

Review Article

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Recent progress in thermal management for flexible/wearable devices

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Abstract

Thermal management for wearable devices is evolving to make ubiquitous applications possible based on advanced devices featuring miniaturization, integration, and ultrathin designs. Thermal management and control integrated with wearable devices are highly desirable for various applications for human body monitoring, including external heat exposure and metabolic heat generation, in various activities. Recently, dynamic change materials have been integrated with micro/nano thermal management platforms to address the potential for active thermal management. In this article, recent advances in the architecture of effective thermal management in wearable devices are reviewed, along with the essential mechanisms for managing thermal conditions for users in external/internal thermal environments. Appropriate thermal management approaches are proposed for the design and integration of materials/structures tailored to specific targets in wearable devices. In particular, this review is devoted to materials/structures based on five thermal management strategies: conduction, radiation, evaporation/convection, heat absorption/release, and thermoelectric (TE). Finally, the challenges and prospects for practical applications of thermal management in wearable devices are discussed.

Keywords: Thermal management, wearable devices, thermal conductors, radiative coolers, evaporative textiles, thermoelectric devices



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INTRODUCTION

Wearable technology has advanced significantly in the past decade, with a range of body-worn electronic and electro-optical devices, such as smart watches, bands, glasses, and goggles, becoming available to consumers^[1-3]. The development of flexible and stretchable electronic materials is driving the creation of new and improved wearable devices to meet the needs of various industries, including the consumer, health, biomedical, and industrial sectors. These devices, such as smart clothes, wearable displays, computing devices, and health technologies, have the ability to monitor real-time physiological and biomechanical signals or provide physiological stimuli^[4-11]. The design and development of advanced wearable devices still pose challenges because of the need to integrate electronic, electrochemical, electro-optical, or multiple types of functionality on a platform that is soft, compact, lightweight, flexible, and stretchable^[12,13]. To do so, various manufacturing technologies, such as laser processing^[14-17], transfer printing^[18-21], and inkjet printing^[22-26], have been used to fabricate a flexible/stretchable device platform. Ensuring long-term reliability and biocompatibility during human body motion, especially in outdoor activities involving external heat exposure and metabolic heat generation, adds to the challenges in material/structure development and device design. Although quantifying heat generation is difficult because of the diversity of wearable device structures and platforms, for devices in contact with the skin, it is necessary to maintain a temperature lower than skin temperature (31.1 °C to 35.4 °C) during heat generation^[27].

Effective thermal management and control are crucial for the reliable performance of advanced wearable devices, which feature miniaturization, integration, and ultrathin designs^[28-38]. The integration of thermal regulators into these devices is challenging because various requirements must be met, including thermal, mechanical, ergonomic, and application-specific needs. The use of rigid materials with high thermal conductivity is problematic in wearable devices because they are unsuitable for flexible or stretchable structures. To address this issue, nanofillers can be incorporated into flexible composites to improve the overall thermal conductivity^[39-41]. However, this approach presents challenges because the thermal contact resistance between nanofillers increases upon tensile deformation, resulting in mechanical contact loss. Moreover, wearable devices that contain highly thermally conductive materials, such as electrodes and components, can become rapidly heated under external heat or direct sunlight, causing adverse problems for the user and the device^[42,43]. For example, rapid heating of wearable devices, which can occur in a matter of hours or minutes depending on the thermal environment, can result in skin burns of varying severity^[44,45]. Surface temperatures of optoelectronic devices lacking proper heat sinks can rapidly increase upon power application, potentially causing skin burns from the light-emitting diode (LED). Low power levels of ≤ 5 mW can raise surface temperatures above normal skin temperature, elevating the risk of burns. Exposure to higher power levels of ≤ 10 mW can cause first-degree burns in just 2 min and third-degree burns after 10 min^[46].

Sweat expelled from heated skin can generate artifacts on electro-based sensors, such as those used for electromyography (EMG) or electroencephalography (EEG), and can mechanically hinder the adhesion of wearable patches^[47]. Accumulated heat can degrade the performance of batteries and wireless communication devices^[48,49]. Furthermore, all-weather or all-day devices that must maintain a stable temperature level in various thermal environments require active thermal management that can heat or cool the external device surface or device-skin interface^[28,50].

This review covers the latest technology for thermal management in wearable devices, including the use of various materials and structures. Previous reviews have primarily focused on presenting theories and concepts related to thermal management or organizing only thermal management methods. In this article, thermal management methodologies are systematically classified based on the underlying heat transfer

mode and materials, elucidating comprehensive guidelines for practical cooling solutions in wearable devices and defining suitable heat dissipation modes across diverse wearable platforms. In Section “Thermal management structures for wearable devices”, the essential mechanisms for managing the thermal conditions of the user, both internally and externally, are introduced, along with the effective structures for thermal management in wearable devices. In five major sections, thermal management structures, multifunctional applications for flexible substrates and wearable devices, and active thermal management techniques for dynamically changing materials and radiative cooling structures are explored. The review concludes with a roadmap for the practical application and development of fully integrated multifunctional thermal management systems for wearable devices and highlights future directions and opportunities in thermal management for advanced wearable devices.

THERMAL MANAGEMENT STRUCTURES FOR WEARABLE DEVICES

Wearable devices are generally composed of sensors, electrodes, and flexible substrates, which are combined with integrated circuits and other parts to enable real-time monitoring of biosignals in daily life. The devices typically include a variety of sensors. Sensors for electrocardiograms (ECGs)^[1,51-56], EMG^[57-60], and photoplethysmography (PPG)^[61-65] are used to monitor heart rate, body motions, and pulse oximeters, respectively. Temperature and humidity are measured by resistance sensors^[66-73], while Galvanic skin response sensors have become popular tools for stress monitoring because of their ability to utilize sweat^[74-77]. Sweat sensors detect glucose levels through an electrochemical process in sweat transported through microfluidic channels^[78-84].

Thermal management through heat transfer mode

Figure 1 shows an overview of thermal control considerations for wearable devices. Generally, different pathways of heat dissipation contribute to wearable device thermal management: conduction, radiation, convection/evaporation, heat absorption/release, and thermoelectric (TE) cooling. The transfer of heat resulting from the temperature difference between two physically contacting objects is known as thermal conduction^[85]. According to Fourier’s law, the rate of heat transmission across a medium increases as the temperature decreases^[86].

$$q = -\lambda A \cdot \frac{\partial T}{\partial x}, \quad (1)$$

where q denotes the heat flux, λ is the thermal conductivity coefficient and $\partial T/\partial x$ is the temperature gradient. Heat transmission in the steady state is primarily defined by effective thermal conductivity. Most heat created by wearable devices is transmitted to the skin or, when fitted with a heat sink, to the ambient air^[87]. Efficient heat dissipation is critical to prevent heat transfer to the skin, which can be achieved by either attaching a flexible heat sink to the device or introducing nanofillers with high thermal conductivity embedded in the substrate material^[88].

