

Spectrally engineered materials for personal thermoregulation

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Abstract

Thermal management of the human body is essential for maintaining health and comfort. Conventional thermal regulation relies heavily on centralized heating, ventilation and air-conditioning systems, which are energy-intensive and poorly suited to individual thermal needs. Spectrally engineered textile materials are a promising alternative, enabling decentralized, personal thermoregulation with low or zero energy consumption by tailoring radiative heat exchange between the skin and the environment. In this Review, we examine advances in spectrally engineered materials for personal thermoregulation from the perspective of multiscale structural design, with an emphasis on relationships between environmental demands, required spectral properties and multiscale structures. We summarize key features and examples of static and tunable thermoregulation textiles, and we analyse how structural features govern the spectral selectivity and tunability. Finally, we discuss challenges and opportunities for improving spectrum selectivity, adaptive tunability, environmental sustainability and scalable manufacturing to translate spectrally engineered textiles from laboratory demonstrations to real-world applications.

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Introduction

Thermal management of the human body is essential for maintaining comfort, daily activities and overall well-being^{1–8}, especially with the increasing frequency and duration of extreme temperature events driven by climate change. Maintaining the human core body temperature within a narrow physiological range around 37 °C is important for sustaining normal metabolic processes and thermal comfort^{1,2,8}. When the balance between heat gain and heat loss is disrupted, physiological homeostasis cannot be maintained, leading to heat-related illnesses, such as heat stroke, cardiovascular mortality, respiratory illnesses and heat exhaustion^{6,9–14}.

Approaches to maintain thermal comfort and health mostly rely on centralized heating, ventilation and air-conditioning (HVAC) systems, which regulate indoor environments through active heating and cooling^{3,12,14,15}. However, such conventional thermal management systems suffer from several intrinsic limitations. First, HVAC systems are highly energy-intensive, accounting for approximately 40–60% of overall building energy use^{12,16–19}. As electricity generation is still dominated by fossil fuels, this high energy demand substantially contributes to carbon emissions, exacerbating global climate change^{12,16,17}. Second, HVAC systems reject large amounts of waste heat into the outdoor environment, which elevates ambient urban temperatures and intensifies the urban heat island effect^{17,19}. Last, centralized HVAC systems are inherently limited in their ability to accommodate individual variability in thermal perception, making it difficult to achieve personalized thermal comfort^{1,2,6–8,12}. Therefore, advanced thermoregulatory strategies that can adapt to dynamic climates while reducing reliance on energy-intensive cooling and heating systems are urgently needed.

Spectrally engineered textile materials are a promising solution to reduce reliance on centralized HVAC infrastructure and provide adaptive personal thermal comfort under diverse environmental conditions while consuming little or no energy. Such thermoregulation devices regulate radiative heat gain and loss at the skin–environment interface and, therefore, manage the skin temperature. Spectrally engineered materials for personal thermal regulation have been widely developed, with an expanding focus on multifunctionality for extreme application scenarios^{11,12,20–26}. However, the performance and practical implementation of these materials remain largely limited owing to challenges in material discovery and design. Additionally, the structure–property relationships governing spectral properties are not yet fully understood^{1,11}; therefore, efforts are needed to better understand the multiscale structures of thermoregulating materials to enable the design of new materials with ideal spectral properties that are suitable for practical implementation^{1,11}.

In this Review, we examine the multiscale structures of wearable spectrally engineered materials and elucidate the relationships between spectral properties and multiscale structures. First, we discuss optimal spectra for personal cooling and heating in various scenarios based on heat transfer models. Then, we outline the multiscale structures of personal thermoregulation materials, spanning from molecular and microscopic levels to mesoscopic and macroscopic structures, and analyse how structural features at each scale influence spectral behaviour. Next, we summarize reported thermoregulation materials for personal cooling, heating and tunable applications. Finally, we highlight the key challenges and opportunities for future development, including spectrum selectivity, tunability, sustainability and scalability, which are essential for translating spectrally engineered materials from laboratory demonstrations to real-world personal thermoregulation technologies.

Optimal spectrum design in personal thermoregulation

To sustain a stable internal temperature, the human body continuously generates metabolic heat while exchanging thermal energy with the surrounding environment^{1,2,7,8,27–29}. Under normal physiological conditions, the core body temperature is regulated at approximately 37 °C, and skin temperature is typically maintained in the range of 33–35 °C (refs. 1,7,8) (Fig. 1a). Heat is transported from the body core to the skin primarily through blood circulation and tissue heat conduction^{1,7}. As the second skin, textiles have a crucial role in regulating thermal exchange between the human body and the surrounding environment, helping to prevent excessive cold or heat stress.

Thermal exchange between the human body and its surroundings occurs through four pathways: radiation, conduction, convection and evaporation (Fig. 1b,c). For a naked human body under thermoneutral indoor conditions (ambient temperature ≈ 23 °C), radiation accounts for over 60% of total heat loss, whereas evaporation contributes approximately 25%, and convection and conduction together contribute around 15% (refs. 1,28,30). For a clothed body during high-intensity exercise, sweating is progressively activated, and evaporative heat loss can contribute approximately 80% of total heat dissipation, whereas conduction and convection together contribute around 15%, and radiation accounts for only approximately 5% (refs. 2,8,30). Overall, thermal radiation engineering is especially important during static or light activity.

Considering the human skin–textile microsystem as a whole, the net thermal power (P_{total}) can be calculated as

$$P_{\text{total}} = F_{\text{sky}} P_{\text{atm}}(T_{\text{amb}}) + F_{\text{terr}} P_{\text{terr}}(T_{\text{terr}}) + P_{\text{sun}} - P_{\text{cond+conv}} + P_{\text{emit}}(T_{\text{tex}}) \quad (1)$$

P_{atm} and P_{terr} are the thermal radiation absorbed by the textile from downward infrared emission of the atmosphere and surrounding surfaces such as the ground and buildings, respectively, and P_{emit} is the thermal radiation emitted by the textile itself. These values are calculated based on hemispherical spectral radiative power derived from Planck's law, which is a function of the temperatures of the ambient air (T_{amb}), ground (T_{terr}) and textile (T_{tex}), respectively³¹. $P_{\text{cond+conv}}$ is the non-radiative heat transfer between the textile and the surrounding environment through conduction and convection. P_{sun} represents the solar power absorbed by the textile and is calculated for the solar wavelength range ($\lambda = 0.28\text{--}2.5\text{ }\mu\text{m}$) as

$$P_{\text{sun}} = \int_0^\infty \eta A_{\text{sol}} I_{\text{AML5}}(\lambda) d\lambda \quad (2)$$

where A_{sol} is the solar absorptivity and solar irradiance, and I_{AML5} is the global horizontal solar irradiance under AML5 conditions^{32,33}. A conversion factor $\eta = 0.4$ is used to account for the projection from horizontal to vertical illumination.

The view factor describes the fraction of thermal radiation exchanged between a surface and its surroundings, as determined by their relative geometry and orientation^{21,34,35}. Accordingly, F_{sky} and F_{terr} are the view factors towards the sky and terrestrial surroundings, respectively. Unlike rooftop radiative cooling and heating materials that predominantly exchange radiation with the sky, wearable textiles simultaneously interact with the sky and surrounding terrestrial objects. Most textiles worn by a standing person are vertically oriented, and over 50% of the view factors are subtended by terrestrial objects, including buildings and the ground, whose temperature is highly dependent on the solar irradiance²¹. The view factors F_{sky} and F_{terr} are calculated as

$$F_{\text{terr}} = \frac{2}{\pi} \int_0^\varphi \int_0^\beta \cos^2 \theta_1 \cos \theta_2 d\theta_1 d\theta_2 + 0.5 \quad (3)$$

$$F_{\text{sky}} = 1 - F_{\text{terr}} \quad (4)$$

where β and φ are the building elevation and azimuth angles, respectively (Fig. 1d) and θ_1 and θ_2 are the angular variables used for

integration. In an open scenario ($\beta = 0^\circ$, and $\varphi = 0^\circ$), F_{sky} and F_{terr} are both 0.5. In urban environments, as β and φ increase, F_{terr} becomes larger and F_{sky} decreases (Fig. 1e). When assessing cooling and heating power under different solar irradiance intensities, in this Review, we assume a typical urban scenario with $F_{\text{sky}} = 0.4$ and $F_{\text{terr}} = 0.6$. We also assume an atmospheric relative humidity of 10%. Increased humidity

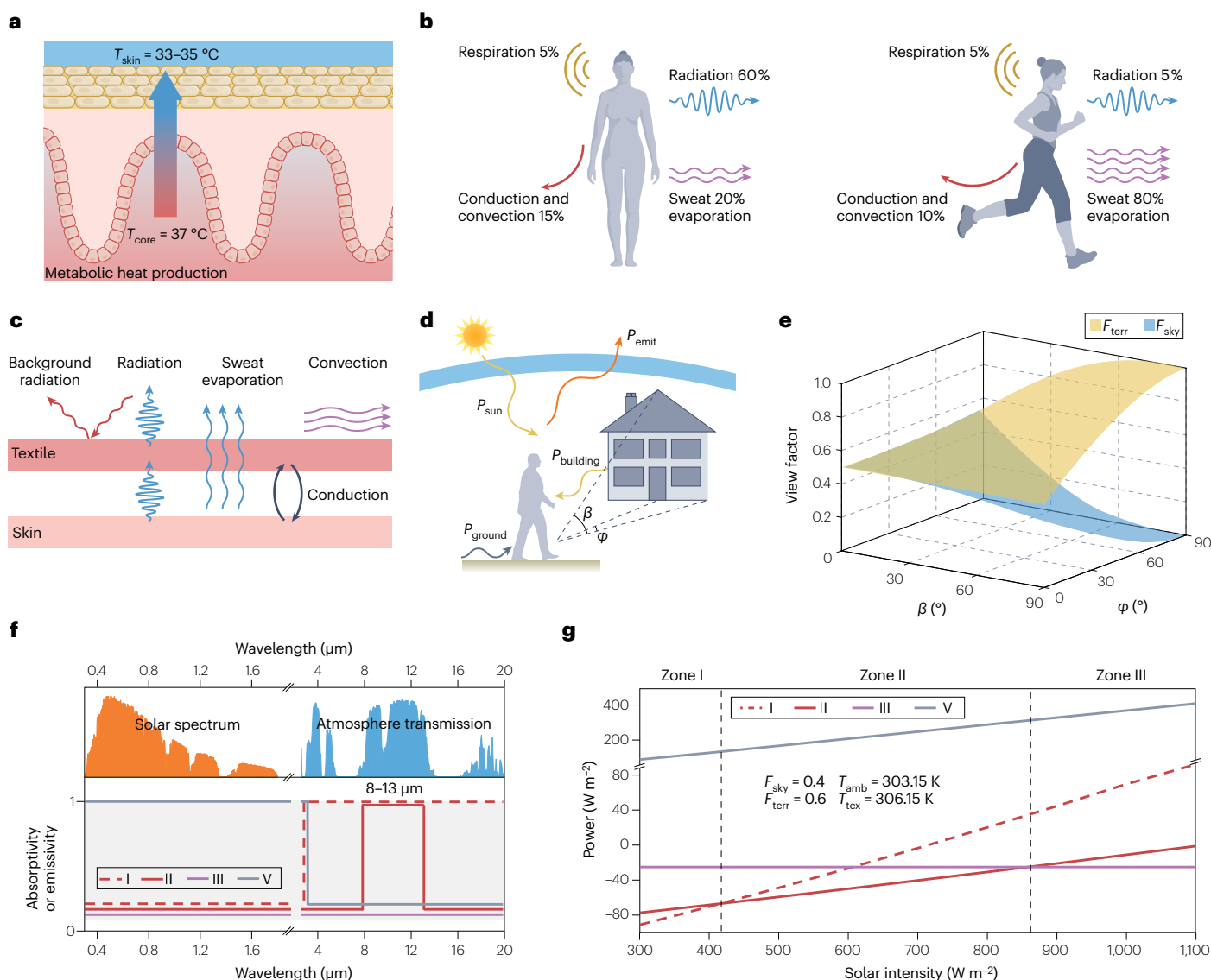
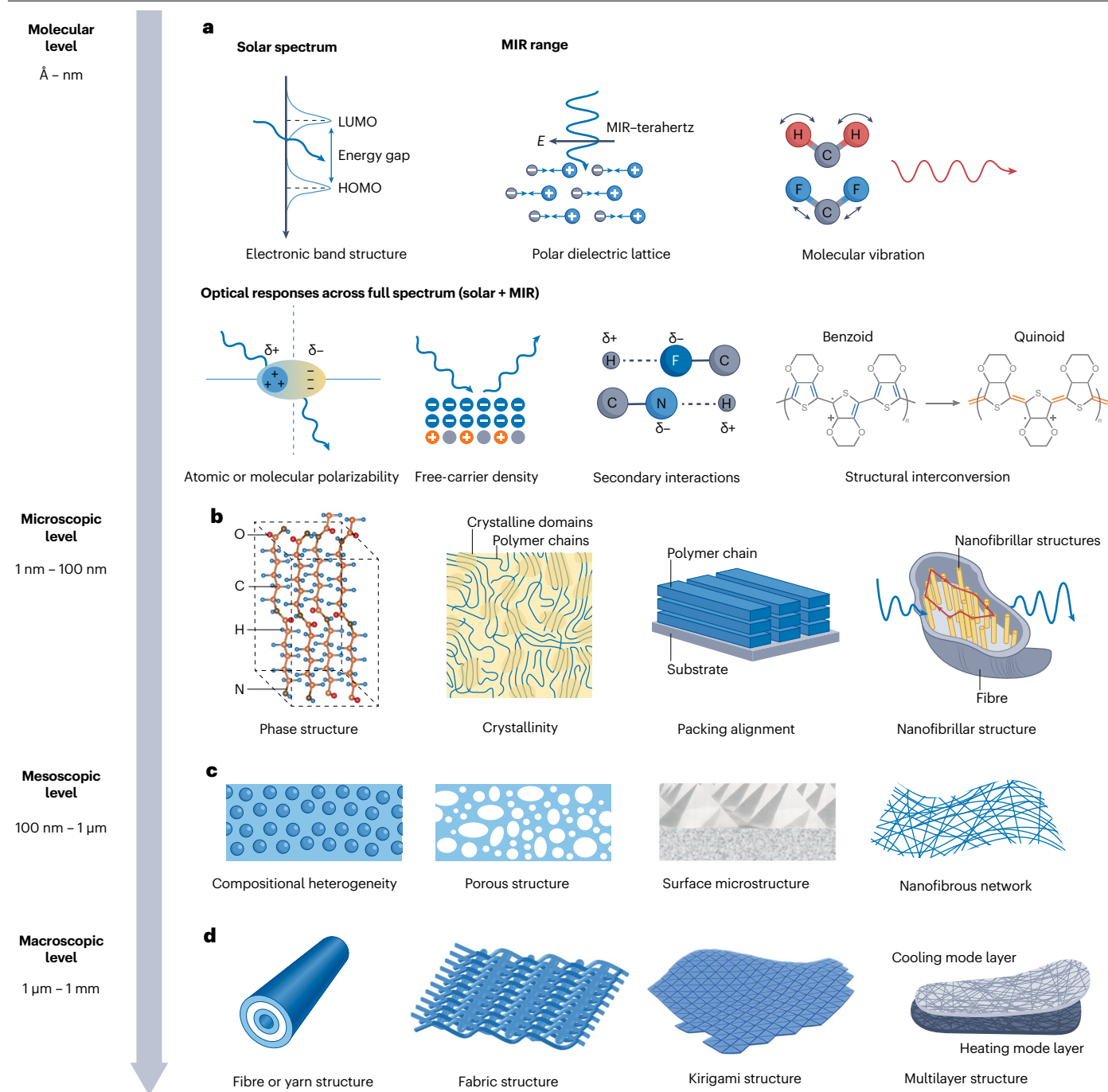


