fiber surfaces of smart fabric cause the pores in the fabric to enlarge, increasing airflow. In the low temperatures, the responsive matrix network expands, resulting in the fabric pores to shrink, reducing breathability and moisture permeability, which helps with insulation and warmth retention (approximately 1.5 °C more than unmodified cotton fabric). This work provides new ideas and methods for the preparation of smart textiles for PTM. Besides, thermochromic thermoregulatory smart fabrics in Fig. 11b were also proposed by Huang et al. [173]. The smart dynamic responsive radiative cooling collagen fibers exhibited an IR emissivity of 0.94. Their solar reflectance could be dynamically adjusted in response to change in ambient temperature, with a high sunlight reflectivity of 0.91 and 0.81 at varied temperatures. This synergistic effect allows the fibers to autonomously manage radiative cooling and sunlight heating, thereby providing intelligent energy-saving temperature modulation for both winter warming and summer cooling. Similarly, Fan et al. [174] developed a dynamic thermoregulatory textile using scalable-manufactured radiative electrochromic fibers in Fig. 11c. These textiles could be easily driven by a low voltage to modulate their emissivity. Consequently, the thermoregulatory textile suppressed significant temperature fluctuations and ensured excellent temperature regulation within 1.6 °C for simulated skin, even with an ambient temperature variation of 11.2 °C.

Sweating is the primary means by which the human body regulates temperature in high-temperature environments and during exercise [178]. When the ambient temperature exceeds skin temperature, the substantial production of sweat makes its evaporation crucial for cooling the body. Wearable smart fabrics can adjust their structure in response to sweat to promote heat dissipation and air circulation: by increasing porosity or using fibers with specific microstructures, the breathability and wettability of the fabric are enhanced, helping to dissipate heat from the body surface more rapidly. This strategy is known as humidity-responsive smart fabrics [179]. For instance, Hu et al. [175] developed a humidity-responsive smart fabric by wool fiber yarns, based on the stretching of molecular chains during hydration and dehydration processes in Fig. 11d. When the wool fibers absorb water, the yarn length increases, and the yarn diameter decreases, causing the knitted fabric pores to open and expand. After losing water, the knitted wool fabric leads to pore closing, maintaining warmth. As a result, the infrared transmittance (9.6–10 μm) of the fabric in a wet state is higher than in a dry state. Infrared temperature tests reveal that the surface temperature of the textile in a humid environment of 24.7 °C was lower than that in a dry environment of 31.2 °C. Additionally, Li et al. [176] introduced a self-adaptive smart textile by coating polyester textile with AgNW in Fig. 11e. This textile could modulate its emissivity from 0.39 to 0.83 in answer to the body's transition from dry to humid environment, showing its potential for dynamic thermal loss during various levels of activity. Furthermore, a programmed meta-louver textile with changeable functions for cold and hot environment has been developed [180]. The effectiveness of adaptive pore channels, achieved by manipulating the orientation of chiral knit loops to modulate evaporation, has been verified. Additionally, double-mode humidity/temperature-controlled textiles are also demonstrated for adaptive modulation of heat and moisture, enhancing the comfort of the microclimate for certain occupational groups. Chen et al. [181] introduced a metafabric composed of bicomponent structured polyester fibers as the foundational unit. They utilized the differing responses of the two components to heat and humidity for regulating the pore size of the metafabric, enabling non-electric smart control of the hydrothermal microclimate. Compared to conventional polyester textiles, this metafabric could gain an additional 6.1 °C temperature adjustment and approximately 55% improvement in moisture permeability under varying temperature and humidity conditions. Another textile like polyurethane based intelligent composite fabrics (PUSF) were successfully developed by Li et al. [177]. Multimodal regulation is achieved by combining a porous protective layer of PVDF and PU with a silver-plated heat and humidity sensitive thermoplastic polyurethane (Ag-THSPU) in Fig. 11f. In the dry and cold state, the Ag domain densely covers the THSPU matrix to achieve low water transmission and high heat reflection, and effectively heat preservation. In the hot and humid state, the THSPU layer forms a micro-hook due to the expansion of water absorption, and the Ag domain is dispersed, promoting sweat evaporation, heat radiation and air convection to achieve cooling.