Radiation is an electromagnetic wave emitted by an object with a temperature above absolute zero^[89]. The energy dissipation rate depends on the temperature differential between the object and its immediate surroundings, the surface emissivity, and the effective surface area. Thus, surface absolute temperature is the main factor used to determine total radiant heat power through the Stefan-Boltzmann law^[90].

$$Q = \varepsilon \sigma |T|^4, \quad (2)$$

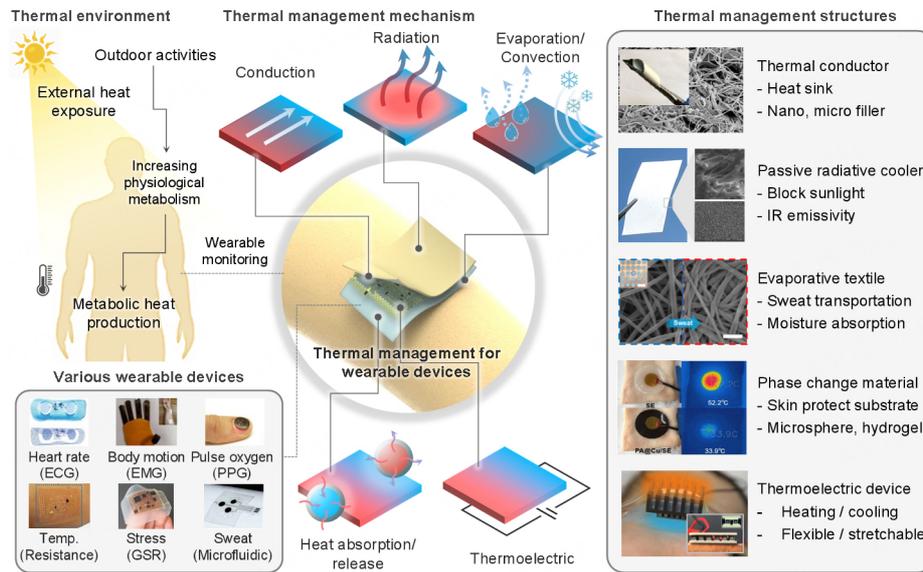


Figure 1. Overview of thermal management for flexible and wearable devices. Flexible and wearable devices that can monitor various biosignals, such as heart rate, body motion, pulse oxygen, temperature, psychological stress, and sweat analysis. Reproduced with permission^[53]. Copyright 2019, American Association for the Advancement of Science^[118]. Copyright 2019, National Academy of Science^[63]. Copyright 2017, Wiley-VCH GmbH, Weinheim^[141]. Copyright 2019, Wiley-VCH GmbH, Weinheim^[77]. Copyright 2020, Wiley-VCH GmbH, Weinheim^[84]. Copyright 2019, American Association for the Advancement of Science. Novel cooling structures based on heat dissipation mechanisms for flexible/wearable devices: (1) high-thermal-conductivity materials; (2) passive radiative cooler; (3) evaporative textile; (4) phase change material; and (5) TE device. Reproduced with permission^[115]. Copyright 2020, Springer Nature^[43]. Copyright 2022, Wiley-VCH GmbH, Weinheim^[120]. Copyright 2021, Springer Nature^[132]. Copyright 2021, Springer Nature^[135]. Copyright 2019, Springer Nature.

where $|T|$ represents the absolute temperature, ε indicates the emissivity of the surface, and σ is the Stefan-Boltzmann constant. Modifying the emissivity, transmittance, and reflectance of the material showed that radiative thermal control has promising cooling potential^[91,92]. The radiative cooler not only facilitates the release of internal heat generation but also impedes the absorption of solar energy. The design of the radiative cooler leverages the spectral properties of solar and atmospheric radiation. In particular, strong emissivity in the atmospheric window (ATW; 8-13- μm wavelength range) optimizes thermal energy emission to the outside space and limits solar energy absorption in the solar spectrum (0.3-2.5- μm wavelength range)^[93,94]. The overall radiative cooling power $P_{cool}(T)$ consists of four contributions to the power terms and is defined as^[95]

$$P_{cool}(T) = P_{rad}(T_{sample}) - P_{Sun} - P_{atm}(T_{ambient}) - P_{cond+conv} \quad (3)$$

where $P_{rad}(T_{sample})$ is the power radiated by the structure per unit area, $P_{atm}(T_{ambient})$ is the absorbed power per unit area from the atmosphere, P_{Sun} is the incoming solar power absorbed by the structure per unit area, and $P_{cond+conv}$ is the conductive and convective heat exchange powers.

Heat transfer through thermal convection occurs through the movement of liquid or air. The air/vapor permeability plays a crucial role in heat transfer from the body to the environment through convection and evaporation^[96]. Increasing permeability improves heat dissipation and can also be used to lower temperatures by modifying convective and evaporative heat transfer processes. The temperature differential between an object and its surroundings determines the rate of convection heat loss, as defined by Newton's law^[97].

$$Q = hA\Delta T, \quad (4)$$

where Q denotes the convective heat flow rate, h is the heat transfer coefficient, A is the surface area of the object, and ΔT is the temperature difference. The evaporative cooling power (P_E) is defined as^[98]

$$P_E(Wm^{-2}) = \frac{\Delta H \times \Delta m}{t \times A}, \quad (5)$$

where ΔH is the enthalpy of water evaporation (2430 J g⁻¹) at 30 °C, t is the evaporation time (s), Δm is the mass loss of an object (g), and A is the surface area (m²). Evaporative coolers cool objects through the evaporation of liquid, resulting in highly efficient energy utilization^[99]. Hence, strategies aimed at reducing the temperature by promoting the evaporation of sweat and moisture wicking are receiving increasing attention^[100].

Thermal management by material

Phase change materials (PCMs) exhibit a change of state within a specified temperature range. During heating, they absorb energy as they undergo phase change instead of transferring it to the environment. In contrast, during cooling, they release energy as they reverse the phase change^[101]. Incorporating a PCM as an intermediate substrate between the skin and a device can provide effective insulation against heat transfer. The temperature of the PCM remains constant until all the latent heat is expended, thus reducing the heat exposure of the skin^[102]. Microspheres, polymer composites, and hydrogels have been developed and demonstrated to be promising thermal protective substrates (TPSs) because they can absorb substantial amounts of heat while retaining their flexible nature^[103].

TE elements, however, offer an active cooling solution. TE devices can be used both to control body temperature and to obtain heat from the skin that would otherwise be wasted^[104]. The Seebeck effect and the Peltier effect largely dictate these functions, and by controlling the current direction, the device can be switched between heating and cooling modes. However, a metal-based heat sink is required for efficiency^[105]. To overcome this restriction, researchers have focused on downsizing and enhancing efficiency in terms of flexible design for wearable compatibility^[106].

In the following sections, different types of cooling structures suitable for flexible substrates and wearable devices are summarized. The most important thermal management strategies are categorized, and material properties, compatibility with devices, and cooling efficiency are reviewed based on those strategies [Table 1]. Furthermore, the thermal stabilities of devices in real-world use are compared, and cooling solutions that offer a variety of features while lowering temperatures are introduced.

THERMAL CONDUCTIVE COOLING MATERIALS AND DEVICES

Recently, wearable devices have become increasingly miniaturized and stretchable/flexible to provide conformal contact on the skin for accurate data acquisition and comfort^[107]. Conventionally, in thermal conductive cooling technologies, such materials as metals and ceramics were employed as heat sinks to dissipate heat. However, their lack of flexibility poses a challenge for their application in wearable devices. Therefore, polymer materials are widely used as substrates for wearable devices because of their flexibility and stretchability. However, polymer substrates generally have low thermal conductivity compared with metal substrates, as well as poor air permeability. In particular, the low thermal conductivity of polymer substrates leads to heat buildup from internal (*i.e.*, device self-heating) and external (atmospheric

Table 1. A summary of experimentally demonstrated thermal management methods for wearable devices