Fig. 1 | Personal thermoregulation enabled by spectral engineering. a, The thermal gradient between core body temperature (T_{core}) and skin temperature (T_{skin}) caused by the exchange of metabolic heat produced by the body with the environment. **b,** Heat exchange pathways between the human body and the surrounding environment and their contributions to total heat loss for a naked body at rest (left) and a clothed body doing exercise (right). **c,** Heat exchange mechanisms between the human skin, textiles and the environment. **d,** The radiation heat gain of a textile in an urban scenario is determined by the thermal radiation absorbed by the textile from the sun (P_{sun}), ground (P_{ground}) and surrounding buildings (P_{building}), and thermal radiation emitted by the textile (P_{emit}). β and φ are the elevation and azimuth building angles, respectively. **e,** View factors from a vertically oriented textile to the terrestrial surroundings (F_{terr}) and the sky (F_{sky}) as a function of the two building angles. **f,** Bottom: representative spectral

emissivity or absorptivity of type I (solar-reflective and broadband-emissive in the mid-infrared (MIR) range), type II (solar-reflective and selectively MIR-emissive), type III (fully reflective across solar and infrared wavelengths) and type V (solar-absorptive and MIR-reflective) thermoregulatory materials. Top: solar spectrum and atmospheric transmission window. **g,** Heating and cooling power of the four types of thermoregulatory material shown in part f under different solar irradiances in which positive power corresponds to net heating and negative power to net cooling. Calculated using equation (1), assuming an ambient air temperature $T_{\text{amb}} = 303.15 \text{ K}$, a textile temperature $T_{\text{tex}} = 306.15 \text{ K}$, $F_{\text{sky}} = 0.4$ and $F_{\text{terr}} = 0.6$. On the basis of the calculated results, the solar irradiance range is divided into three zones: zone I, overcast conditions; zone II, intermediate irradiance; and zone III, extreme solar exposure, as indicated by the black dashed lines. Part b adapted with permission from ref. 1, RSC.



reduces the effective transmission of thermal radiation to outer space, suppressing cooling performance.

Thermoregulation textiles primarily operate across three key spectral regimes (Fig. 1f): the solar spectrum (0.28–2.5 µm), atmospheric transparency window (ATW, 8–13 µm), and non-ATW mid-infrared (MIR) region (2.5–8 µm, 13–20 µm)^{3,11,15,32}. The long-wave infrared (LWIR) region, typically defined as 8–14 µm, largely overlaps with the ATW. In addition to the well-known ATW at 8–13 µm, the atmosphere also exhibits transmittance in the 2.5–5.0 µm and 16–20 µm regions²². Among them, the 8–13 µm window has gained the most attention

because it overlaps with the peak of blackbody emission at around 300 K, allowing radiation to be transmitted through the atmosphere into outer space, which has a temperature of 3 K (refs. 12,22,32,36). By contrast, the 2.5–5.0 µm window makes a limited contribution to radiative thermoregulation because it has minimal overlap with the thermal emission spectrum of the human body, and transmittance in the 16–20 µm region decreases markedly with increasing humidity. Therefore, throughout this Review, ATW refers to the 8–13 µm wavelength range and non-ATW to 2.5–8.0 µm and 13–20 µm wavelength ranges, unless stated otherwise.

Fig. 2 | Multiscale structures of spectrally engineered materials. **a**, Molecular-level structures that govern optical properties at different spectral ranges. The energy gap between the highest occupied molecular orbital (HOMO) and the lowest unoccupied molecular orbital (LUMO) determines the ability of a material to absorb incident solar radiation. Mid-infrared (MIR) optical responses are determined by the relative lattice vibrations in polar dielectric lattices (E is the electric-field direction of the incident electromagnetic radiation) and the vibrational modes associated with specific chemical bonds. Responses across the full optical spectrum are influenced by atomic or molecular polarizability, which determines the refractive index of a material and, hence, the solar reflectance at an interface (δ^+ and δ^- show the positive and negative poles, respectively); the density of free carriers (blue circles), which contributes to the high reflectance of metals; secondary interactions between molecular dipoles (dashed lines); and structural interconversion, such as the transition from a benzoid to quinoid structure triggered by doping, which transforms single bonds into double bonds (shown in orange), increasing MIR reflectivity. **b**, Microscopic-level structures

influence optical responses through phase-separated structures, for example, the γ -phase structure of Nylon 6 in which the chains are aligned parallel to one another has low infrared absorption; crystallinity (the fraction of crystalline and amorphous regions); packing alignment (molecular orientation) of polymer chains on a substrate; and nanofibrillar networks such as nanofibrils that form a quasi-2D disordered scattering network, which produces strong visible and near-infrared reflection. **c**, Mesoscopic architectures control optical responses using compositional heterogeneity, porous structures, surface microstructures and nanostructures, and nanofibre membranes. **d**, Macroscopic textile architectures that influence optical responses include fibre and yarn structures, fabric architectures, and kirigami and multilayer structures. Polar dielectric lattice in part **a** adapted with permission from ref. 46, Wiley. Phase structure in part **b** reprinted from ref. 69, CC BY 4.0. Nanofibrillar structure in part **b** adapted from ref. 77, CC BY 4.0. Kirigami structure in part **d** adapted from ref. 87, CC BY 4.0. Multilayer structure in part **d** adapted with permission from ref. 50, ACS.

Four key optical parameters are considered in spectral engineering: reflectivity (R), absorptivity (A), transmissivity (T) and emissivity (ϵ). Energy conservation requires $R(\lambda) + A(\lambda) + T(\lambda) = 1$ at each wavelength (λ). According to Kirchhoff's law of thermal radiation, under thermal equilibrium, the emissivity of a material equals its spectral absorptance $A(\lambda) = \epsilon(\lambda)$ (ref. 37). These properties are wavelength dependent and can be specified for different spectral regions using subscripts (for example, ϵ_{LWIR} denotes emissivity within the LWIR region).

On the basis of these considerations, there are five idealized classes of spectrally engineered materials (Fig. 1f). Type I materials are solar-reflective and broadband MIR-emissive, exhibiting near-unity reflectance ($R \approx 1$) across the solar spectrum ($\lambda = 0.28\text{--}2.5\ \mu\text{m}$) and high emissivity ($\epsilon \approx 1$) throughout the MIR region ($\lambda = 2.5\text{--}20\ \mu\text{m}$). Type II materials are solar-reflective but selectively MIR-emissive, reflecting nearly all incident solar radiation while emitting thermal radiation predominantly within the ATW ($\epsilon \approx 1$ at $\lambda = 8\text{--}13\ \mu\text{m}$). Type III materials are fully reflective across solar and infrared wavelengths ($R \approx 1$ at $\lambda = 0.28\text{--}20\ \mu\text{m}$). Type IV materials are MIR-transparent ($T \approx 1$ at $\lambda = 8\text{--}20\ \mu\text{m}$), enabling thermal radiation to pass through the textile and dissipate into the environment. Type V materials correspond to radiative heating systems^{5,6,38} and strongly absorb incident solar radiation ($R \approx 0$ at $\lambda = 0.28\text{--}2.5\ \mu\text{m}$) while suppressing thermal emission in the infrared ($\epsilon \approx 0$ at $\lambda = 2.5\text{--}20\ \mu\text{m}$). Although an ideal type V design involves full band spectral regulation, many practical materials achieve heating by selectively tuning only part of the spectrum. For example, visibly transparent and MIR-reflective materials represent an important subclass³⁹.

Equation (1) can be used to compare the net heating or cooling power of different types of vertically oriented textile under varying solar irradiance (Fig. 1g). Type IV materials are not included in this comparison, as their thermal regulation mechanism primarily relies on transmitting human-body thermal radiation in the MIR region, rather than interacting directly with solar irradiation. For heating purposes, type V materials perform the best with heating power increasing with enhanced solar intensity. By contrast, the performance of most cooling materials (except type III materials) in an outdoor environment decreases as solar irradiance increases. The descending rate differs substantially with irradiance conditions. Under overcast conditions ($P_{\text{sun}} < 497\ \text{W m}^{-2}$; zone I), type I materials exhibit the strongest cooling performance. In the intermediate irradiance regime ($497\ \text{W m}^{-2} < P_{\text{sun}} < 863\ \text{W m}^{-2}$; zone II), type II materials

provide the highest cooling efficiency. Under extreme solar exposure ($P_{\text{sun}} > 863\ \text{W m}^{-2}$; zone III), the building and ground temperatures increase dramatically, and type III materials become the most effective option.

Scenario-driven spectral design strategies can be fundamentally categorized according to cooling and heating functionalities. For cooling applications, optical modulation in the solar spectral region ($\lambda \approx 0.28\text{--}2.5\ \mu\text{m}$) follows the relatively universal principle that maximizing solar reflectance is essential to minimize heat gain and achieve high cooling power. By contrast, spectral design in the MIR region ($\lambda \approx 2.5\text{--}20\ \mu\text{m}$) is highly scenario dependent. Although solar radiation does not directly include MIR wavelengths, increased solar irradiance enhances thermal radiation from surrounding environments (for example, ground, buildings and atmosphere), which overlaps with the emission spectrum of the human body. Therefore, MIR emissivity must be carefully tailored according to specific thermal scenarios, and in extreme environments, high reflection of infrared radiation can become advantageous.

For heating applications, the optimal solar spectral design is also well-defined, requiring strong solar absorption to enable efficient photothermal conversion. Under cold conditions in which the human body becomes the dominant heat source, MIR emission must be suppressed (that is, maintaining low emissivity) to reduce radiative heat loss. Under extreme solar irradiation, even materials typically designed for cooling (for example, type I and type II materials) can exhibit net heating behaviour owing to the dominant effect of absorbed solar energy. Therefore, no single spectral design is universally optimal, particularly under dynamically changing thermal environments. Instead, textiles with different spectral characteristics must be strategically coordinated to maintain personal thermal comfort across diverse environmental conditions^{1,2,11}.

Multiscale structures

To ensure flexibility and conformability to the human body, wearable textile materials are mostly organic or organic–inorganic composite materials. Structural formation across multiple length scales has a decisive role in determining the optical characteristics of these materials. This section discusses properties that influence the optical response of spectrally engineered materials and categorizes them into four structural levels^{11,40}: molecular, microscopic, mesoscopic and macroscopic structures, based on their characteristic structural length scales (Fig. 2).

Molecular-level design

At the molecular level, the optical response of materials originates from intrinsic electronic structures and vibrational characteristics, leading to design principles of MIR spectral engineering (Box 1). To establish a physically intuitive framework, the discussion in this section is organized using a spectral regime-based classification, in which molecular-level design principles are discussed according to their influence on the solar spectrum ($\approx 0.28\text{--}2.5\text{ }\mu\text{m}$), the MIR spectrum ($\approx 2.5\text{--}20\text{ }\mu\text{m}$) and across the full spectral range.