Conclusion and outlook

With the gradual depletion of energy resources, the development and integration of radiative thermal modulating textiles in wearable electronics have garnered increasing attention and experienced significant growth in the areas of energy saving and smart wearables. Emphasizing human body's thermal comfort and integrated textiles provides innovation sources for designing high-performance PTM smart textiles. This work offers a comprehensive understanding of recent advances in radiative modulating smart textiles for PTM, investigating the interplay between heat models, function-oriented design strategies, and numerous applications in recent years due to these remarkable developments. Firstly, the basic concepts of radiative heat transfer pathways and principles of radiative thermal regulation are analyzed. For radiative cooling, we summarize smart textiles including IR transparent materials, high IR emissive materials, and solar reflective materials. For radiative heating, we also review the smart textiles including IR reflective materials, low IR emissive and solar absorptive materials. Additionally, in view of the requirements for the individual thermal management, we provide an in-depth discussion on the design strategies of smart textile systems for both heating and cooling. Furthermore, Janus radiative textiles, which offer both cooling and

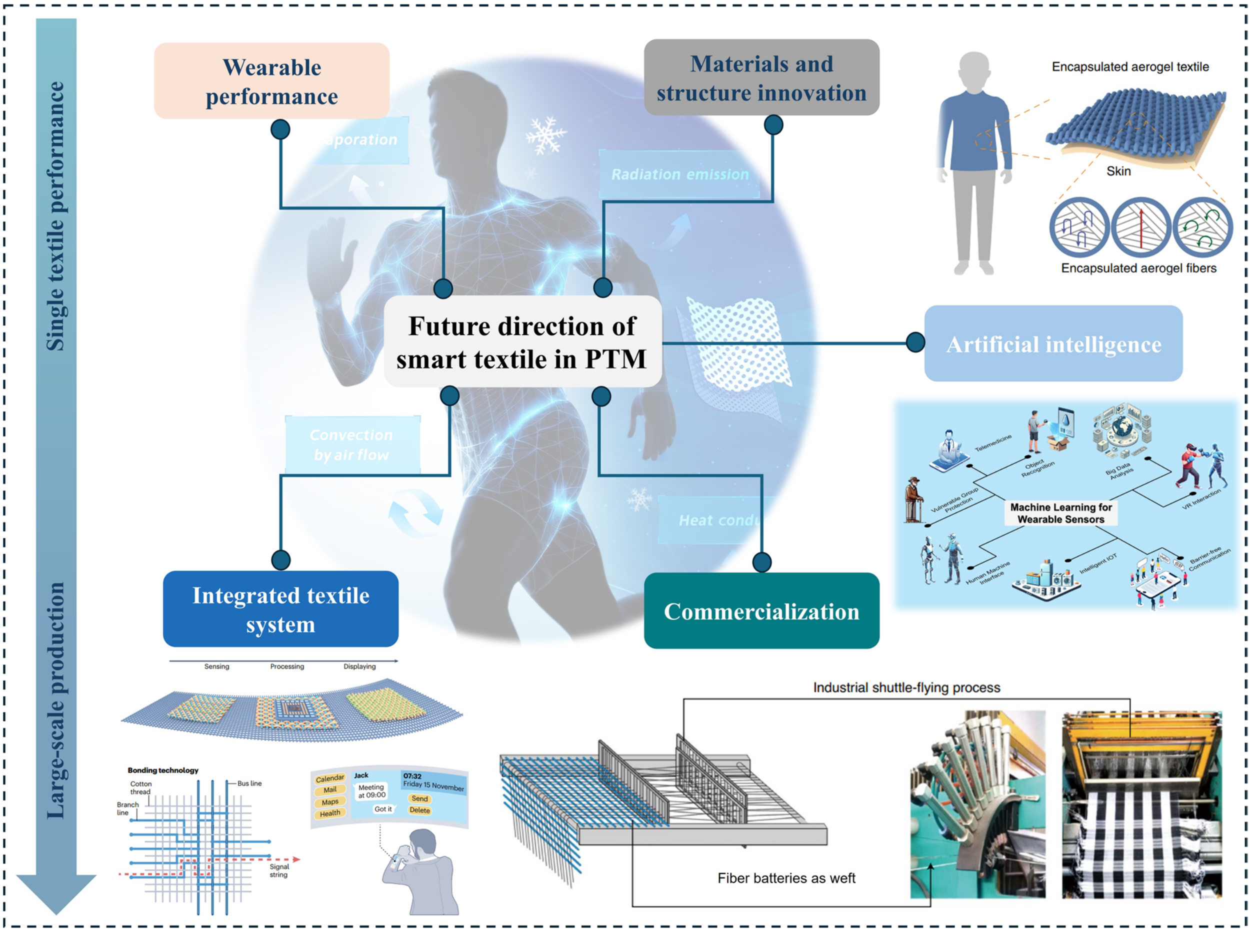

Fig. 12 Schematic of future direction of smart textile in personalized thermal management, including wearable performance, material and structure innovation, artificial intelligence, integrated textile system and industrialization [182–185]

heating functions through flipping, have been reported, and the responsive smart textiles have also demonstrated promising solutions for PTM. In conclusion, these crucial advances in PTM show considerable promise in the development of PTM, offering an in-depth understanding of the current research, models, modulating mechanisms, and exploratory approaches. Despite the rapid progress in radiative modulating smart textiles, numerous efforts are still required to achieve industrialization and widespread adoption. Looking forward, there are still challenges related to infrared radiative modulating textiles for PTM which need to be addressed. These challenges will be discussed as follows in Fig. 12.