Technique	Material	Structure	Wearable platform	Cooling performance (Other performance)	Application	Ref.
Conduction	Cu	Thin layer	Patch-type oximetry	10 °C lower than without a metal layer	Heat dissipation from PPG sensor	Jung <i>et al.</i> ^[46]
	PDMS/BN	Nanocomposite island	-	Heat guidance using selective heat dissipating composite [1.234 W/(m-K)]	Substrate for multiple chip arrays cooling	Kang <i>et al.</i> ^[131]
	BN/PVA	Fabric	Textile	55% higher than commercial cotton fabric [0.078 W/(m-K)]	Heat transfer from the skin	Gao <i>et al.</i> ^[113]
	TPU/BN/GNR	Fibrous mat	Motion monitoring	32% drop of the saturated temperature [1.37 W/(m-K)]	Cooling resistance change under mechanical stimuli	Tan <i>et al.</i> ^[115]
Radiation	SiO ₂ /Si ₃ N ₄ /Ag	Multilayer	Smartwatch	3.9 °C below the ambient air in the daylight	Colored cooler for wearable devices	Lee <i>et al.</i> ^[117]
	SEBS	Porous film	Bioelectronic	6 °C cooling effects than without film	Thermal management of on-skin electronics	Xu <i>et al.</i> ^[118]
	SEBS/PMMA	Bilayer porous film	PTO	Sub-ambient cooling of 6 °C in daytime	Heat dissipation from PPG sensor	Kang <i>et al.</i> ^[42]
	SEBS	Multilayer porous film	Transformative electronic systems	4.5 °C below the ambient air in the daylight	Prevent unwanted mode conversion in a hot outdoor	Byun <i>et al.</i> ^[43]
Convection / evaporation	Cu/Ag/Nylon 6	Cu matrix/nanofiber	-	3 °C cooling effect with greatly reduced sweat consumption than cotton	Rapid sweat transport & evaporation	Peng <i>et al.</i> ^[120]
	Aramid/MnO ₂	Nanofiber membrane	Textile	3.8 °C lower than cotton clothes	Personal comfort in activities	Chen <i>et al.</i> ^[122]
	CA/Al ₂ O ₃ /PA6/SiO ₂	Nanofiber membrane	Textile	16.6 °C lower than cotton, 8.2 °C by management of the humidity	Personal comfort in activities	Zhang <i>et al.</i> ^[123]
	MIL-101(Cr)	Coating	-	Maximum temperature reduction of 7 °C	Moisture sorption-desorption	Wang <i>et al.</i> ^[124]
Phase change material	n-eicosane/melamine-formaldehyde resin	Film with microsphere	Substrate	Minimized peak skin temperature rise by 82%	Thermal protection for skin	Nie <i>et al.</i> ^[129]
	Paraffin/Cu	Embedded film	Substrate	Minimized peak temperature rise by 85%	Thermal protecting substrate	Shi <i>et al.</i> ^[130]
	SAHM	Hydrogel matrix	Substrate	2 °C lower than without heat sink	Personal comfort in activities	Jung <i>et al.</i> ^[131]
	PA@Cu/SE	Substrate with microcapsule	Substrate	18.6 °C lower than pure SE	Thermal protecting substrate	Sun <i>et al.</i> ^[132]
Thermoelectric	p-/n-type Bi ₂ Te ₃	TE legs	-	8.2 °C lower than ambient air	Personalized cooling	Kishore <i>et al.</i> ^[135]
	Inorganic commercial TE	TE pillars	-	10 °C lower than without heat sink	Personalized thermoregulation	Hong <i>et al.</i> ^[136]
	p-type Bi _{0.5} Sb _{1.5} Te ₃ /n-type Bi ₂ Se ₃	TE fibers	Textile	4.9 °C temperature difference between heat source and heat sink	Electric generator by the difference between source and sink	Zhang <i>et al.</i> ^[104]
	p-/n-type Te	TE pellets	VR glove	13 °C temperature difference in localized cooling and heating	Switching sensations by changing heat flux direction	Lee <i>et al.</i> ^[138]
	PLCL/PEDOT:PSS	Microfiber membrane	-	17 °C temperature difference between heat source and heat sink	Electric generator by the difference between source and sink	Han <i>et al.</i> ^[139]

temperature and sunlight) heat sources. Accumulated heat causes thermal adverse effects, such as thermal discomfort, reduced device reliability, and skin burn when used indoors or outdoors. Nevertheless,

polymers are gaining attention as a thermal conductive cooling technology for wearable devices because of their higher flexibility compared with such materials as metals and ceramics^[30,108-110].

Various heat dissipation strategies have been developed to solve these limitations. For example, Jung *et al.* integrated an optoelectronic device and a thin metal heat sink that can measure heart rate using a PPG sensor^[46]. The PPG sensor makes it possible to monitor blood flow in real time in a noninvasive manner through light emitted from an LED. The metal heat sink attached to the substrate dissipates heat through light, as illustrated in [Figure 2A](#). [Figure 2B](#) shows an optoelectronic device structure. The Cu layer (thickness: 16 μm) is deposited by electrochemical deposition between a polymer substrate and an LED to create a mechanically flexible heat sink. Research has been reported in which the thermal conductivity of the polymer substrate itself was increased using a high-thermal-conductivity filler as well as a heat sink in a device. Generally, the thermal conductivities of polymer materials are between 0.1 and 0.5 W/mK ^[111]. Strategies for making composite materials by adding fillers, such as graphene and boron nitride (BN), to such polymers are being studied.

Kang *et al.* reported a nanocomposite of aligned BN nanosheet (BNNS) islands with porous polydimethylsiloxane (PDMS) foam^[112]. The composite contains (1) porous PDMS (p-PDMS) foam for stretchable and thermal barriers and (2) islands of tetrahedrally structured BN (s-BN) for heat dissipation [[Figure 2C](#)]. The p-PDMS foam is located between s-BN islands and operates as a nonthermal interface to prevent thermal interference in the electronics array. The s-BN islands have vertical and lateral directions of thermal conduction (*i.e.*, 1.219 $\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ in the through-plane and 11.234 $\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ in the in-plane direction) through the tetrahedral pathway of BNNS. Furthermore, by stacking a multilayer composite, heat dissipation can be guided according to the contact interface of p-PDMS and s-BN in the top and bottom layers, as shown in [Figures 2D](#) and [E](#). Gao *et al.* reported highly aligned BN/poly (vinyl alcohol) (PVA) composite fibers to enhance heat transfer from the human body^[113]. The uniform dispersion and high alignment of BNNS improve not only the heat dispersion but also the mechanical strength (355 MPa), as illustrated in [Figure 2F](#). The fiber is fabricated uniformly and on a large scale using a three-dimensional printing method [[Figure 2G](#)]. Aligned and interconnected BNNS implanted in PVA fiber can supply various thermal pathways, and it achieved 55% better cooling performance than commercial cotton fiber. Yu *et al.* developed highly thermoconductive, breathable superhydrophobic nanofibrous membranes that were used to fabricate hydrophobic fluorinated polyurethane and a BNNS fiber membrane using electrospinning^[114]. The membrane consists of BNNS connected along the nanofibers, forming an interpenetrated BNNS network that enhances thermal conductivity while maintaining moisture permeability. An in-plane thermal conductivity of 17.9 $\text{W m}^{-1} \text{K}^{-1}$, a cross-surface thermal conductivity of 0.29 $\text{W m}^{-1} \text{K}^{-1}$, a water vapor transmission rate of 11.6 $\text{kg m}^{-2} \text{day}^{-1}$, a contact angle of 153°, and a hydrostatic pressure of 32 kPa were demonstrated.

Tan *et al.* designed a stretchable strain sensor with thermoplastic polyurethane (TPU) fibrous mats/graphene nanoribbons (GNRs)/TPU-BNNS^[115]. [Figure 2H](#) is a schematic diagram of a strain sensor that contains a conductive nanonetwork because GNRs make it possible to monitor human body motion precisely. In addition, the TPU-BNNS layer has high thermal conductivity through BNNS heat pathways for heat transportation to the environment, and the porous electrospun fibrous TPU membrane acts as a thermal insulation layer for skin-attachable electronics. They conducted a stability test of the strain sensor during the resistance change. The sensor makes stable heat transfer possible, even when joints are bent or extended, as shown in [Figure 2I](#). The surface temperature of the strain sensor displayed thermal stability and showed only a 3.5 °C equilibrium temperature change during a continuous stretching-releasing process between 0 and 100% strain for more than 30 cycles. In conclusion, a 242%-improved thermal conductivity, a 32%-lower real-time saturated temperature, and biocompatibility were achieved.