Solar optical responses. The electronic band structure of a material directly governs its solar absorption spectrum⁴⁰ (Fig. 2a). Modulation of absorption within the visible region is primarily associated with ground-state to excited-state electronic transitions, which are determined by the bandgap and the density of electronic states. For cooling applications, spectrally engineered materials with large bandgaps display extremely low extinction coefficients (k), where k denotes the imaginary part of the complex refractive index and represents the optical attenuation of the material¹¹. Such materials include non-conjugated polymers, such as polyethylene⁴¹ and polypropylene⁴², as well as inorganic dielectric fillers such as silicon dioxide⁴³. For heating applications, a suitable bandgap ($\approx 1.5\text{--}2.5\text{ eV}$) promotes solar absorption for effective heating. Materials with bandgaps in this range can effectively absorb light in the visible spectrum (400–800 nm), enabling efficient solar energy harvesting and photothermal conversion. Representative examples include conjugated polymers, such as poly(3,4-ethylenedioxythiophene)–polystyrene sulfonate (PEDOT:PSS)⁴⁴, and inorganic systems such as MXenes⁴⁵, which exhibit strong broadband absorption owing to their electronic structure.

MIR optical responses. Inorganic dielectric materials possess long-range crystalline order, equipping them with well-defined collective lattice dynamics and distinctive optical properties^{11,15}. From a spectroscopic perspective, the dielectric function of a material is jointly determined by the atomic species and their spatial arrangement. In polar dielectrics, the relative lattice vibrations of oppositely charged ions give rise to optical phonon modes that can induce a macroscopic oscillating dipole moment⁴⁶ (Fig. 2a). These optical modes, excitation of which is strictly governed by symmetry-imposed selection rules, dominate the MIR optical response. Specifically, the strong coupling between electromagnetic waves and polar optical phonons results in pronounced transverse–longitudinal optical mode splitting and gives rise to a Reststrahlen band, within which the real part of the dielectric permittivity becomes negative. Therefore, crystalline polar dielectrics typically exhibit relatively narrow and well-defined infrared absorption features associated with phonon resonances, reflecting their ordered lattice structure and phonon-mediated optical response^{11,47,48}.

At the molecular level, infrared absorption in polymers is often governed by vibrational modes associated with specific chemical bonds. Different vibrational motions – including stretching, bending, wagging, rocking and twisting – give rise to distinct emission frequencies (Fig. 2a). Even for identical atomic compositions, variations in vibrational modes can result in markedly different spectral features. For example, C–H rocking, wagging and twisting vibrations occur in the 8.3–10 μm , 7.4–8.7 μm and 7.7–8.3 μm ranges, respectively⁴⁹. Thus, specific atomic species and functional groups are often selected to enhance selective emission within the ATW, including C–F bending vibrations ($\approx 7.4\text{--}10\text{ }\mu\text{m}$) and Si–H vibrations ($\approx 10.5\text{--}11.1\text{ }\mu\text{m}$)¹¹. Similarly, poly(4-methylpentene-1) (PMP)²¹ has vibrational modes dominated by

Box 1 | Molecular-level design principles for MIR spectral engineering in cooling materials

Spectral engineering of radiative cooling materials requires simultaneous regulation of optical responses in the solar spectrum and the mid-infrared (MIR) region. In the solar range, the design objective is generally straightforward: minimizing solar absorption to suppress parasitic solar heat gain. By contrast, MIR engineering is strongly dependent on the spectral characteristics required for different cooling or heating strategies and, therefore, requires distinct molecular-level design principles (see the table). These molecular-level design strategies provide structure–property relationships that govern MIR spectral responses and provide the basis for the rational design of spectrally engineered radiative cooling and heating materials.

For type I and type II materials, MIR spectral properties are primarily governed by molecular vibrational modes associated with specific chemical bonds. Type I materials are typically constructed by incorporating multiple infrared-active functional groups to generate broad absorption and emission throughout the MIR region. By contrast, type II materials require selective emission concentrated within the atmospheric transparency window. This spectral selectivity can be achieved through molecular structures containing functional groups with vibrational modes that overlap with the atmospheric window.

For type III and type IV materials, the MIR optical response originates primarily from the intrinsic electronic or molecular structures of the materials themselves. Type III materials are

Materials for MIR spectrum modulation	Targeted MIR spectrum range (μm)	Molecular-level structure design	Example materials
Type I materials (broadband MIR-emissive)	2.5–25	N–H, S–H, O–H, C $\equiv$ C, C=C, C $\equiv$ N, C=O, C=N, C–Cl, C–Br, C–I and S=O bonds	PA, PET, PMMA, PLA and silk
Type II materials (selectively MIR-emissive)	8–13, 16–25	C–O, C–O–C, C–H, C–F, Si–O–Si, Si–H and S=O bonds	PMP, PEO, PVF and POM
Type III materials (MIR-reflective)	2.5–25	High free-electron densities	AgNW, Al, Cu and MXene
Type IV materials (MIR-transparent)	2.5–25	C–C backbone	PE and SEBS

AgNW, silver nanowires; MIR, mid-infrared; PA, polyamide; PE, polyethylene; PEO, polyethylene oxide; PET, polyethylene terephthalate; PLA, polylactic acid; PMMA, poly-methyl methacrylate; PMP, poly(4-methylpentene-1); POM, polyoxymethylene; PVF, polyvinyl formal; SEBS, styrene–ethylene–butylene–styrene.

generally highly conductive metals or inorganic materials with high free-electron densities, which result in strong MIR reflection and low emissivity. By contrast, type IV materials are typically non-conjugated polymers composed mainly of simple carbon–carbon backbones that lack strong infrared-active vibrational modes in the MIR region and, therefore, exhibit high MIR transparency.

C–C (954–1,004 cm⁻¹), –CH₂ (1,176–1,241 cm⁻¹), –CH (862–881 cm⁻¹) and –CH₃ (≈931 cm⁻¹) bonds, which selectively overlap with the ATW. By contrast, for heating applications, molecular design aims to suppress MIR absorption and emission to reduce radiative heat loss, typically by using nonpolar bonds, rigid backbones and symmetric molecular structures, which minimize dipole-active vibrational modes^{45,50}.

Optical responses across full spectrum. According to the Lorentz–Lorenz relation, the refractive index (n) of a material is directly linked to its molecular polarizability¹¹ (Fig. 2a). Polymers are primarily composed of light elements such as C, H, N and O, which possess relatively low number densities of atoms and, thus, low polarizabilities. By contrast, inorganic dielectric materials incorporate metal or metalloid elements with higher polarizability and, therefore, generally exhibit higher refractive indices than polymers ($n \approx 1.5$) and air ($n \approx 1$). Representative examples include barium sulfate (BaSO₄, $n \approx 1.64$)⁵¹, aluminium oxide (Al₂O₃, $n \approx 1.77$)⁵² and titanium dioxide⁵³ (TiO₂, $n \approx 2.74$)⁵³. The reflectance at a planar interface under normal incidence (R) is given by the Fresnel equation⁵⁴:

$$R = \left(\frac{n_1 - n_2}{n_1 + n_2} \right)^2 \quad (5)$$

where n_1 and n_2 are the refractive indices of the two adjoining media with interfacial reflectance increasing with the refractive-index difference $|n_1 - n_2|$ (ref. 55). Therefore, the pronounced refractive-index contrast between inorganic materials and the surrounding air or polymer matrices facilitates efficient scattering of incident sunlight at interfaces, contributing to high solar reflectance (R_{sol}) for effective radiative cooling. For heating applications, refractive-index mismatch and porosity should be minimized to suppress interfacial scattering and reflection, promoting efficient solar absorption⁶.

According to the Drude free-electron gas model, the high density of free electrons in metals enables a strong collective response to an incident electromagnetic field, giving rise to high optical reflectance⁵⁶ (Fig. 2a). The Hagen–Rubens relation states that materials with higher electrical conductivity generally exhibit higher reflectance at long wavelengths; therefore, metallic materials typically exhibit high reflectance across the solar and MIR regions⁵⁷ and are often used as reflective layers in thermoregulatory systems. These reflective layers are integrated with other functional materials to form composite macroscopic architectures for tailored spectral and thermal management^{21,39,58–60}.

Hydrogen bonding, as a key secondary interaction, strongly influences polymer planarity, self-assembled microstructures and vibrational spectral responses⁶¹. Secondary intermolecular interactions refer to noncovalent electrostatic interactions between molecular dipoles or coordination interactions between heteroatoms. For example, hydrogen bonds form between hydrogen donors (for example, –OH and –NH) and electron-rich acceptors⁶¹ (Fig. 2a). Although highly electronegative atoms such as O and N are classical hydrogen bond acceptors, other heteroatoms, including sulfur, can also act as hydrogen bond acceptors, but the interaction is generally weaker^{61,62}. Intramolecular hydrogen bonding can act as a conformational lock in conjugated polymers. For example, in F4BDOPV-2T, intramolecular F–H interactions effectively lock the backbone conformation and induce a redshift in the optical absorption spectrum⁶³. By contrast, intermolecular hydrogen bonding primarily promotes supramolecular self-assembly, which can simultaneously alter spectral features and

enhance mechanical integrity. For example, in a system comprising a blend of poly[(*R,S*)-3-hydroxybutyrate] and catechin⁶⁴, intermolecular catechin–OH...O=C–PHB hydrogen bonds induce a redshift of the carbonyl stretching vibration from approximately 1,739 cm⁻¹ to a hydrogen-bonded peak at approximately 1,713 cm⁻¹.

In conjugated conductive polymers, chemical or electrochemical doping induces structural reorganization, which alters their optical and infrared spectral responses^{65,66}. For example, oxidative doping with iron(III) triggers a transition from an aromatic to a quinoidal backbone configuration, yielding poly(3,4-ethylenedioxythiophene)–tosylate (PEDOT:Tos)^{67,68} (Fig. 2a). Subsequent reversible dedoping decreases the oxidation level and charge-carrier concentration, driving the polymer backbone back towards the aromatic configuration. This structural interconversion not only changes the nature of the chemical bonding along the polymer backbone (for example, by partially transforming single bonds into double bonds), but also substantially increases the charge-carrier concentration and generates new species (such as polarons and bipolarons), leading to increased reflectivity in MIR after doping.

Microscopic-level structures

Microstructures represent an intermediate structural hierarchy that bridges molecular properties and macroscopic optical behaviour. At this level, structural organization beyond individual molecules governs the intrinsic spectroscopic characteristics of materials. Microscopic-level structures primarily determine the spectral intensity and anisotropy, that is, the wavelengths at which and directions in which the material emits or absorbs radiation.

At the microscopic level, ordered molecular arrangements give rise to distinct phase structures (Fig. 2b), providing a route for tailoring infrared emissivity. Different crystalline phases impose distinct spatial arrangements of polymer backbones and intermolecular interactions, which directly modify vibrational force constants and dipole-moment variations associated with infrared-active modes. For example, processing-induced phase regulation can produce Nylon 6 nanofibres with γ phase structure for infrared-transparent radiative cooling textiles⁶⁹. These structures suppress vibrational coherence and dipole coupling, increasing infrared transmittance by 70% relative to the α phase structure, especially in the ATW.

Polymer materials can exhibit different degrees of crystallinity and adopt different microstructures because they comprise long chains of molecules, varying from completely amorphous to highly crystalline domains^{40,70–72}. In crystalline domains, polymer chains exhibit a higher degree of orientational order than in amorphous regions, resulting in anisotropic infrared absorption (Fig. 2b). The fraction of crystalline domains within a polymer, defined as the crystallinity, has a key role in determining its optical properties. For example, the crystallinity of semicrystalline poly(vinyl alcohol) can be quantitatively determined based on the Fourier-transform infrared (FTIR) spectrum⁷⁰. Polymers with lower crystallinity tend to exhibit broadband infrared absorption and emission, whereas semicrystalline or highly crystalline polymers such as PMP have a higher tendency to exhibit selective emissive behaviour²¹.

When conjugated polymers are deposited onto substrates, polymer chains can adopt different anisotropic orientation modes relative to the substrate (Fig. 2b), such as edge-on, face-on and chain-on configurations⁴⁰, which can be quantitatively characterized using polarization-resolved FTIR spectroscopy⁷³. For example, the optical properties of liquid crystal display systems are governed by the

orientational ordering of anisotropic molecules^{74–76}. In the widely used twisted nematic configuration, liquid crystal molecules are aligned by two substrate surfaces with orthogonal alignment directions, forming a helical structure that rotates the polarization of transmitted light in the absence of an electric field^{74,76}. When an electric field is applied, the molecular alignment reorients along the field direction, suppressing polarization rotation and enabling efficient modulation of light transmission. Therefore, molecular packing orientation represents an additional and often overlooked degree of freedom for spectrum engineering in polymer-based thermoregulation textiles.

Many natural fibres (such as cotton and silk) contain nanofibrillar substructures within individual fibres. These nanoscale features primarily influence intrinsic optical properties by modulating local light–matter interactions, thereby affecting the optical spectra of fibres and textiles (Fig. 2b). For example, quasi-parallel protein nanofibrils, based on densely packed native silkworm silk, form a quasi-two-dimensional disordered scattering network that induces Anderson localization of light (that is, the suppression of wave transport arising from multiple coherent scattering and interference in strongly disordered media)⁷⁷. In these nanofibrillar fibres, strong disorder at the mesoscale confines photons in the visible and near-infrared regions, producing strong reflection without the need for intrinsically high-index inorganic components, enabling selective optical properties and efficient radiative cooling.