Wearable performances

Textile industry often faces the challenge of achieving a well-balance combination of thermal comfort and wearable comfort. For commercial clothing, the wearable properties including mechanical strength, moisture absorption, softness, breathability, and antibacterial potential, play a significant role in designing comfortable garments. Given the long-term contact of smart textiles with human skin, continuous wear and service reliability are essential to meet comfort, health and safety standards. PTM should not induce any form of skin irritation or inflammation, particularly with prolonged wear. Furthermore, during practical wear, the repeated abrasion between the textiles themselves can occur thousands of times, potentially degrading their performance. Ensuring the practicality of PTM textiles also requires considering their washability, which is often overlooked in numerous studies. During laundering or dry cleaning, textiles are typically treated with various types of detergents, solvents, and abrasives in a liquid medium, which can potentially deteriorate their specific functional micro/nanostructure or functional groups.

Materials and structures innovation

Progress in material science and structural engineering plays a crucial role in PTM technologies. The ongoing search for novel materials and structures in PTM field is essential, with a strong emphasis on scalability and cost-effectiveness in manufacturing. Consequently, optimizing commercial textiles with radiative-related materials is a scalable method to enhance wearable performance. However, the application of nanotechnology necessitates careful consideration of the safety of nanomaterials, as their small size allows them to penetrate human skin, potentially causing adverse health effects [186]. Additionally, the drive towards sustainability is a pivotal stride. As wearable electronics continue to rapidly expand, it becomes increasingly important to consider environmental factors [187]. Emphasizing research into materials that are recyclable and environmentally friendly is essential for promoting a more sustainable future for wearable technologies. Moving forward, the development of more appropriate and safe materials will enable the achievement of both radiative PTM and wearable characteristics, paving the way for significant breakthroughs in the field of PTM smart textiles. Apart from the optimization of PTM materials, different microstructures and advanced designs of radiatively thermal management materials can significantly influence the thermal radiation properties to optimize the thermal emissivity and regulate solar reflectivity, which play a significant role in improving the efficiency of PTM smart textiles.

Function integration and optimization

Radiative modulating represents only a small fraction of the potential technologies available in the field of PTM. Moreover, smart textiles with integrated functions are preferred by individuals, offering features including flexibility, sweat manipulation, air ventilation, Janus heating, energy storage and conversion. The primary objective of PTM is to continually enhance efficiency while advancing towards greater intelligence and system integration. However, there is currently an absence of a comprehensive optimization model for designing textiles tailored to various environments and individual needs. Therefore, beyond basic functions like cooling and warming, integrating diverse wearable technologies such as self-powering, wireless sensing, energy storage and computing is necessary to develop practical and commercial devices for personalized and on-demand PTM applications. Furthermore, the underlying combination of smart textile systems for PTM with Internet of Things and Artificial Intelligence technology, along with innovative fabric microstructures, can pave the way for optimally maintaining thermal conditions and enhancing both convenience and efficiency.

Commercialization

Smart textiles are crafted to cater to the specific demands of consumers and should be made available at a reasonable cost. In recent years, numerous research studies have concentrated on PTM using cutting-edge processing technologies, which are often too expensive and complicated to be widely adopted in the market. Although many textiles have reached factory-level production, there remains a significant gap from the laboratory-scale production to the industry-scale commercialization of PTM textiles. The inefficiencies and complexities of lab manufacturing often hardly align with market production needs. Achieving adaptive thermal management performance must be balanced with considerations such as durability, washability, suitability, and comfort. Thus, some small-sized products, like hats, gloves, etc., are expected to be released to the market in the earlier stage. Besides, advanced manufacturing techniques, moisture/heat transforming mechanisms, progressive weaving methods, and innovative textile structures are required to fabricate a commercialized PTM product. From a long-term perspective, there is still a considerable journey ahead for the future PTM textiles.

Looking ahead, the emphasis on the environmental impact of these technologies is imperative. Research focused on recyclable and biodegradable materials is essential for fostering sustainable surroundings for smart wearables. The pursuit for multifunctionality is a notable advancement; it involves progressing beyond single-purpose PTM to incorporate advanced algorithms and sensing performances. Moreover, the domain of material and structure engineering for radiative PTM in smart wearables is also brimming with potential, offering numerous opportunities and challenges that call for creative approaches. This progression will mark an important leap for wearable devices, which not only maintain thermal comfort but also optimized and versatile, offering a wide array of personalized services.

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Authors' contributions W.Z. and L.C. coordinated data collection, analysis and writing of the manuscript. D. Y.; Y. Q.; J. L.; B. Z.; Y. G. and S. J. helped with figure design and made technical comments. X.Y. initialized and supervised the project. authors contributed to the discussions and revised the manuscript at all stages. The author(s) read and approved the final manuscript.

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Data availability The data that support the findings of this study are available from the corresponding author upon reasonable request.

Declarations

Ethics approval and consent to participate Not applicable.

Consent for publication Yes.

Competing interests There are no conflicts to declare.

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