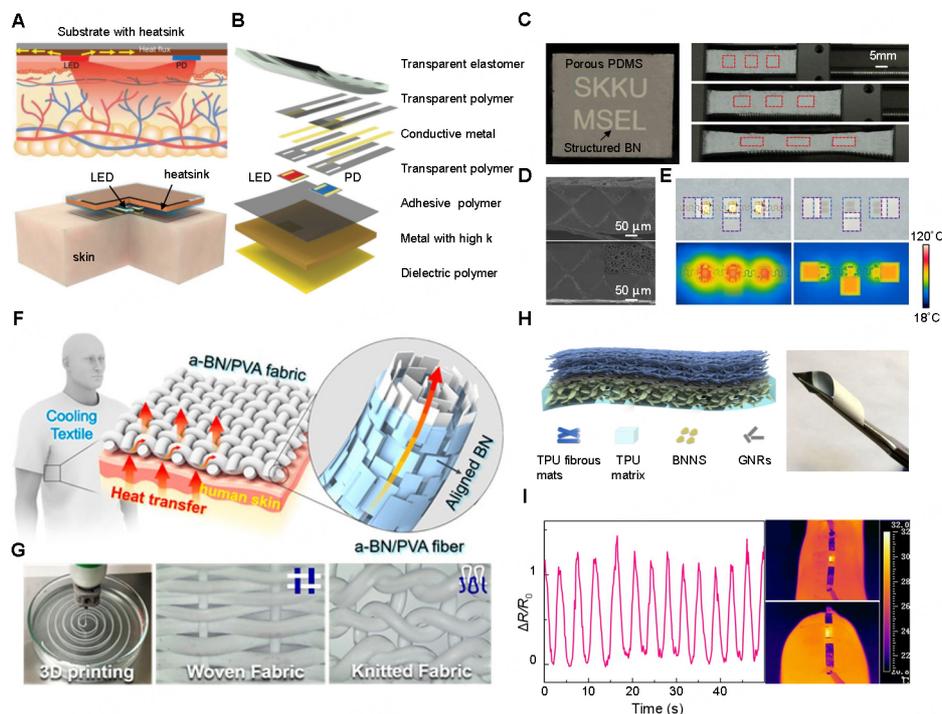


Figure 2. Thermal conductive cooling materials and devices. (A) The optical path and heat flux between μ -ILED and μ -IPD on skin; (B) optoelectronic device structure for blood flow monitoring with metallic heat sink. Reproduced with permission^[46]. Copyright 2018, WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim; (C) nanocomposite of aligned BNNS islands with porous PDMS foam; (D) cross-sectional SEM images of contact interface between s-BN islands and p-PDMS; (E) thermography of LED arrays on the double-layer s-BN/p-PDMS film. Reproduced with permission^[12]. Copyright 2021, Springer Nature; (F) conceptual view of thermal regulation textile. (G) a-BN/PVA fiber using a 3D-printing machine and various fabric structures. Reproduced with permission^[13]. Copyright 2017, American Chemical Society; (H) multilayer wearable strain sensor with TPU fibrous mats/graphene nanoribbons (GNRs)/TPU-boron nitride nanosheet (BNNS); (I) reliability test for temperature and resistance variations of the strain sensor mounted on the knee. Reproduced with permission^[15]. Copyright 2020, Springer Nature.

PASSIVE RADIATIVE COOLING MATERIALS AND DEVICES

The process of cooling an object or system by radiating thermal energy as electromagnetic radiation into outer space or a surrounding environment is called “radiative cooling,” which is expected to reduce energy consumption as part of the next generation of cooling. In radiative cooling, heat transfer is performed by (1) solar radiation; (2) conduction and convection; and (3) ATWs. Solar radiation with wavelengths shorter than $4 \mu\text{m}$ scatters the target, while nonradiative heat transfer occurs through conduction and convection by air. Finally, the atmosphere has highly transparent radiation for heat transfer in the ATW ($8\text{--}13 \mu\text{m}$ wavelength range). The total energy flow is the consequence of solar and atmospheric heat absorption, radiation-induced heat loss, and nonradiative heat exchange^[116]. However, passive radiative cooling techniques exhibit lower cooling performance than active cooling technologies, such as air and water cooling, and their manufacturing on a large scale can be challenging. Nevertheless, these cooling techniques are advantageous because they are flexible, compact, environmentally friendly, and suitable for outdoor applications owing to their ability to protect against external heat. In particular, their flexibility, light weight, and heat resistance make them appropriate for use in wearable devices^[43,78].

Because of the outstanding cooling performance, zero power requirement, and versatile platforms, several researchers have attempted to integrate stretchable/flexible wearable devices with a cooling solution, as summarized in Table 2. For example, Lee *et al.* fabricated a colored passive radiative cooler (CPRC) composed of a metal-insulator-metal (MIM) structure^[117]. Figure 3A is a diagram of the CPRC, which consists of a SiO₂ (650 nm) and Si₃N₄ (910 nm) bilayer as an emitter and Ag film (100 nm) as a metal reflector. The origin of each color was controlled by varying the thickness of the insulator layer (*i.e.*, the SiO₂ capacity) in the MIM, which was determined by interference in the 1D stacked layers. It was shown experimentally that, in the daytime, the CPRC was 3.9 °C cooler than the ambient air throughout the day. They also demonstrated cooling performance integrated with wearable devices [Figure 3B]. Al foil was used as a substrate considering compatibility with the wearable device, and a MIM and emitter layer were deposited on Al foil and encapsulated using PDMS for protection and outstanding emissivity in the thermal infrared (IR) region. The flexible and stretchable mechanical properties make integration of the radiative cooler and wearable devices possible. In addition, the radiative cooler should consist of nonmetallic materials to avoid interference with wireless communications.

Xu *et al.* designed highly versatile on-skin electronics with a radiative cooler substrate considering user comfort^[118]. Using a phase inversion method with polystyrene-block-poly(ethylene-ran-butylene)-block-polystyrene (SEBS), isopropyl alcohol, and chloroform, a radiative cooler substrate was fabricated. The multiscale porous SEBS structure is depicted in Figure 3C, where the micropores exhibit high solar reflectivity while maintaining low long-wave IR reflectivity (4–13 μm). Bioelectronic devices, including various biosignals (ECG, temperature, humidity, and body motion), were fabricated by spray printing silver nanowires onto a multiscale porous SEBS substrate, as shown in Figure 3D.

Kang *et al.* developed a thermally stable near-field communication (NFC)-based patch-type tissue oximeter (PTO) with a radiative cooler^[42]. The nanovoid/microvoid polymer (NMVP) used a SEBS and poly(methyl methacrylate) (PMMA) bilayer for radiative cooling [Figure 3E]. By obtaining Mie scattering enhancement and antireflection effects through the porous PMMA layer, the NMVP could achieve high solar reflection and heat emission. The PTO could measure muscle oxygenation during activity with compact dimensions (20 × 17 × 2 mm). Figure 3F displays a photograph of the NMVP-integrated PTO, with all layers flexible and conformal contact to the skin. Figure 3G exhibits the difference in temperature between black elastomer (BE), white elastomer (WE), and NMVP on the skin when exposed to sunlight. The BE and WE reached 40 °C and 35 °C, respectively, 8 min later, while the NMVP stayed at the usual skin temperature. Stability tests of the PTO with and without NMVP were also performed. The PTO with NMVP exhibited a tissue oxygen saturation (StO₂) value of approximately 80%, which was an accurate measurement compared to the normal state, *i.e.*, approximately 80%). However, the PTO without NMVP showed an unstable measurement (StO₂ value of ~67%) because of heating by solar absorption.