Mesoscopic-level structures

The spectral performance of thermoregulation textiles is strongly influenced by mesoscopic structural design and light–matter interactions at nanometre to micrometre length scales. Light-scattering effects – such as Mie scattering arising from fibres, pores and hierarchical surface textures – can substantially increase R_{sol} and modulate angular and spectral light distribution. Accordingly, extending design considerations to larger scales is essential for precise control of optical pathways and radiative performance.

Compositional heterogeneity in inorganic–organic hybrid composites offers a balance between spectral properties and mechanical flexibility (Fig. 2c). On the basis of the refractive index difference between material components at the molecular level, equation (5) underscores compositional heterogeneity with large refractive index contrast as a fundamental driver of optical reflection. Inorganic materials can be incorporated as nanoscale dopants into polymer fibres to improve mechanical properties while preserving their optical performance. For example, a hierarchical-morphology metafabric based on a hybrid composite uses size-distributed TiO_2 nanoparticles embedded in a polymeric polylactic acid matrix⁵³ to achieve a high $R_{\text{sol}} \approx 92.4\%$. Wider-band-gap nanoparticles can also be used to reduce parasitic solar absorption. For example, BaSO_4 nanoparticles (approximately 400 nm)⁵¹, which exhibit strong Mie scattering, have been incorporated into a porous ethyl cellulose matrix to produce a high $R_{\text{sol}} \approx 98.6\%$.

Porous structural engineering (Fig. 2c) introduces abundant material–air interfaces with pore sizes tailored to the ultraviolet–visible–near-infrared (UV–vis–NIR) region to increase interfacial reflections and Mie scattering, suppressing solar energy absorption. For example, a poly(vinylidene fluoride-co-hexafluoropropene) coating with coupled microporous and nanoporous architectures fabricated via a phase-inversion process⁷⁸ has strong broadband solar reflection ($R_{\text{sol}} \approx 96\%$) and high $\epsilon_{\text{LWIR}} \approx 97\%$, owing to collective Mie scattering and diffuse backscattering. In another example, a hierarchically structured poly-methyl methacrylate (PMMA) film was fabricated by selectively

removing ordered SiO_2 arrays⁷⁹. The resulting film features symmetric micropores with diameters of approximately 4.6 μm and randomized nanopores with average diameters around 250 nm, achieving $R_{\text{sol}} \approx 95\%$ and $\epsilon_{\text{LWIR}} \approx 98\%$. Similarly, a polydimethylsiloxane film incorporating built-in three-dimensional microvoid arrays via sacrificial templating exhibits desirable spectral properties, with $R_{\text{sol}} \approx 93.4\%$ and $\epsilon_{\text{LWIR}} \approx 95\%$ (ref. 80).

In thermal management devices, surface microstructures define the interface between the material and ambient air and constitute the first point of interaction with incident solar radiation. Consequently, tailoring the surface microstructure can regulate solar reflectance through geometry-induced scattering^{52,59,81}. For example, wrinkled surfaces can introduce quasiperiodic corrugations with characteristic wavelengths comparable to visible and near-infrared solar wavelengths, promoting diffuse scattering and angular redistribution of sunlight while maintaining a high overall solar reflectance ($R_{\text{sol}} > 90\%$)⁵⁹. Additionally, polymer matrices incorporating replicated micropyramid arrays create gradual refractive-index transitions and multiple internal reflection pathways (Fig. 2c), which suppress specular reflection and enhance dielectric scattering across the solar spectrum, yielding high solar reflectance values of approximately $R_{\text{sol}} \approx 95\%$ (ref. 52).

Nanofibre-based architectures operate at larger length scales than natural fibre microstructures and the strong refractive-index contrast at nanofibre–air interfaces enables efficient Mie scattering across the solar spectrum (Fig. 2c). For example, an electrospun polyethylene oxide (es-PEO) nanofibre film, which has intrinsically low A_{sol} , achieves highly efficient solar reflection, minimizing solar heat gain for personal thermal regulation⁸². These properties are achieved through the hierarchical order of the fibrous network, whereby the PEO nanofibres exhibit a diameter distribution predominantly in the range of approximately 500–1,200 nm (centred at approximately 730 ± 120 nm), which closely matches the characteristic wavelengths of the solar spectrum spanning the visible and near-infrared regions (0.28–2.5 μm). Additionally, the random orientation and multilayered stacking of the fibres cause incident sunlight to undergo multiple forward and lateral scattering events within the fibrous network.

Macroscopic-level structures

To realize wearable thermoregulatory systems, spectrally engineered materials need to be ultimately integrated into wearable architectures that are conformable to the human body. It is, therefore, important to consider macroscopic-level design, typically from micrometres to millimetres^{1,83,84}. Hierarchical textile structures not only determine wearability, human body conformability and mechanical robustness, but also regulate radiative and non-radiative heat transfer between the human body, textile and surrounding environment.

Spectrally engineered functionalities can be incorporated into a single one-dimensional fibre or yarn through compositional and structural design (Fig. 2d). Multicomponent fibre architectures, such as coaxial (core–shell) fibres⁸⁵ and twisted or braided yarns⁸⁶, could enable the integration of emissive, functional and transparent layers. Such structures can be fabricated via spray-coating, coaxial spinning, twisting, braiding or 3D printing⁵. Alternative designs, including blended fibres and hollow fibres, further expand the design space for tailoring optical and thermal properties^{1,84}.

Assemblies of one-dimensional functional fibres and yarns define mechanical performance and collective optical responses at the fabric scale (Fig. 2d). At this level, one-dimensional fibres can be organized into different textile architectures through weaving or knitting. In

woven structures, fibres serve as warp and weft yarns and are interlaced orthogonally on a loom, forming ordered and mechanically robust networks. By contrast, knitted structures are formed by interlocking fibre loops, resulting in more flexible and stretchable textiles. Knitted textiles normally have higher porosity and lower opacity ($1 - \text{transmission}$) over the entire visible range than woven textiles. For example, woven and knitted radiative-cooling textiles fabricated from industry-standard particle-free, nonporous microstructured polyethylene and polypropylene fibres achieve opacities of 75% and 99%, respectively⁴². Key textile properties – including breathability, moisture transport and softness – must be simultaneously optimized to ensure overall thermal comfort.

Kirigami structures provide an effective macroscopic design strategy for tuning the mechanical and optical properties of wearable systems^{87,88}. By introducing predefined cut patterns, planar membrane materials can achieve high stretchability and conformal adaptability, enabling intimate contact with complex, curved human body surfaces such as joints (Fig. 2d). For example, a wearable variable-emittance device uses laser-defined kirigami patterns to achieve scalable and precise fabrication while accommodating diverse body geometries⁸⁷. Another kirigami system undergoes reversible out-of-plane deformation upon stretching, progressively opening to conform to the skin morphology while preserving structural integrity and device functionality⁸⁸. These mechanically reconfigurable architectures have potential to dynamically control the exposure of silver nanowires, enabling effective ϵ_{MIR} switching of approximately 50% with minimal energy input.

Fully integrated textile systems at the fabric scale enable practical wearable applications (Fig. 2d). Multilayer fabric architectures can be engineered for dual-mode thermoregulation^{50,89}. For example, a single fabric was developed that integrates a BaSO₄ layer, which offers high solar reflectance ($R_{\text{sol}} \approx 96\%$) and strong MIR emissivity ($\epsilon_{\text{MIR}} \approx 92\%$) for radiative cooling, and a carbon-black layer, which has high solar absorptivity ($A_{\text{sol}} \approx 91\%$) for efficient photothermal heating⁵⁰. Thus, the exposed functional layer can be switched by flipping the textile to deliver either heating or cooling, enabling spectrally programmable thermal regulation within one wearable system. These macroscopic design strategies bridge the gap between material-level spectral engineering and real-world wearable performance^{21,89}.

Structural characteristics at smaller scales are often inherited and propagated to larger scales. For example, microscopic phase structures, such as the γ -phase in Nylon 6, originate from hydrogen-bond-driven molecular self-assembly, and compositional heterogeneity can be traced back to differences in atomic polarizability at the molecular level, which manifest as refractive-index contrast and Mie scattering in larger (mesoscopic) length scales⁶⁹. This hierarchical coupling highlights the intrinsic linkage between molecular design and macroscopic optical performance. Therefore, a multiscale structural design strategy is needed in which different structural levels have distinct yet interconnected roles. In such a strategy at the molecular level, materials are screened according to their intrinsic spectral properties; at the microscopic level, structural modulation is performed through processing strategies, including alignment, crystallization and processing conditions; at the mesoscopic and macroscopic levels, compositional and structural engineering defines device architectures and determines the overall optical response. Building on this understanding, the rational design of spectrally engineered materials can be guided by a bottom-up strategy from molecular screening to device-level engineering.

Spectrally engineered materials for static thermoregulation

This section summarizes progress in radiative cooling and heating materials for personal thermoregulation.

Static cooling materials

Static radiative cooling materials can be systematically understood through their spectral selectivity across the solar and MIR regimes. Type I–IV materials share a common design paradigm: achieving high solar reflectance while using multiscale structural engineering to tailor spectral selectivity in the MIR regime, thereby maximizing cooling performance under different thermal scenarios. Under certain scenarios – such as strong solar radiation (zone III in Fig. 1g), fire exposure, outdoor high-temperature operations, or dense urban environments where tall buildings substantially reduce the sky view factor – radiative exchange with the sky becomes limited, and heat fluxes reflected from surrounding surfaces, including the ground and nearby buildings, can dominate the thermal stress. Under these conditions, type III materials, which reflect both solar and MIR radiation, are beneficial; however, these conditions are not frequently considered in current research. Therefore, this Review primarily concentrates on the other three categories of radiative cooling materials.

Solar-reflective and broadband MIR-emissive materials. Solar-reflective materials with broadband MIR emissivity (type I) are the most extensively explored class of radiative cooling materials. By simultaneously suppressing solar absorption and approximating blackbody-like thermal emission across the MIR region, these materials maximize net radiative heat loss to the cold sky under a wide range of environmental conditions.

PMMA is a representative type I radiative cooling material (Fig. 3a). In the MIR region, intrinsic molecular-level vibrational modes of PMMA, particularly C–O–C stretching vibrations between 770 and 1,250 cm^{−1}, give rise to strong infrared absorption within the ATW. In the solar region, hierarchically porous PMMA films exhibit strong solar back-scattering with high $R_{\text{sol}} \approx 95\%$, achieving approximately 6.0–8.9 °C sub-ambient cooling under midday sunlight⁷⁹.

A subset of organic type I materials derive their performance from mesoscopic-level structural engineering. For example, a nano-processed silk textile, in which ~300-nm Al₂O₃ nanoparticles are introduced into the hierarchical silk fibre network through a tetrabutyl titanate-assisted dip-coating process⁹⁰, achieves high solar reflectance ($R_{\text{sol}} \approx 95\%$) and preserves the intrinsically high emissivity ($\epsilon_{\text{LWIR}} \approx 90\%$). These properties enable sub-ambient daytime radiative cooling (approximately 3.5 °C below ambient temperature) without compromising the breathability, flexibility and wearability of the textile. Additionally, electrospun silk nanotextiles (Fig. 3a) achieved ultrahigh solar reflectance ($R_{\text{sol}} \approx 96.5\%$) via strong Mie scattering from randomly oriented nanofibres and micropores, and intrinsic molecular vibrations yield near-blackbody infrared emissivity ($\epsilon_{\text{LWIR}} \approx 97.1\%$)⁹¹.

Inorganic materials with high refractive indices and wide electronic bandgaps provide an alternative route to broadband radiative cooling by maximizing solar scattering while minimizing intrinsic absorption. For example, in a hierarchical TiO₂-based metafabric⁵³ (Fig. 3a), the TiO₂ nanoparticles provide strong solar scattering, and polymer components contribute broadband MIR emission, enabling sub-ambient cooling approximately 4.8 °C below that of commercial cotton fabric. In other examples, Al₂O₃ nanoparticles^{52,92} exhibit negligible solar absorption as phonon resonances of Al₂O₃ further