Furthermore, Byun *et al.* reported gallium-based transformative electronics integrated with a radiative cooler for outdoor use^[43]. The transformative electronics system (TES) was used to switch the shape and stiffness between rigid handheld and soft wearable configurations. The TES used gallium ($T_{\text{melt}} = 29.76$ °C, where T_{melt} represents the melting point of gallium) as a core material to implement stiffness tuning by changing the phase between solid and liquid. However, the TES has difficulty maintaining a rigid form in outdoor applications because of excessive heat accumulated from itself or environmental sources, such as the sun. Figure 3H shows a conceptual illustration of the TES integrated with a multi-layered, flexible, and stretchable radiative cooler (m-FSRC) that can be used in the rigid mode under sunlight. The integrated radiative cooler can reflect solar energy and radiate thermal energy. Thus, the transformative platform minimizes the temperature increase during continuous operation under sunlight exposure. The m-FSRC is

Table 2. A summary of radiative cooler characteristics integrated into wearable devices

Fabrication method	Application method	Breathability/Waterproof	Thickness	Solar reflectance	LWIR emission	Reference
Deposition	Coating	X/O	~125 μm	R_{solar} : ~85%	ϵ : ~80%	Lee <i>et al.</i> ^[117]
Drop casting	Lamination	O/O	~100 μm	R_{solar} : ~90%	ϵ : ~85%	Xu <i>et al.</i> ^[118]
Drop casting/spraying	Lamination	X/X	~500 μm	R_{solar} : ~95%	ϵ : ~85%	Kang <i>et al.</i> ^[42]
Drop casting/stack	Encapsulation	O/O	~700 μm	R_{solar} : ~99%	ϵ : ~90%	Byun <i>et al.</i> ^[43]

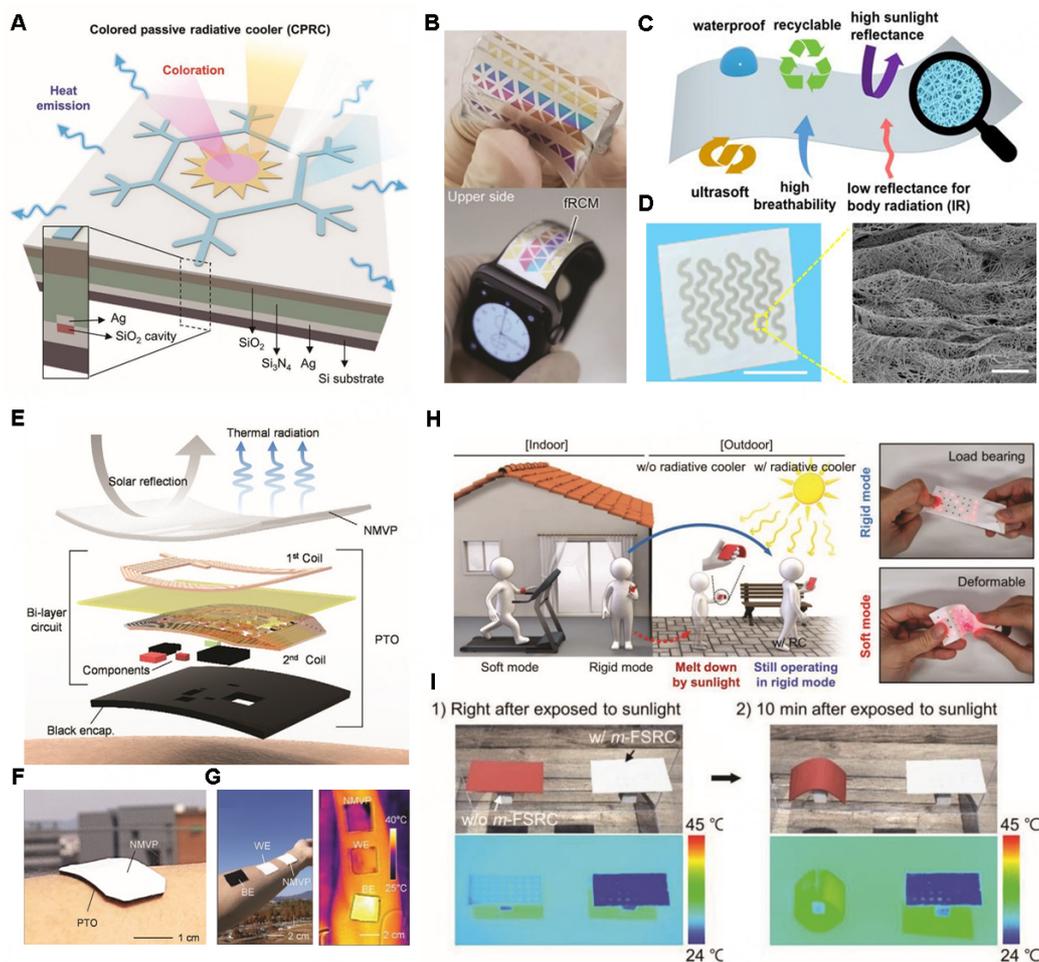


Figure 3. Passive radiative cooling materials and devices. (A) Colored passive radiative cooler (CPRC) integrated with wearable device; (B) photographs of CPRC on flexible substrate with wearable device. Reproduced with permission^[117]. Copyright 2018, Wiley-VCH GmbH, Weinheim; (C) high versatile porous SEBS substrate for on-skin electronics; (D) spray-printed Ag nanowire electrodes for on-skin electronics. Reproduced with permission^[118]. Copyright 2019, National Academy of Science; (E) NFC-based patch-type tissue oximeter (PTO) with nanovoid/microvoid polymer (NMVP); (F) optical image of device mounted on the forearm (G) temperature comparison of black elastomer (BE), white elastomer (WE), and NMVP. Reproduced with permission^[42]. Copyright 2021, Wiley-VCH GmbH, Weinheim; (H) conceptual illustration of gallium-based TES with multi-layered flexible and stretchable radiative cooler (m-FSRC); (I) outdoor temperature test of gallium-based transformative substrates with and without m-FSRC under the sunlight. Reproduced with permission^[43]. Copyright 2022, Wiley-VCH GmbH, Weinheim.

fabricated as five stacked single-layered FSRCs with porous structures, which lead to multiple Mie scattering for outstanding reflectivity within the solar spectrum. **Figure 3I** verifies the cooling effect of a radiative cooler for the transformative platform. The transformative platform with the integration of a radiative

cooler keeps flat and stiff under sunlight exposure, while a bare sample without a radiative cooler becomes soft. In the corresponding IR images, the surface temperatures of the samples with and without the radiative cooler are 24 °C and 38 °C, respectively. Therefore, the transformative platform based on gallium ($T_{\text{melt}} = 29.76$ °C) maintains its rigid mode owing to the significant cooling performance of the radiative cooler.

EVAPORATIVE COOLING MATERIALS AND DEVICES

One cooling solution in the human body is evaporative cooling, particularly sweat evaporation, which can transfer a significant amount of heat. However, wearable devices lack the capacity to regulate moisture because of their hydrophobic properties, which cause discomfort and ineffective cooling during perspiration resulting from heating. Excessive residual perspiration on the skin absorbs heat because water is denser and more heat-resistant than air, which can be detrimental to thermal comfort and cooling effectiveness^[119]. An evaporative cooler moves sweat and maximizes breathability, making it easy for sweat or moisture to evaporate. Cooling power caused by evaporation can dissipate heat at a higher level than other passive coolers^[120]. Furthermore, an evaporative cooler is comfortable for the user because it enables the skin to breathe and sweat to evaporate naturally. The effectiveness of evaporative cooling depends highly on environmental conditions such as temperature, humidity, and wind speed^[121]. In addition, an evaporative cooler requires direct contact with the skin for sweat transport. Therefore, careful consideration of the specific requirements of the wearable device is necessary before choosing evaporative cooling technology.

Recently, Peng *et al.* reported integrated cooling (i-Cool) textiles for enhancing sweat transportation^[120]. These textiles provide enhanced sweat evaporation capacity and high cooling effectiveness for sweat evaporation, in addition to a liquid sweat draining function, by efficiently integrating water transport routes and heat conducting pathways. In contrast to traditional fabrics, i-Cool textiles efficiently remove a significant amount of heat from the skin by wicking sweat as well as creating heat conduction channels for quick evaporation, as illustrated in [Figure 4A](#). [Figure 4B](#) shows optical and scanning electron microscopy (SEM) images of i-Cool (Cu) textiles. Nylon 6 nanofibers not only coat the Cu surface but also fill the pores. Compared with those found in the pores of the Cu matrix, the nanofibers on the skeleton of the Cu matrix are denser and have less space between them. The difference in capillarity caused by the variance in shape makes unidirectional water passage possible from the inner to the outer surface.

Chen *et al.* developed aramid nanofiber-MnO₂ nanowire (ANFMN) hybrid membranes with heat dispersion and sweat transport^[122]. Using a hydrothermal process, vacuum filtration, and steam modification, a bilayer ANFMN hybrid membrane was constructed with hydrophilic aramid nanofiber-MnO₂ nanowire (HAFMW) and hydrophobic MnO₂-nanowires@MnO₂-nanosheet (HMWMN), as illustrated in [Figure 4C](#). The ANFMN hybrid membranes have strong radiation heat dissipation capabilities, as shown by the greater IR emissivity of the HMWMN layer and the 3.8 °C temperature differential between clothes and membranes in the IR image. Remarkable sweat transportation capabilities were demonstrated through simulation, with sweat moving from the HMWMN layer into the HAFMW layer in only 13.4 s. When sweat contacts the HMWMN layer, it penetrates below and progressively moves up to the AFMW layer as time passes. SEM images of HAFMW and HMWMN are shown in [Figure 4D](#). MnO₂ nanowires with a high aspect ratio are entangled with one another to form a network structure in the HAFMW layer, and smaller-diameter aramid nanofibers are entangled between the MnO₂ nanowires. The HMWMN layer morphology changed little from before to after the hydrophobic alteration.

Zhang *et al.* developed a metafabric that integrates nanofiber membranes to combine evaporative cooling with radial cooling^[123]. A hierarchical metafabric that can selectively emit IR radiation and reflect sunlight is made up of layers of cellulose acetate (CA), aluminum oxide (Al₂O₃), and polyamide 6 (PA6). CA/Al₂O₃ was

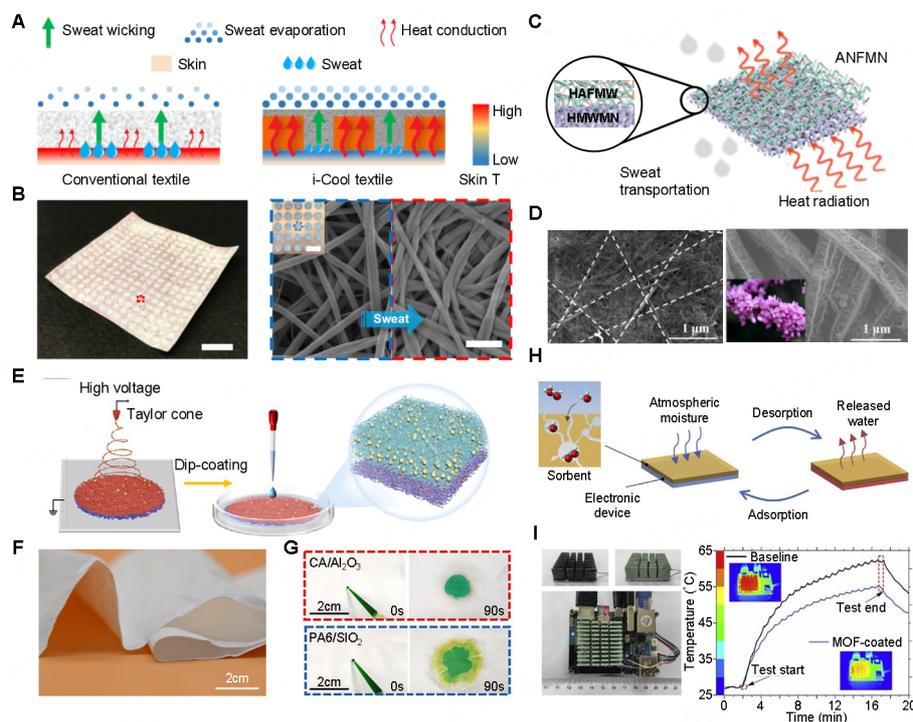


Figure 4. Evaporative cooling materials and devices. (A) Heat conduction and sweat evaporation of i-Cool textile compared with conventional textile; (B) optical and SEM images of i-Cool (Cu) textile that consist of Nylon 6 nanofiber on Cu foil. Reproduced with permission^[120]. Copyright 2021, Springer Nature; (C) aramid-nanofiber-MnO₂-nanowire (ANFMN) hybrid membrane; (D) SEM images of hydrophilic aramid-nanofibers-MnO₂-nanowires (HAFMW) and hydrophobic MnO₂-nanowires@MnO₂-nanosheets (HMWMN), respectively. Reproduced with permission^[122]. Copyright 2022, American Chemical Society; (E) fabrication process of the hierarchical metafabric using electrospinning; (F) optical image of metafabric; (G) viewed from above, the wetting responses of the CA/Al₂O₃/HPX and PA6/SiO₂/HPX layers, respectively. Reproduced with permission^[123]. Copyright 2022, American Chemical Society; (H) thermal management of MIL-101(Cr) through moisture adsorption-desorption process; (I) temperature measurement of electronics with MIL-101(Cr)-coated heat sink. Reproduced with permission^[124]. Copyright 2020, Elsevier.

changed by HPX (a moisture control agent) at the bottom nanofiber membrane layer, which is near the skin. The HPX changes the PA6/SiO₂ layer of the top nanofiber membrane [Figure 4E and F]. Sweat is removed from the skin surface by the CA/Al₂O₃/HPX layer, and it is then quickly absorbed and diffused by the PA6/SiO₂/HPX layer. The penetration and spreading characteristics of 100 μ L of water droplets on the CA/Al₂O₃/HPX and PA₆/SiO₂/HPX layers were investigated to study the sweat evaporation process, as shown in Figure 4G. Comparing the hierarchical metafabric to conventional textiles in cooling performance testing showed that the hierarchical metafabric reduced overheating by 16.6 °C on simulated skin.

A novel evaporative cooler that absorbs moisture from the ambient air rather than sweat, and uses it to facilitate evaporation, thereby reducing the temperature, has been reported. Wang *et al.* introduced a thermal control approach based on sorbent desorption^[124]. The adsorbents absorb moisture from the atmosphere throughout the adsorption cycle [Figure 4H]. The desorption cycle, which might result in additional heat flux, starts because of the rising temperatures caused by the increased activity of the device. The desorption procedure extracts some heat, which is then released into the environment by vapor diffusion. Thus, it is possible to stop the temperature from rising. The quantity of desorbed water is related directly to the amount of heat taken from the electronics. Because of the well-studied molecular behavior of the suggested material, including its strong water absorption and characteristic S-shaped isotherm, a metal-organic framework [MIL-101(Cr)] was selected^[125]. A practical application for thermal control of electronics

was also tested. [Figure 4I](#) shows that the temperature of the case shell grew more slowly with the coated heat sink than with the original heat sink. After 15 min of stress testing, a maximum temperature drop of 7 °C was achieved.

PHASE CHANGE MATERIALS FOR THERMAL PROTECTING

PCMs are suitable for thermal management solutions in a variety of situations because they can absorb or release heat from the target through the phase transition mechanism. Although PCMs have the potential to enhance the performance of thermal management, the impact of their concentration on heat transfer characteristics, such as latent heat, remains uncertain. In addition, improved numerical models and analytical techniques are necessary to evaluate the cooling performance of PCMs in various situations^[126]. Nevertheless, their shape adaptability and flexibility make them highly effective for equipment thermal control because they can maintain a consistent temperature throughout the phase transition process.

In recent years, PCM substrates have been studied extensively as viable solutions for the heat management of flexible electronic devices. Researchers have reported that these materials possess adequate flexibility and resilience to adapt to changes in the shape of the body^[127,128].