Cooling materials

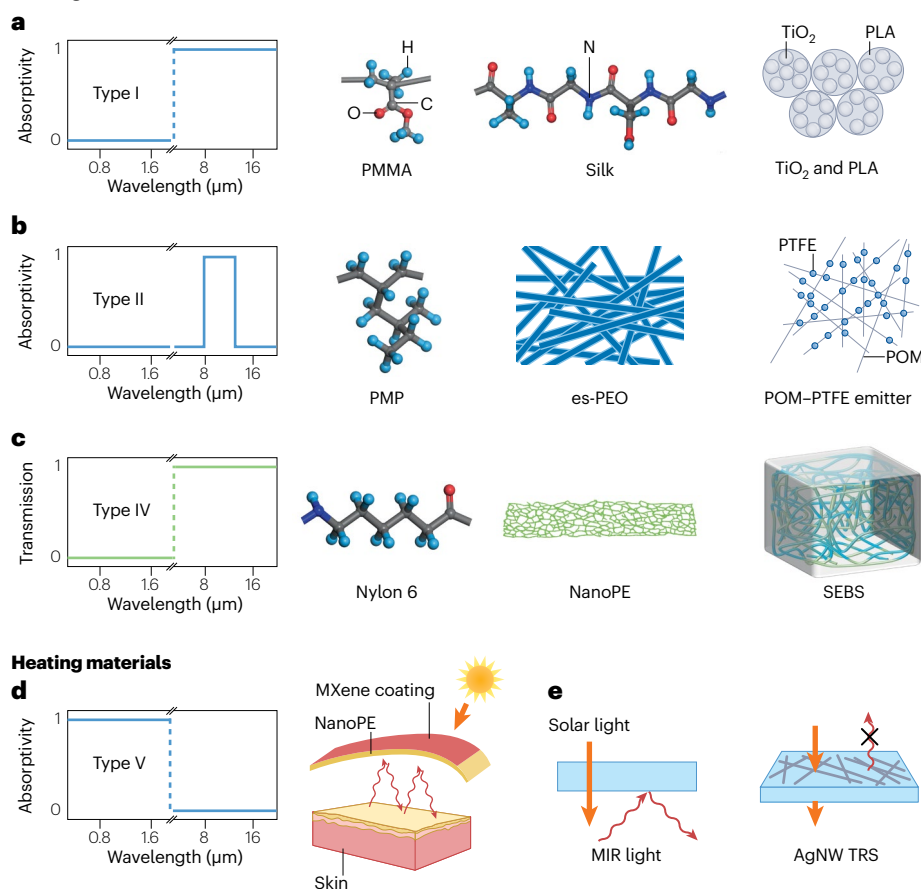


Fig. 3 | Ideal spectra and representative spectrally engineered materials for static cooling or heating. **a**, The ideal absorptivity spectrum of type I (solar-reflective, broadband mid-infrared (MIR)-emissive) materials and examples of such materials, including poly-methyl methacrylate (PMMA) polymer structures⁷⁹, fibrous silk textiles⁹¹ and a composite of TiO₂ nanoparticles embedded in a polylactic acid (PLA) matrix⁵³. **b**, Ideal absorptivity spectrum of type II (solar-reflective, selectively MIR-emissive) materials and representative examples, including a polymethylpentene (PMP)-based selective hierarchical fabric²¹, electrospun polyethylene oxide (es-PEO)⁸² and polyoxymethylene-polytetrafluoroethylene (POM-PTFE) emitter²². **c**, Ideal transmission spectrum of type IV (MIR-transparent materials) and representative examples, including infrared transparent Nylon 6 (ref. 69), nanoporous polyethylene (nanoPE)⁴¹ and

styrene-ethylene-butylene-styrene (SEBS) materials^{50,98,99}. **d**, Ideal absorptivity spectrum of type V heating materials that are solar-absorptive and have low emissivity in the MIR range and an example nanoPE textile coated by Ti₃C₂T_x MXene⁴⁵. **e**, A schematic of a heating material that is transparent to visible light and has high reflectivity and low emissivity in the MIR range and an example transparent radiation shield (TRS) based on a silver nanowire (AgNW) network³⁹. TiO₂ and PLA in part **a** adapted with permission from ref. 53, AAAS. es-PEO in part **b** adapted from ref. 82, Springer Nature Limited. POM-PTFE emitter in part **b** adapted from ref. 22, CC BY 4.0. nanoPE in part **c** adapted with permission from ref. 41, AAAS. MXene coating in part **d** adapted with permission from ref. 45, ACS. AgNW TRS in part **e** adapted with permission from ref. 39, ACS.

increase broadband infrared emissivity, yielding ϵ_{MIR} values over 96% (ref. 52). Optimized BaSO₄ nanoparticles (approximately 400 nm) combined with hierarchically porous polymer binders produce high $R_{\text{sol}} \approx 98.6\%$ alongside near-blackbody $\epsilon_{\text{LWIR}} \approx 98.1\%$ (ref. 51). Additionally, MgO-based paints provide broadband phonon-polariton resonances to achieve high $R_{\text{sol}} \approx 95\%$ and $\epsilon_{\text{MIR}} \approx 93\%$ (ref. 93).

A distinct class of radiative cooling materials was designed primarily for infrared camouflage, exhibiting low emissivity in the 3–5 μm and 8–14 μm regions for infrared concealment, while maintaining selective high emissivity in the 5–8 μm region to mitigate heat accumulation^{94,95}. For example, a ZnS-Ge multilayer emitter achieves $\epsilon \approx 11\%$ in the 3–5 μm and 8–14 μm regions and $\epsilon \approx 61\%$ in the

5–8 μm region, resulting in infrared signal reduction of up to 53.4% and a surface temperature decrease of approximately 5.9 °C with a heat source of 2,500 W m⁻² power density compared with Cr – a broadband low-emittance material⁹⁴. Similarly, a metal-polymer bilayer film known as X-film, comprising aluminium and polyamide 66 (ref. 95) exhibits high reflectance ($R \approx 80\%$) within the 3–5 μm and 8–14 μm regions and laser bands of 10.6 μm , and polyamide 66 promotes selective thermal emission ($\epsilon \approx 70\%$) within the 5–8 μm and 14–20 μm regions, enabling efficient radiative heat dissipation. Owing to its randomly stacked nanofibrous architecture, the X-film maintains effective infrared camouflage over a broad viewing-angle range (–60° to 60°) with weak angular dependence, while achieving

a surface temperature reduction of approximately 5–10 °C compared with an aluminium foil reference.

Type I materials represent the most mature class of spectrally engineered thermoregulatory textiles, and their spectral properties already approach ideal targets, with R_{sol} often exceeding 95% and ϵ_{MIR} approaching unity. Despite the diversity of material systems – including polymer textiles and polymer–inorganic particle composites – their performance consistently relies on two key design principles: multiscale structural engineering to enhance solar reflectance via Mie scattering, and intrinsic molecular or lattice vibrations to enable broadband MIR emissivity. Future developments might rely less on further improvements in intrinsic spectral performance and more on addressing practical deployment challenges. Many high-performance cooling textiles achieve their optical properties through increased material loading or multilayer architectures, resulting in higher areal densities than conventional summer garments^{52,53,91}. Consequently, lightweight textile engineering should be a key focus for future development. Strategies such as porous fibre engineering and fabric dewetting treatments might enable high cooling performance while reducing areal density and improving wearer comfort^{79,80}.

Solar-reflective and selectively MIR-emissive materials. Solar-reflective, selectively MIR-emissive (type II) materials exhibit effective radiative cooling performances, especially in urban scenarios. By confining thermal emission to the ATW, these materials maximize radiative heat rejection to the cold sky and minimize parasitic infrared heat gain from the environment. The selectively high emissivity within the ATW is primarily derived from the molecular vibrations of specific functional groups in polymeric materials at the molecular level (Box 1). By contrast, the high R_{sol} required across the solar spectrum is typically achieved through mesoscopic-level and macroscopic-level structural engineering, such as porous architectures, hierarchical scattering structures and textile-scale optical designs that enhance solar backscattering.

An MIR spectrally selective hierarchical fabric, which contains a PMP fibrous layer, a silver nanowire (AgNW) layer and a high-emissivity fabric, has demonstrated radiative cooling in urban environments²¹. In the MIR range, the intrinsic vibrational modes of PMP predominantly confine emissivity to the ATW, with an average $\epsilon_{\text{LWIR}} \approx 85\%$. The AgNW with high MIR reflectivity prevents the transmission of thermal radiation from the environment to the skin. The MIR spectral selectivity of this fabric is quantified by the selective ratio, defined as the ratio of average emissivity within ATW to that outside the ATW, with a value of 2.23. In the solar wavelength range, the mesoscopic fibrous PMP layer (Fig. 3b), composed of a hybrid of nanoscale and microscale fibres, induces strong Mie scattering, yielding a high $R_{\text{sol}} \approx 97\%$. In outdoor conditions, this fabric achieved sub-ambient cooling of approximately 6.2 °C under peak solar irradiance and nighttime cooling exceeding 12 °C.

PEO is also MIR spectrum-selective because the C–O–C and C–OH bonding vibrations enable selective emissivity in the ATW^{82,96}. In a selective-emissive radiative-cooling es-PEO nanofibre film⁸² (Fig. 3b), the randomly stacked nanofibrous network efficiently scatters solar radiation ($R_{\text{sol}} > 96.3\%$), while emissivity is concentrated within the ATW ($\epsilon_{\text{LWIR}} \approx 78\%$) and suppressed outside this range. Consequently, this film achieves approximately 5 °C sub-ambient cooling under sunlight.

Beyond mono-selective emitters that have high emissivity in the main atmospheric window in 8–13 μm , dual-selective thermal emitters have emerged as an advanced strategy to further exploit the radiative cooling potential of MIR spectrum. A scalable dual-selective radiative

cooling emitter made from polyoxymethylene (POM) and polytetrafluoroethylene (PTFE) simultaneously exhibits high emissivity at both 8–13 μm and 16–25 μm regions²² (Fig. 3b). The emitter consists of a disordered stack of bead-like fibres composed of nanoscale POM fibres and microscale PTFE particles. This structure achieves the dual-window selectivity through a synergistic molecular and structural design, in which C–O–C vibrational modes in POM dominate emission in the 8–13 μm range, and C–F vibrations in PTFE selectively activate emission within the 16–25 μm window. Additionally, the hierarchically disordered nanofibrous–microparticle architecture enables the emitter to reach emissivities of $\epsilon_{\text{window1}} \approx 83\%$ and $\epsilon_{\text{window2}} \approx 68\%$ in the two atmospheric windows. Consequently, the dual-selective emitter achieves sub-ambient cooling of approximately 9 °C under strong solar irradiation ($>700 \text{ W m}^{-2}$), substantially outperforming mono-selective and non-selective counterparts, particularly in arid climates.

Although type II materials can theoretically provide higher cooling power than type I broadband emitters in urban scenarios under high solar intensity, existing strategies typically require complex textile architectures, which often rely on electrospinning-based fabrication. Consequently, most reported type II textiles remain at the proof-of-concept stage. Although electrospinning could be considered as a scalable manufacturing technology, the resulting nonwoven structures often exhibit limited mechanical robustness, washability and abrasion resistance compared with conventional textile products^{21,82}. Future efforts should focus on exploring the use of fibre spinning, yarn engineering and weaving technologies to produce spectrally selective textiles with improved mechanical durability, washability and wearer comfort^{1,5}.

MIR transparent materials. MIR transparent materials (type IV) represent a distinct class of spectrally engineered cooling materials that suppress solar heat gain while enabling direct transmission of thermal radiation from underlying high-emissivity objects, rather than radiating heat themselves. These materials typically achieve high solar reflectance through mesoscopic structural engineering, including porous architectures and scattering structures that efficiently reflect incident solar radiation. By contrast, their infrared transparency primarily originates from simple molecular structures with low vibrational absorption in the MIR region, such as the $-\text{CH}_2-\text{CH}_2-$ backbone found in polyethylene-based materials (Box 1).

Nanoporous polyethylene (nanoPE) is a prototypical example of a type IV material^{41,97} (Fig. 3c), which can enable passive personal cooling by allowing efficient transmission of MIR radiation emitted from the human body. By engineering pore sizes on the scale of visible wavelengths but far below those of thermal infrared radiation, the textile is opaque to visible light yet has a high MIR transmittance of approximately 96% in the 7–14 μm range. Consequently, nanoPE enhances radiative heat dissipation, reducing the temperature of skin by approximately 2–3 °C compared with cotton fabrics, while maintaining air permeability, mechanical robustness and wearability comparable to conventional textiles. Similarly, Nylon 6 (PA6) textiles minimize MIR absorption, particularly at approximately 9–10 μm in which human thermal emission is strongest⁶⁹ (Fig. 3c). The resulting infrared-transparent PA6 textiles can reduce body temperature by approximately 2–3 °C relative to conventional nylon and cotton fabrics.

Styrene–ethylene–butylene–styrene (SEBS) elastomers are widely used as infrared-transparent and mechanically compliant functional layers in advanced thermal-management systems^{60,98,99} (Fig. 3c). In transmission-type radiative cooling films and wearable devices,

SEBS is often integrated as a flexible superstrate or encapsulation layer that preserves infrared transparency while imparting mechanical robustness, durability and adaptability to complex surfaces⁹⁹.

Although MIR transparency has been demonstrated in several polymer systems, including SEBS and high-drawn PA6, polyethylene remains the only material platform that has been translated into woven textile structures. In addition, the R_{sol} of existing polyethylene-based textiles remains lower than that of type I materials, limiting their applicability for outdoor cooling under strong solar irradiation. Future development could, therefore, focus on enhancing solar reflectance while maintaining MIR transparency. Unlike type I and type II materials, however, this objective cannot be readily achieved through the incorporation of high-loading scattering particles, as such additives might increase MIR absorption and reduce transparency^{5,41,99}. Instead, porous microstructures and fibre-level optical engineering should be explored.

Static heating materials

Heating materials enable personal thermal regulation in cold environments by harvesting solar radiation and retaining body-emitted thermal energy^{100,101}. Existing heating materials can be broadly classified into two mechanistic categories^{11,102}. The first category is type V materials, which rely on high A_{sol} and low ϵ_{MIR} . The second category focuses on high visible transparency and low ϵ_{MIR} , allowing heating through the transmitted visible light.