In wearable devices, these flexible PCMs can be used as TPSs. Nie *et al.* created a polymer-based TPS that can be used in wearable devices^[129]. As illustrated in [Figure 5A](#), the wearable device uses a functional heating component that generates heat energy, which is employed through its phase shift of n-eicosane to avoid overheating of the skin. To achieve this, an n-eicosane heat-absorbing microsphere with a melamine-formaldehyde resin coating is combined with PDMS to provide a thermal insulation function [[Figure 5B](#)]. Through optimization, it was demonstrated that the thermally protective substrate could withstand complicated deformations of more than 150% and minimize the peak skin temperature rise by 82% or more. Furthermore, studies conducted on the skin of a mouse have shown the thermal protection potential of the device for wearable thermal management.

Shi *et al.* presented the concept of a PDMS substrate comprising an embedded PCM with a thin copper film on top^[130]. A functional soft composite that serves as a TPS for wearable electronic devices was proposed, comprising two key components: a PCM and a thin metal film. As illustrated in [Figure 5C](#), the paraffin (transition temperature: 18-71 °C), located beneath the metal film, can absorb excessive heat above its transition temperature to reduce heat dissipation to the skin. Because of its high thermal conductivity, the copper film implanted in the PDMS efficiently modifies the heat flow directions to reduce heat transfer to the skin further. The proposed thermal protecting substrate has been demonstrated to reduce the peak temperature rise by more than 85% compared with a conventional substrate. In addition, [Figure 5D](#) shows finite-element analysis FEA simulations and temperature tests on pig skin and a comparison with conventional substrates. The functional soft composite substrate was found through FEA to lower the maximum temperature increase significantly (by 65%), and no skin burns were observed when the device was applied to pig skin in the experimental trial. Furthermore, research has been conducted on utilizing composite PCM materials to enhance the phase transition characteristics and conformal contact on the skin.

Jung *et al.* fabricated an advanced thermal skin (ATS) using a hybrid-based approach that exhibits outstanding thermal diffusivity and thermal storage properties^[131]. The ATS is composed of a silver flake/PDMS serpentine structure (SPS) and a sodium-acetate-based hydrogel matrix (SAHM). By incorporating thermally conductive metallic fillers, the SPS made efficient heat dispersion possible throughout the ATS network. The intrinsic softness of the SPS also allowed the ATS to conform to the highly malleable surface

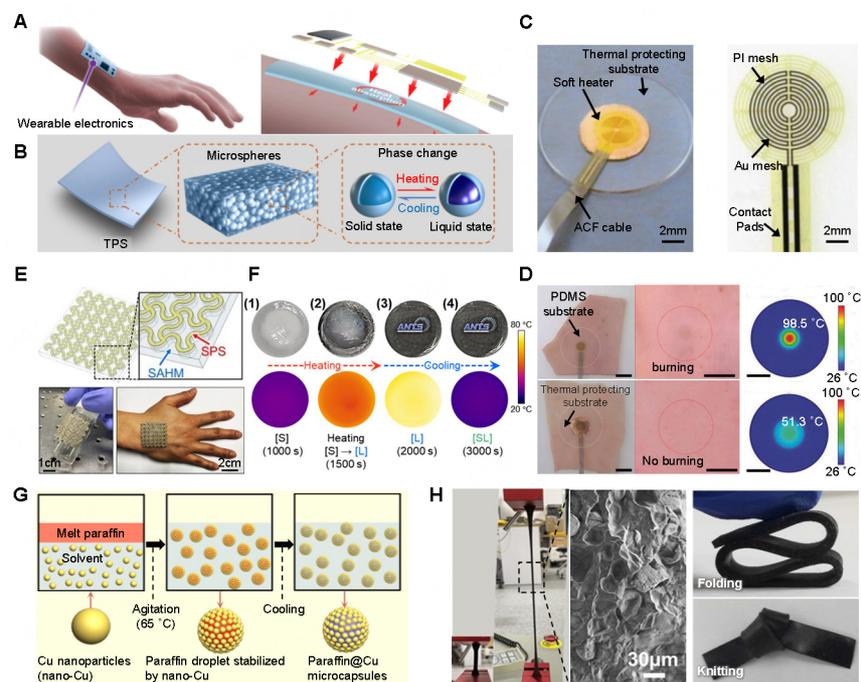


Figure 5. Phase change material for thermal protection. (A) Heat flow direction of wearable device with the thermal protective substrate (TPS); (B) heat-absorbing microspheres composed of PCM. Reproduced with permission^[129]. Copyright 2022, Springer Nature; (C) a wearable device composed of a soft heater and a thermal protective substrate; (D) heat shielding test at pig skin attribute TPS. Reproduced with permission^[130]. Copyright 2019, Wiley-VCH GmbH; (E) advanced thermal skin (ATS) imparted with silver flake/PDMS serpentine structure (SPS) and sodium-acetate-based hydrogel matrix (SAHM); (F) on-demand solid-to-liquid phase shift of SAHM. Reproduced with permission^[131]. Copyright 2022, Elsevier; (G) fabrication process of Paraffin@Cu microcapsules; (H) optical and SEM images of Paraffin@Cu/silicone elastomer composite. Reproduced with permission^[132]. Copyright 2021, Springer Nature.

of human skin, resulting in improved comfort during strenuous activity [Figure 5E]. Furthermore, unlike the spontaneous release of latent heat below the melting point during the phase transition of PCMs, the exothermic process of SPS can only be activated when needed. This selective phase transition of SPS protects the human body from unwanted temperature discomfort, whereas the heat reactions of conventional PCMs are uncontrolled [Figure 5F]. Flexibility was achieved with a low modulus variation of 4.8, a high thermal diffusivity of 0.307 mm²/s, and a large latent heat of 94.29 J/cm³, surpassing that of paraffin.

Sun *et al.* designed highly extensible composite PCMs with an embedded paraffin@copper microcapsule (PA@Cu)^[132]. The nano-Cu metal shell used to encase PCMs through the Pickering emulsion method is illustrated in Figure 5G. Because of the alignment of nano-Cu particles on the PCM particle surface, the nano-Cu shell is elastic. By manufacturing PA@Cu microcapsules with a high PCM encapsulation ratio of 98%, a composite of flexible PCMs was formed. The silicone elastomer (SE) that the PA@Cu microcapsules were tightly enclosed in demonstrated their great compatibility. The composite PCMs that arise are flexible and thermally stable. Tensile tests have shown that flexible composites with a considerably greater loading of 40-wt% PA@Cu have an extensibility of more than 730% [Figure 5H]. Despite the improvement in the thermal conductivity of SE because of the PA@Cu, the thermal conductivity of the PA@Cu/SE composite is only 0.212 W/(mK). The improved ability to regulate thermal energy makes these composites suitable for wearable electronics because they provide superior thermal protection for human skin.

THERMOELECTRIC COOLING MATERIALS AND DEVICES

TE cooling, which exploits the Peltier effect to transfer energy directly from electricity to heat, is attracting significant interest owing to its many benefits. These include being quiet, motionless, miniaturized, lightweight, capable of cooling and heating, and eco-friendly because TE does not require the use of refrigerants. However, the high cost and low power efficiency of TE materials remain to be addressed. Furthermore, TE cooling systems generate heat as a by-product, so it is important to design a structure with heat dispersion. Because it is one of the few miniaturized active coolers that can be applied to wearable devices, not only conventional rigid TE coolers but also TE coolers with various flexible structures have been reported^[133,134]. The development and application of wearable technology with TE coolers is based on the principle of TE cooling. As shown in [Figure 6A](#), Kishore *et al.* investigated the impact of the thermal resistances of the heat source/sink and the TE material parameters on the performance of a TE cooler^[135]. They lowered the skin temperature by 8.2 °C in ambient air, representing a 170% improvement over the cooling performance of commercial TE modules.