Solar absorptive and MIR-reflective materials. Type V materials use efficient absorption of UV–vis–NIR radiation to enhance solar-driven heating^{6,7,11}, and suppress MIR emission to reflect and retain infrared radiation emitted by the human body³⁸. This dual spectral strategy facilitates net heat accumulation and sustained warming in wearable heating systems. The development of type V materials begins with the selection of highly conductive inorganic materials, which intrinsically exhibit low MIR emissivity owing to their high free-carrier concentrations while simultaneously absorbing solar radiation through electronic transitions within the UV–vis–NIR region^{45,50}. However, such inorganic materials are generally difficult to process directly into fibres or textiles. Consequently, the realization of wearable heating systems primarily relies on mesoscopic-level structural engineering in which photothermal inorganic materials are incorporated into polymer-based fibres and textile architectures through coating, deposition or composite strategies. For example, a $\text{Ti}_3\text{C}_2\text{T}_x$ MXene coating with low ϵ_{LWIR} was incorporated into a nanoPE textile to simultaneously suppress body thermal radiation and efficiently absorb solar radiation, allowing efficient heat retention and solar heating⁴⁵ (Fig. 3d). The 12- μm -thick MXene–nanoPE textile achieves an average emissivity of 17.6% (in the wavelength range 7–14 μm) and increases skin temperature by approximately 4.9 °C compared with cotton under passive radiative heating in an indoor environment.

Existing solar absorptive and MIR-reflective textiles are predominantly realized through coatings and multilayer films, which often exhibit limited wearability, breathability and mechanical durability compared with conventional woven textiles. Similar to radiative cooling textiles, future efforts should focus on developing intrinsically solar absorptive and MIR-reflective fibres through wet spinning, melt spinning or other fibre drawing technologies, followed by yarn and fabric engineering. Such approaches would enable the integration of photothermal functionality with the comfort, durability and manufacturability required for practical wearable applications.

Visibly transparent and MIR-reflective materials. Another class of heating textiles, regarded as a subclass of type V materials, only focuses on suppressing MIR radiative heat losses while allowing visible light transmission³⁹. Given that commercial garments are available in various visible colours and patterns, personal heating textiles should ideally be designed as transparent to minimize their impact on aesthetics. This design is achieved at the expense of full-spectrum control, while preserving effective thermoregulation through MIR spectral management¹⁰³. Similar to conventional type V materials, this class of textiles typically relies on highly conductive inorganic materials, which intrinsically exhibit low MIR emissivity. Additionally, mesoscopic structural engineering is used to tailor the geometry, thickness and spatial distribution of these components to minimize visible-light attenuation and, therefore, maximize transparency, while maintaining strong reflection of thermal radiation emitted by the human body.

An example of such materials is AgNW networks, which reflect MIR radiation while preserving visible transparency³⁹ (Fig. 3e). This response arises from forward-dominated Mie scattering of thin AgNWs, which enables visible transparency, and the infrared cut-off behaviour of the AgNW mesh, which produces high R_{MIR} and low ϵ_{MIR} . The AgNW–SEBS composite device achieves approximately 75% visible transmittance (T_{vis}) and low ϵ_{MIR} of approximately 35%, effectively suppressing radiative heat loss and preserving visible transparency for passive personal heating. However, the widespread adoption of such materials is constrained by the relatively high cost of silver and the challenges associated with large-scale manufacturing and long-term durability of nanowire networks. Developing and deploying low-cost conductive networks, such as copper nanowires, metallic meshes, conductive polymers or hybrid conductor systems, could enable further progress.

Dynamic tuning in spectrally engineered materials

Dynamic thermal management represents a versatile strategy to maintain thermal comfort in thermal environments and climatic conditions^{11,12,15}. Research has shifted from merely switching between ‘on’ and ‘off’ thermal states towards precise spectral tuning, in which thermal radiation and optical properties can be dynamically modulated in a controlled and tunable manner^{11,12}. This section categorizes progress developing in spectrum-tuning materials for dynamic thermoregulation according to their dominant modulation mechanisms: thermochromic, electrochromic, mechanically responsive and humidity-responsive mechanisms. Each subsection analyses the underlying spectral tuning mechanisms, with emphasis on the hierarchical structural level – molecular, microscopic or macroscopic – that governs the observed optical modulation. By correlating specific structural transformations, we aim to establish clear structure–property relationships to support the development of more spectrum-tuning materials.

Thermochromic materials

Thermochromic materials constitute one of the most extensively investigated classes of spectrum-tuning platforms for dynamic thermoregulation with two major groups: organic thermoresponsive systems, including temperature-responsive polymers and hydrogels, and inorganic thermochromic materials, such as vanadium dioxide (VO_2) and germanium–antimony–telluride (GST) alloys^{11,104–107}. The spectral modulation of thermochromic materials primarily originates from temperature-induced structural transformations at the microscopic level. In organic systems, temperature-dependent phase

transitions, molecular rearrangements, and swelling and deswelling processes alter light scattering and optical absorption characteristics, whereas inorganic thermochromic materials undergo reversible crystal-structure transitions that modify their electronic structures and optical constants^{104,108–110}.

Thermoresponsive polymers and hydrogels possess intrinsic temperature-responsive behaviour and are often integrated into multilayer architectures to enable spectrum and thermal regulation^{104–106,108,109}. Upon temperature variation, such polymers undergo phase transitions that allow other functional layers within the composite system to participate in spectral modulation, enabling automatic switching between heating and cooling modes. For example, a temperature-triggered dual-mode radiative thermal management device¹¹¹ was developed in which a temperature-sensitive actuating layer based on a two-way shape memory polymer undergoes reversible shrinkage and expansion driven by the reversible melting–crystallization process of polymer segments. At low temperatures, the actuating layer contracts, causing the radiative cooling layer to coil and expose the underlying solar-absorbing layer for heating. At high temperatures, the actuating layer elongates, unfolding the radiative cooling layer to fully cover the solar absorber. This thermally induced structural reconfiguration enables an ultra-large emissivity modulation $\Delta\epsilon_{\text{LWIR}} \approx 90\%$.

Another example is a smart thermoregulating window based on poly(*N*-isopropylacrylamide) (pNIPAm)¹¹⁰, in which a temperature-driven hydrophilic–hydrophobic transition induces reversible water redistribution and microphase separation within the hydrogel network (Fig. 4a). Below the transition temperature ($T_c = 31^\circ\text{C}$), water is uniformly distributed throughout the pNIPAm hydrogel beneath the AgNW mesh, resulting in a solar-transparent state with high infrared reflectivity. Above the transition temperature, temperature-triggered phase separation of the pNIPAm hydrogel induces a hydrophilic-to-hydrophobic transition, driving water out of the polymer network to cover the AgNW mesh. The water layer switches the system to a thermal-emissive state by increasing ϵ_{MIR} , whereas the phase-separated pNIPAm network produces strong solar scattering, enabling cooling. This macroscopic structural gating enables high modulation of solar transmittance ($\Delta T_{\text{sol}} \approx 58.4\%$) and thermal emissivity ($\Delta\epsilon_{\text{MIR}} \approx 57\%$).

Despite their excellent mechanical flexibility and intrinsic optical tunability, these polymer and hydrogel systems are typically implemented in multilayer architectures incorporating inorganic or metallic components, and they are predominantly demonstrated in rigid or window-based configurations. As such, their direct integration into wearable textiles remains limited. Nevertheless, their mechanical compliance and stimulus-responsive behaviour highlight their potential for adaptive, textile-compatible thermoregulation systems, although further advances in scalable fabrication, durability and fibre-level integration are still required.

Thermochromic textile systems have also been developed through the electrophoretic deposition of commercial organic thermochromic microcapsules onto conductive fibres¹¹². However, these systems primarily regulate solar absorption in the visible spectral region through temperature-induced colour transitions, and their infrared emissivity remains largely unchanged. Consequently, the achievable thermal-management performance and spectral modulation range of such textile systems are generally more limited than those of emissivity-switching thermoregulation systems.

Tunable systems using inorganic thermochromic materials have also been explored. VO_2 is a thermochromic material owing to its

well-defined and reversible temperature-induced phase transition^{113–115}. At temperatures above approximately 68°C , VO_2 exists in a rutile metallic phase with high infrared emissivity ($\epsilon_{\text{MIR}} \approx 75\%$)^{113–115}. When temperatures drop below this transition temperature, VO_2 undergoes a structural transformation to a monoclinic insulating phase, in which its infrared absorption is substantially suppressed ($\epsilon_{\text{MIR}} \approx 25\%$). Consequently, the thermochromic behaviour of VO_2 primarily originates from phase-structure reorganization at the crystallographic level, rather than molecular-scale chemical modification. Another example of an inorganic thermochromic system is GST alloy, which undergoes a reversible phase transition between an amorphous, low-emissivity state and a crystalline, high-emissivity state at the crystallization temperature (approximately 160°C)^{116–118}. GST alloys integrated with nanostructured metallic substrates undergo a transition from the amorphous phase to the emissive crystalline phase while the anisotropic nanocolumn architecture further provides polarization-controlled emissivity tuning, yielding a combined modulation of $\Delta\epsilon_{\text{LWIR}} \approx 50\%$ (ref. 118).

Despite their spectral tunability, thermoresponsive inorganic materials are predominantly developed for applications such as smart windows and building envelopes. Their limited mechanical compliance, reliance on multilayer or rigid device architectures, and relatively high phase-transition temperatures that do not match the thermal comfort range of the human body constrain their direct application in wearable systems. Therefore, these inorganic thermoresponsive materials are not suitable for practical textile-based personal thermoregulation.

Electrochromic materials

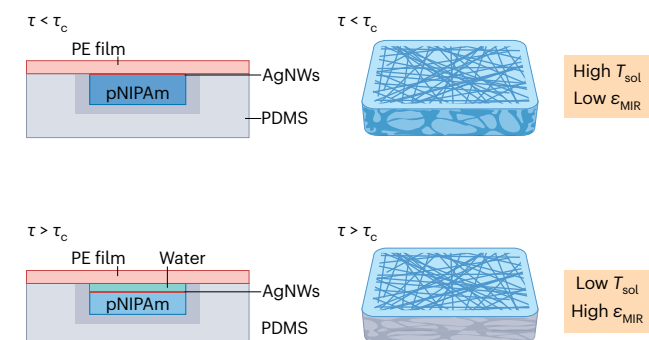
For electrochromic materials, spectral modulation is achieved by voltage-induced oxidation and reduction processes, which alter the spectral properties of the active layer^{11,119,120}. In most cases, these redox-driven transformations occur at the molecular level, involving changes in electronic structure and bonding configuration. Such changes in molecular structure alter charge delocalization, optical transitions and infrared absorption characteristics. Consequently, molecular-level structural modulation directly governs the emissivity and spectral response of electrochromic materials, enabling dynamic thermal management through reversible electrochemical control.

Under electrochemical bias, conjugated polymers undergo reversible redox reactions accompanied by transitions between aromatic and quinoidal configurations, which represent molecular-level structural transformations of the conjugated backbone. On the basis of this principle, an electrochemically responsive thermoregulatory device has been developed with a sandwich architecture comprising two PEDOT:Tos electrodes separated by an electrolyte-infused porous cellulose layer¹²¹ (Fig. 4b). Upon applying a negative electrical bias (from top to bottom), the upper PEDOT:Tos layer is electrochemically reduced, leading to a transition from the quinoid to the more benzenoid structure and a corresponding increase in ϵ_{LWIR} . Simultaneously, the lower PEDOT:Tos layer is oxidized, adopting a more quinoid structure. As the applied potential is varied from -1.5 V to 1 V , this system achieves a $\Delta\epsilon_{\text{LWIR}} \approx 25\%$, enabling reversible control of device temperatures of around 0.25°C at ambient conditions in a sky simulator.

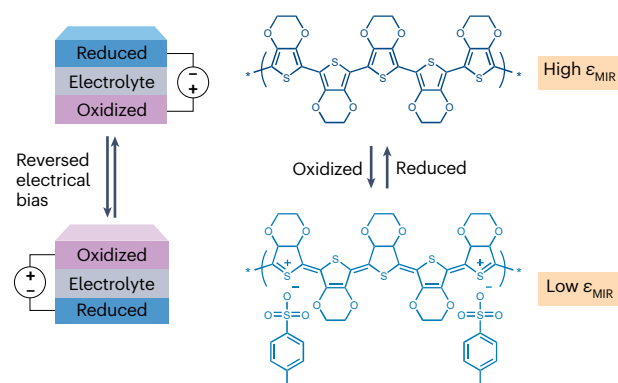
To extend electrochromic spectrum tuning towards wearable applications, a thermoregulatory device based on polyaniline (PANI)⁸⁷ has been introduced with a kirigami-inspired structural design that conforms closely to the human body. The optical properties of PANI can be reversibly tuned by switching between different oxidation states under an applied potential. At -0.1 V , PANI is predominantly in the leucoemeraldine state and is relatively transparent in the infrared, exposing the

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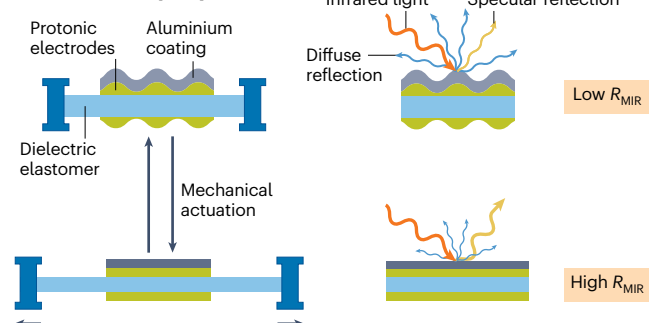
a Thermochromic



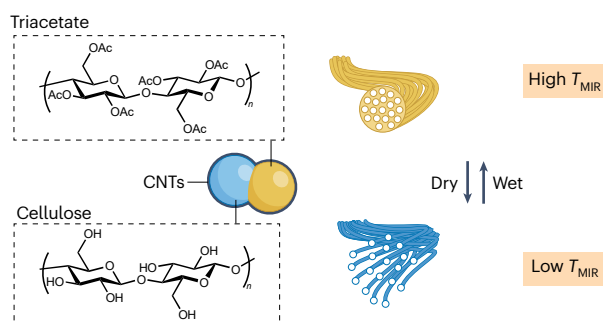
b Electrochromic



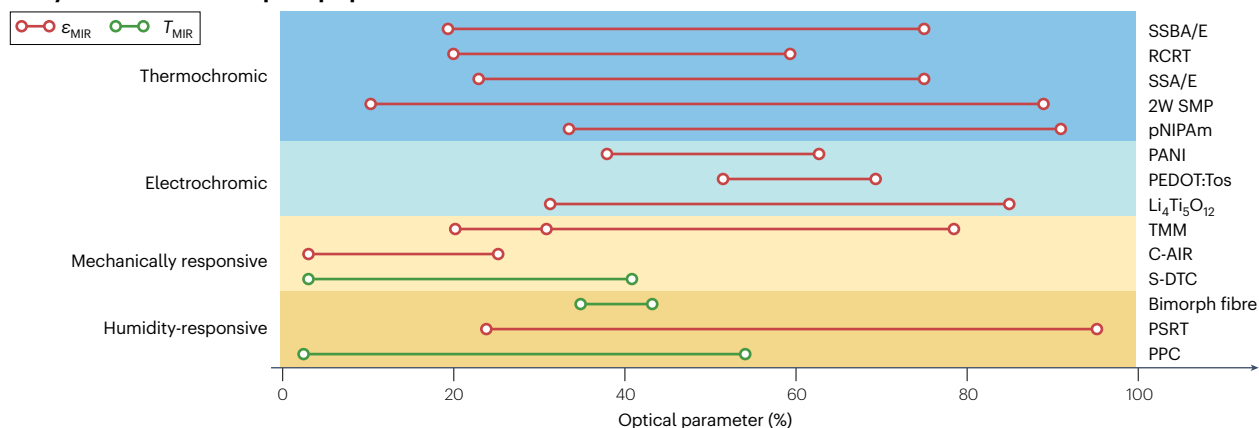
c Mechanically responsive



d Humidity-responsive



e Dynamic modulation of optical properties



low emissivity of the underlying Au layer ($\epsilon_{\text{MIR}} \approx 0.38$). Increasing the potential oxidizes PANI to the emeraldine salt state, simultaneously increasing its optical conductivity and MIR emissivity, which reaches a maximum of $\epsilon_{\text{MIR}} \approx 0.65$ at 0.4 V. At higher potentials, further oxidation towards the poorly conductive pernigraniline state decreases the emissivity and compromises reversible switching. This device also demonstrates the compatibility of electrochromic mechanisms with mechanically adaptive form factors.

Building on these electrochromic mechanisms, a series of conducting-polymer-based active photonic platforms have been

developed to enable dynamic control of infrared optical and radiative properties through electrochemical modulation^{122–126}. The underlying mechanism is electrochemical oxidation and reduction, which governs the plasmonic behaviour, resonance strength and radiative properties of the conducting polymer. For example, in a plasmonic antenna array based on PEDOT:Tos, dedoping suppresses the plasmonic response, reducing the extinction at the resonance wavelength by approximately 40% (ref. 125). Similarly, in polymer-gated optical lattices¹²⁴ and polymer nanoantenna plasmonics¹²⁶, carrier-density modulation dynamically alters electromagnetic confinement and optical mode

Fig. 4 | Dynamic modulation strategies in personal thermoregulatory materials.

a, The architecture and microstructural evolution of scalable thermochromic smart windows based on poly(*N*-isopropylacrylamide) (pNIPAm) hydrogel, which undergoes a reversible phase transition at a transition temperature (T_c). Above T_c , water covers the silver nanowire (AgNW) mesh leading to a low solar transmission T_{sol} and high emissivity in the mid-infrared range ϵ_{MIR} . Below T_c , water is uniformly distributed throughout the pNIPAm hydrogel beneath the AgNW mesh, leading to a solar-transparent state with low ϵ_{MIR} (ref. 110). **b**, As in part **a** but for a reversible electrochromic radiative-cooling device in which the poly(3,4-ethylenedioxythiophene)-tosylate (PEDOT:Tos) layers either side of the electrolyte switch between a high-emissivity reduced state and a low-emissivity oxidized state under an applied electrical bias¹²¹. **c**, As in part **a** but for a mechanically responsive infrared-reflecting system, with a geometry and interlayer spacing that can be actively tuned to achieve low reflectivity R_{MIR} when wrinkled and high R_{MIR} when stretched⁵⁹. **d**, As in part **a** but for humidity-responsive meta-fibre architectures, comprising yarns of cellulose and triacetate

surrounded by carbon nanotubes (CNTs), which tighten and relax in response to moisture to reshape the effective optical response⁸⁶. **e**, The estimated optical parameter (MIR transmission (T_{MIR}) and ϵ_{MIR}) ranges achieved in response to various stimuli across different mechanisms and material classes. Data from: spectrally self-adaptive broadband absorber/emitter (SSBA/E), ref. 113; radiative cooling regulating thermochromic window (RCRT window), ref. 114; spectrally self-adaptive absorber/emitter (SSA/E), ref. 115; two-way shape memory polymer (2W SMP), ref. 111; pNIPAm, ref. 110; polyaniline (PANI), ref. 87; PEDOT:Tos, ref. 121; $\text{Li}_4\text{Ti}_5\text{O}_{12}$, ref. 160; triple-mode mid-infrared modulator (TMM), ref. 98; cephalopod-based adaptive infrared-reflecting system (C-AIR), ref. 59; squid skin-based dynamic thermoregulatory composite (S-DTC), ref. 60; bimorph fibre, ref. 86; passive sweat-responsive thermoregulatory textile (PSRT textile), ref. 140; porous polymer coatings (PPC), ref. 161. PDMS, polydimethylsiloxane; PE, polyethylene. Part **a** adapted from ref. 110, CC BY 4.0. Part **b** adapted from ref. 121, CC BY 4.0. Part **c** adapted with permission from ref. 59, AAAS. Part **d** adapted with permission from ref. 86, AAAS.

distribution, enabling electrically programmable spectral responses and infrared field localization.

Although electrochromic conducting polymers exhibit intrinsic mechanical flexibility and dynamic tunability, they face challenges for applications in wearable thermoregulation. PEDOT-based polymers have been incorporated into mechanically flexible electrochromic fibres for reversible colour switching^{127,128}; however, these systems are primarily demonstrated in visible electrochromic displays and wearable optoelectronics, and their application in radiative cooling and personal thermal management remains largely unexplored. The stability and durability of this doping system are also concerns, especially under repeated redox cycling. In addition, most systems rely on multilayer, electrolyte-containing device architectures, which complicate integration into fibre-based or textile formats. Furthermore, when transitioning from planar films to deformable or fibre-based systems, maintaining large-area uniformity of optical response becomes increasingly challenging. Therefore, further efforts are needed to realize wearable and breathable textile electrochromic thermal management systems.

Mechanically responsive materials

In contrast to the first two systems, mechanically responsive materials regulate thermal radiation by reconfiguring device microstructures at the macroscopic level^{11,12,107,129}. In this type of system, spectral tunability is achieved by dynamically altering macroscopic device architectures rather than modifying the intrinsic optical properties of the constituent materials.

Two fundamental mechanical mechanisms, namely wrinkling and cracking, are predominantly used to reversibly reconfigure surface morphologies and structural geometries, enabling dynamic control over reflectance, emissivity and transmittance. Inspired by the adaptive skin textures of cephalopods, a wrinkle-based device has been developed with a surface morphology that can be adapted to control the reflectivity of the structure. In the wrinkled state, diffuse reflections account for approximately 71% of the average total R_{MIR} (ref. 59) (Fig. 4c). Upon mechanical actuation to a flattened state, the average total R_{MIR} exceeds 96%, corresponding to an effective emissivity modulation ($\Delta\epsilon_{\text{MIR}}$) of 25%. Additionally, a crack-based dynamic thermal regulation device was developed, which is coated with a low-emissivity copper nanopillar layer⁶⁰. When subjected to mechanical stretching, the metallic layer fractures and separates, exposing the underlying infrared-transparent SEBS polymer matrix, resulting in a ΔR_{MIR} of 47% and ΔT_{MIR} of 39%.

By integrating wrinkling and cracking mechanisms, a versatile triple-mode LWIR modulator has been developed⁹⁸. Through controlled mechanical deformation, the system can reversibly switch between three distinct operational modes: an emission mode with high ϵ_{MIR} induced by surface wrinkling, a reflection mode characterized by low ϵ_{MIR} and high R_{MIR} achieved via surface flattening, and a transmission mode in which extensive cracking allows visible light to pass through, rendering the device optically transparent.

Mechanically responsive systems with flexible polymer substrates generally exhibit good stretchability and potential for wearable applications; however, the development of air-permeable textile devices remains restricted. Future progress requires the rational design of mechanically responsive fibre and yarn architectures to achieve mechanically adaptive textile systems while maintaining the breathability of the whole textile.

Humidity-responsive materials

Similar to mechanically responsive systems, humidity-responsive materials primarily rely on macroscopic structural regulation, particularly through dynamic reconfiguration of yarn architectures, textile assemblies, and multilayer or pore structures. However, the driving force originates from the differences in the hydrophilicity and hydrophobicity of the constituent materials.

A yarn comprising triacetate–cellulose fused bimorph fibres coated with a thin layer of low-emissivity carbon nanotubes (low- ϵ CNTs)⁸⁶ (Fig. 4d) leads to a relative MIR transmission change of approximately 35% over a relative humidity range of 10–75%, corresponding to an absolute change of approximately 12% after correction for scattering, enabling adaptive heat dissipation without external energy input. In hot and humid conditions, the hydrophilic cellulose component swells whereas the hydrophobic triacetate component remains relatively unchanged, and the yarn untwists and opens the pores in a fabric. In addition, the distance-dependent electromagnetic coupling between neighbouring carbon-coated fibres further tunes the MIR emissivity. Overall, humidity-responsive systems have demonstrated strong compatibility with textile architectures and have progressed towards wearable implementations, highlighting their substantial potential for practical personal thermoregulation.

Multiscale considerations for dynamic tuning

Despite the rapid development of dynamic tuning materials, important challenges remain before they can be widely implemented in wearable

thermoregulatory systems, particularly in terms of wearability and spectral selectivity. These limitations could be addressed through coordinated structural engineering across multiple length scales.

Electrochromic modulation offers the most precise and reversible regulation of spectral properties, as the applied electric field can be switched on and off on demand, but typically has a small modulation range and increased system complexity, and relies on external power sources (Fig. 4e). Thermochromic materials enable passive, self-adaptive regulation and often provide relatively large modulation amplitudes. Nevertheless, their tunability is constrained by fixed transition temperatures and strong environmental dependence, which might not always align with human thermal comfort requirements. Mechanically responsive and humidity-responsive systems can provide rapid and reversible spectral tuning, but their practical applicability is often restricted by specific operating conditions and usage scenarios. Additionally, the macroscopic deformation in mechanically responsive systems can compromise comfort and aesthetics during daily wear. Humidity-responsive textile systems show potential for wearable and adaptive thermoregulation without external energy input. However, these systems require perspiration or ambient humidity to trigger the change and might be ineffective under thermal discomfort conditions that occur without substantial sweating.

At molecular and microscopic levels, future developments should focus on increasing the emissivity modulation range through molecular design of polymer and inorganic materials. One important direction is to maximize the spectral contrast between the metallic and dielectric states in electrochromic materials, for example, by increasing the ion-storage capability of conjugated polymers to increase the carrier-density contrast between the neutral and doped states^{120,122,127}.

At mesoscopic and macroscopic levels, fibre and textile engineering will be essential for translating dynamic materials into wearable thermoregulatory systems. Most existing dynamic tuning materials are developed as thin-film devices or mechanically rigid structures, which

do not inherently satisfy the requirements of wearable devices¹³⁰. The development of fibre-based and textile-based platforms could provide breathability, air permeability, mechanical robustness, sweat-wicking capability and long-term comfort¹³¹. Textile structural design also provides an additional degree of freedom for dynamic thermal regulation. For example, double-layer knitted fabrics with distinct emissivities on opposite surfaces can be combined with dynamic tuning yarns to selectively expose different thermal-radiation interfaces under changing environmental conditions^{132,133}.

Conclusions and perspectives

Spectrally engineered materials offer substantial opportunities for maintaining thermal comfort and reducing heat-related illnesses. In addition, widespread deployment of low-energy thermoregulatory technologies could substantially reduce the demand for air conditioning, which is increasingly important under intensifying anthropogenic warming and urban heat island effects. However, the use of personal thermoregulation textiles in everyday life remains limited^{1,4,5}. This section outlines the challenges and emerging directions for the further development of wearable thermoregulation materials (Fig. 5).

Material innovation

Innovative materials need to be developed to further increase the selectivity, tunability and adaptability of spectral properties (Box 2). For passive cooling, solar reflectance of over 95% has already been achieved^{1,6,11}. However, such performance is often achieved through high loadings of inorganic nanoparticles or relatively thick scattering layers, resulting in a high areal density. Future cooling materials should, therefore, maximize scattering efficiency per unit mass. Introducing controlled microscale and nanoscale porosity can increase the number of refractive-index discontinuities, thereby maintaining high solar reflectance at reduced thickness and areal density. For inorganic particle–polymer composites, lightweight hollow particles,

a Towards practical wearable thermoregulatory systems

Material innovation

- Rational molecular engineering
- Novel electrochromic materials
- Efficient and stable ionic conductors

Spectral and thermal engineering

- Scenario-specific spectral engineering
- Angularly selective thermoregulation
- Multi-mode heat transfer synergy
- Colour and thermal co-design

Manufacturing

- Continuous functional fibre spinning
- Scalable yarn and fabric formation
- Garment manufacturing and integration
- Monomaterial textiles for recyclability

b Autonomous wearable system

Physiological sensing



Energy generation and utilization



Signal-driven adaptive regulations



Human-machine interface



Fig. 5 | Key challenges and prospects for spectrally engineered thermoregulatory textiles. **a**, Future directions towards a practical wearable thermoregulatory system through material innovation, spectral and thermal engineering, and addressing manufacturing challenges. **b**, A vision for a future autonomous wearable system with integrated multifunctional capabilities, including physiological sensing to drive adaptive thermal regulation, on-body energy generation and utilization, and adaptive human–machine interfaces for personalized thermal management.

Box 2 | Design roadmap and technology readiness

Scenario-driven design strategies

From the perspective of environmental demands, personal thermoregulation requirements can be broadly categorized into three categories: cooling demand, heating demand and dynamic demand (see the figure, left panel). Cooling applications generally require type I–IV materials, which suppress solar heat gain and/or increase or decrease radiative heat exchange. The spectrum targets vary depending on the environmental scenario, including view factors and solar intensities. Heating applications primarily rely on type V materials, which promote solar-energy harvesting and heat retention. Dynamic demanding applications require tunable materials with spectra that can switch between cooling and heating states.

The realization of these spectral functions depends strongly on structure modulation across multiple length scales. For type I and type II materials, spectral selectivity is primarily governed by coupled regulation at the molecular, microscopic and mesoscopic levels, whereas macroscopic structures generally have a relatively minor role. By contrast, type III–V materials rely fundamentally on molecular-level design to establish their intrinsic optical properties. For type III materials, mesoscopic structural design can also enhance reflectivity. For type IV materials, additional microscopic structural engineering is often required to enhance infrared transparency within the mid-infrared region. Tunable materials involve structural modulation across all length scales, representing the most comprehensive form of multiscale structural engineering among spectrally engineered thermoregulatory materials.

Technology readiness

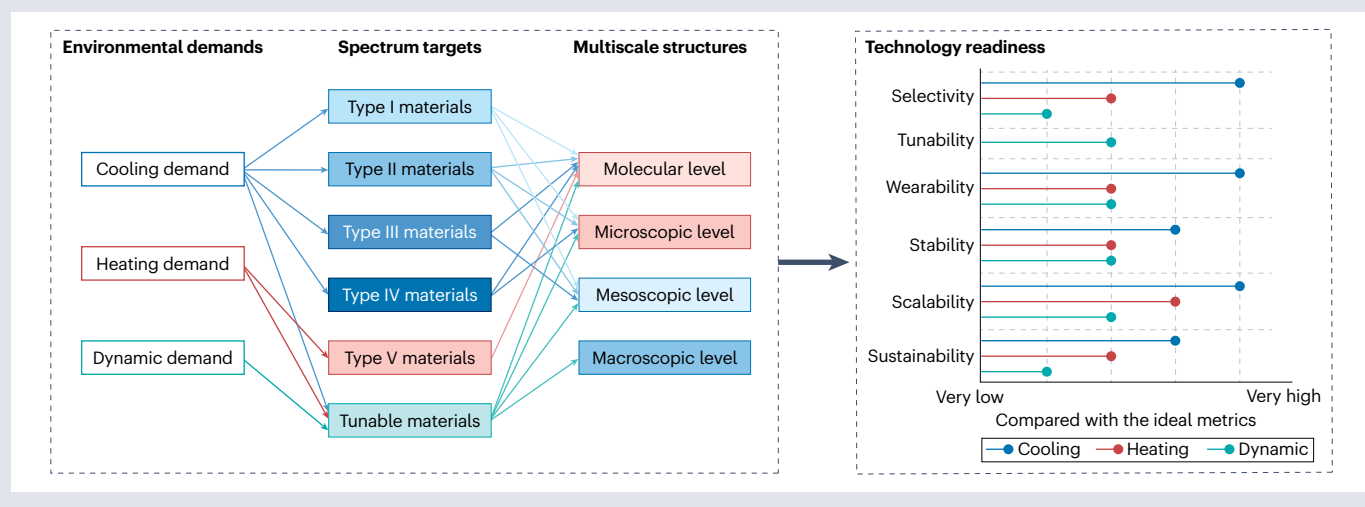
We summarize the practical potential of the thermoregulatory materials discussed throughout this Review based on the technology readiness level (TRL) and performance across six key metrics: spectral

selectivity, tunability (applicable only to tunable materials), wearability, stability, scalability and sustainability (see the figure, right panel).

Static cooling materials are generally evaluated at TRL 7, indicating near-commercial readiness^{11,12,32}. For example, nanoPE-based structures⁴¹ feature simple fabrication routes, structural robustness and pronounced passive cooling performance. These materials have already demonstrated strong potential for scalable manufacturing and commercialization as wearable cooling textiles^{1,8,50,162}. However, challenges in long-term stability and sustainability remain, primarily owing to polymer degradation during extended use and the limited recyclability and reuse of polymer-based systems^{1,5}.

Static heating materials are typically assessed at TRL 4, corresponding to laboratory-scale validation^{1,6,7}. Despite their effectiveness in photothermal heating, these materials face substantial limitations in large-area fabrication, spectral selectivity and comfort for wearables^{45,113,115}. The complexity of multilayer architectures in static heating materials continues to hinder stability, comfort and environmental compatibility^{45,101,113}. Consequently, static heating materials exhibit moderate scalability but lag behind in most other performance criteria.

Tunable personal thermoregulatory materials remain at an early stage of development (TRL 3) and are largely confined to exploratory research^{11,12}. The key challenge is to achieve effective and reversible tunability while maintaining high spectral selectivity. Tunability is often limited in magnitude, and even when dynamic modulation is achieved, selective control within the atmospheric transparency window is rarely realized¹⁶³. Moreover, tunable systems often rely on complex device architectures, which not only compromise sustainability, recyclability and long-term durability but also limit their compatibility with textile-based wearable systems^{59,106,114,119,121}.



porous particles, low-density fillers and optimized particle distributions could further reduce the required filler loading. Meanwhile, the spectral selectivity of thermal emission remains insufficient in the MIR region²¹. Rational design of molecular absorption can increase the spectral selectivity of materials, such as in the ATW¹³⁴ (Box 1).

For heating materials, low MIR emissivity is currently achieved mainly using metallic or carbon-based components³⁹, which can be costly or difficult to integrate into recyclable textiles. Processable polymer-based MIR reflectors with nanophotonic design will be a promising solution.

For tunability, conjugated polymers with electrochromic properties are good candidates for realizing mechanically flexible, stable and tunable thermoregulatory devices. Rational molecular design is needed to enable electrochromic systems with large-amplitude, reversible and stable emissivity modulation. The development of efficient ionic conductors is equally important to facilitate effective electric-field-induced doping and ensure fast, uniform and energy-efficient modulation^{119,135–138}. Additionally, body temperature-responsive actuating fibres could provide another route to tune the emissivity of the textiles.

Spectral and thermal engineering

Synergy of multi-mode thermal engineering should be designed to further enhance heating or cooling performance compared with single-mode radiation control. Besides radiative heat exchange, evaporation, convection and conduction also have important roles in practical thermoregulation^{139–141}. In outdoor urban environments, angular-selective radiative designs can be leveraged to expand cooling capacity by increasing the view factor towards the sky while suppressing radiative exchange with hot ground surfaces and surrounding buildings¹⁴². Furthermore, cooling textiles should combine high breathability and efficient moisture transport with adequate thermal conductivity to facilitate simultaneous sweat evaporation, convective heat dissipation and conductive heat transfer. Integrating these coupled heat exchange mechanisms with rational multiscale structural design is essential for achieving effective and robust personal thermoregulation under realistic environmental conditions.

Moreover, existing thermoregulation textiles are mostly evaluated under simulated conditions in which the textile is placed in direct contact with the measurement setup. However, there are often air gaps between clothing and the human body, which substantially alter other heat-transfer modes and overall thermoregulatory performances. Therefore, standardized evaluation protocols that better replicate realistic wearing conditions should be introduced, including environmental factors and evaluation metrics. Furthermore, many high-performance thermoregulation textiles rely on thick, low-porosity structures to maximize spectral selectivity, often at the expense of breathability, moisture transport, softness and garment weight (or grams per square metre). Future evaluations of the performance of textile systems should simultaneously consider optical, thermal, and wearability and aesthetic requirements, including colour compatibility¹⁴³, rather than aiming to optimize a single performance metric.

Manufacturing

Another challenge lies in the manufacturing of personal thermoregulation textiles (Fig. 5a). Existing methods for fabricating personal thermoregulation textiles are largely based on electrospinning, surface coating or the integration of flexible films. Although electrospun fibrous films offer precise control of fibre diameter and porous structures, they often have limited mechanical robustness and abrasion resistance²¹. Surface coating or treatment can obstruct textile pores, reduce breathability, and increase areal density and stiffness. Similarly, flexible thermoregulation film devices often consist of multilayer composite architectures that integrate multiple organic and inorganic components. Perforation, patterning and kirigami designs can increase air permeability and deformability; however, such systems can introduce substantial challenges in materials processing and large-scale manufacturing. Emerging approaches such as roll-to-roll printing^{82,95} offer promising routes towards scalable production, but in some

cases, device fabrication also relies on nanofabrication techniques (for example, photolithography), which present barriers to large-area manufacturing and scalable production⁸⁹.

Future manufacturing strategies should, therefore, adopt bottom-up approaches spanning fibres, yarns and fabric architectures. Textiles are intrinsically hierarchical structures in which pores between fibres, within yarns and among yarns collectively provide low weight, flexibility, air permeability and moisture transport. Constructing optical functionality directly at the fibre and yarn levels has a higher tendency to preserve these interconnected pores than attaching dense functional layers to finished fabrics. Techniques such as continuous wet spinning, dry spinning, melt spinning and thermal drawing can incorporate functional polymers, inorganic particles, porous domains and multiphase interfaces into mechanically processable fibres^{53,131,144,145}. The solar and MIR properties of such fibres can be regulated through material composition, cross-sectional geometry, internal porosity and component distribution. Micrometre-scale fibres generally offer greater mechanical robustness, processing stability and compatibility with industrial winding and textile manufacturing than electrospun nanofibres^{53,131,144,145}.

Twisting, plying, wrapping, braiding and composite-yarn formation can improve fibre cohesion and load transfer while altering fibre orientation, packing density, surface exposure and internal porosity^{1,2,83,84}. These structural changes could be used to modify effective optical path length and directional radiation. The spatial distribution of reflective, emissive or conductive fibres within the yarn cross-section might also enable asymmetric or multiband optical responses. At the fabric level, weaving, knitting, nonwoven processing and three-dimensional textile manufacturing can convert functional yarns into large-area, flexible and breathable thermoregulatory materials.

From a sustainability perspective, the recycling and reuse of multi-component fibre systems require the separation of individual constituents before recovery, inevitably increasing processing complexity and cost^{26,146,147}. Many existing thermoregulatory textiles contain multiple polymers, metals, inorganic particles, binders and encapsulation layers that are difficult to separate after use^{45,50,53,59}. Monomaterial thermoregulatory structures offer a possible route to reduce this complexity. By controlling fibre diameter, crystallinity, molecular orientation, porosity, cross-sectional morphology and hierarchical assembly, different components derived from the same material family can exhibit distinct optical and mechanical functions^{41,79}. Such designs could simplify recycling while retaining spectral selectivity and textile performance and, therefore, offer more favourable prospects for sustainability across the material life cycle.

Autonomous wearable systems

We envision that these advances could lead to the development of autonomous wearable thermoregulatory systems (Fig. 5). Owing to their intrinsic flexibility, conformability and skin compatibility, personal thermoregulation fibres can form effective human-machine interface platforms^{84,148,149}. Such systems could be integrated with additional sensing functionalities for real-time monitoring of physiological signals, including temperature, respiration and cardiovascular activity^{150–153}. Such data could be wirelessly transmitted to cloud-based platforms for real-time health monitoring and data sharing. By combining real-time sensing, data processing, and adaptive spectral or thermal regulation, these systems could autonomously adjust their thermoregulatory performance to maintain thermal comfort under dynamically changing conditions and reduce the risk of heat-related health issues.

In parallel, polymer-based thermoelectric devices can harvest and convert thermal energy from the human body into electrical energy to enable the self-powered operation of such autonomous systems^{154–158}. Moreover, the mechanical flexibility and chromic tunability of thermoregulation fibres can also enable additional functionalities such as thermally or electrically driven flexible displays¹⁵⁹. When combined with artificial intelligence-assisted materials and structural design, and advanced data processing and analysis, these integrated capabilities point towards next-generation wearable systems with autonomous operation. Such intelligent thermoregulation textiles are expected to shape future lifestyles, offering sustainable, adaptive and personalized thermal comfort for human well-being.

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Author contributions

R.W. and J.-T.L. researched data for the article. All authors contributed substantially to the discussion of the content. All authors wrote the article and reviewed and/or edited the manuscript before submission.

Competing interests

The authors declare no competing interests.

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