Conventional TE coolers have bulky, inflexible components, which are a significant obstacle to their application in flexible systems. To solve this problem, several studies on the construction and materials of flexible TE coolers have been conducted. Hong *et al.* fabricated a wearable TE device that had high elasticity owing to the combination of elastomer and rigid TE pillars^[136]. The TE device is easily embeddable into clothing and is suitably thin, flexible, and lightweight. A double elastomer layer structure, consisting of an air gap insulating layer sandwiched between two stretchable sheets and high-ZT inorganic TE pillars with an optimal aspect ratio and spatial density, is used to provide mechanical flexibility and excellent cooling performance [[Figure 6B](#)]. The top stretchable sheet stretches and the bottom sheet contracts when the double-layer TE device is bent. To achieve low thermal conductivity and high flexibility in the TE device, TE pillars with a high aspect ratio are implanted with several elastomer layers and air gap thermal insulation. This eliminates the need for the massive heat sinks commonly used in previous devices. Without using a heat sink, the TE device lowers the temperature by 10 °C.

Zhang *et al.* proposed inorganic TE wire using a thermal drawing process^[137]. [Figure 6C](#) shows optical and SEM images of the fiber. The core material is composed of p-type $\text{Bi}_{0.5}\text{Sb}_{1.5}\text{Te}_3$ and n-type Bi_2Se_3 , and borosilicate glass is used as the cladding material. At a ΔT of 140 K, the TE power generator, composed of inorganic TE fibers, exhibits a high output power of 3 W. The fibers are woven into the fabric to create a flexible TE device, as depicted in [Figure 6D](#), which shows the experimental temperature profile captured by an IR camera. Using two sets of p-n core fibers and applying a 2 mA current, a simulation of a temperature profile is produced to assess the TE cooling capability. The analysis of the TE cooling performance demonstrates that the devices can reduce the temperature by 5 °C. Fiber-woven fabrics can serve not only as TE generators, which use heat from the body to produce electricity, and TE coolers, which cool the body through the application of low currents, but also as thermal sensors. Moreover, because of their thin composition, these fabrics retain air permeability in the covered area, a crucial factor for extended comfort on curved human skin. Combining the cooling/heating modes of TE with a wearable sensor makes active temperature regulation possible.

Lee *et al.* assembled a skin-like, stretchable, and dual-mode thermo-haptic device for a virtual reality experience^[138]. The conceptual process of the skin-like thermo-haptic (STH) device is shown in [Figure 6E](#). The device was designed to make it possible to sense cold and heat in virtual reality. The cooling and heating are achieved by TE with system feedback. The p- and n-type telluride TE pellets, which are capable of rapid temperature variation with the application of voltage, are connected by Cu electrodes coated with polyimide on one side and encapsulated in a thin layer of thermally conductive elastomers. The Cu

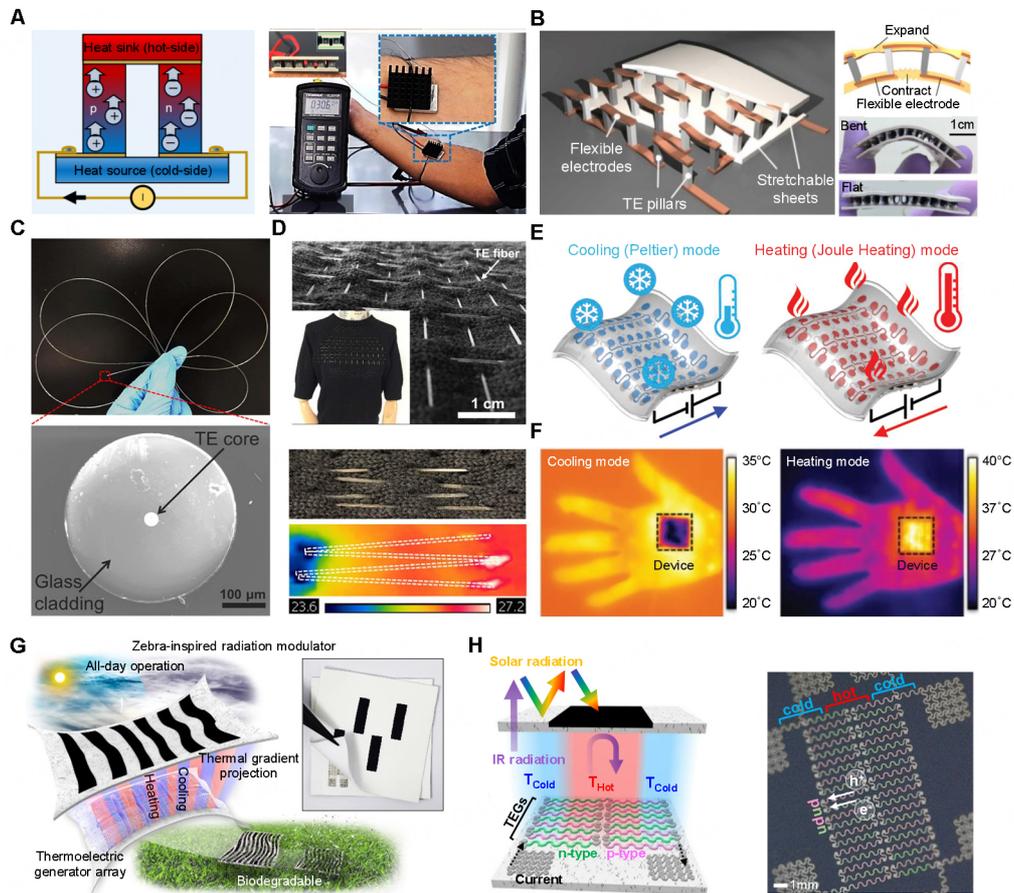


Figure 6. Thermoelectric (TE) cooling materials and devices. (A) Operation mechanism and photograph of TE cooler module. Reproduced with permission^[135]. Copyright 2019, Springer Nature; (B) wearable TE device with high flexibility. Reproduced with permission^[136]. Copyright 2019, American Association for the Advancement of Science; (C) optical and SEM images of flexible crystalline TE fiber (D) wearable TE fabric knitted with TE fibers and thermography of TE fiber cooling test. Reproduced with permission^[137]. Copyright 2017, Elsevier; (E) dual-mode operation of skin-like thermo-haptic device by changing current flow; (F) IR images of device cooling/heating mode mounted on the palm. Reproduced with permission^[138]. Copyright 2020, Wiley-VCH GmbH; (G) conceptual view of zebra-inspired radiative cooling membrane with TE generator; (H) energy flow of energy-harvesting system and photograph of n- and p-type Si NM TE generator array. Reproduced with permission^[139]. Copyright 2023, American Association for the Advancement of Science.

serpentine electrodes, encased in thermally conductive elastomers, can endure significant strain in both directions without sacrificing electrical circuits with low resistance. As a result, by utilizing a thermal feedback process for precise and immediate temperature control, STH devices can actively cool and heat flexible skin surfaces, thereby simulating ideal heat with a level of flexibility of 230% [Figure 6F]. The TE cooler is integrated not only with the wearable sensor but also with other cooling solutions.

Han *et al.* developed a zebra-pattern-inspired radiative cooling/heating system with a TE generator^[139]. Figure 6G shows a dual-mode eco-resorbable cooler with strong solar reflection and IR emission made using poly(L-lactide-co- ϵ -caprolactone) (PLCL) as the white base material. The membrane was partially coated with conductive black PEDOT:PSS with high solar absorption and IR reflectance, creating clear hot and cold regions in a plane geometry resembling the black-and-white stripes of a zebra. Because of the substantial temperature difference created by the soluble magnesium (Mg) connection at the bottom layer, charge carriers in the doped p- and n-type silicon nanomembrane (Si NM) arrays could produce TE potentials. The conductive PEDOT:PSS-coated area experienced heating by hindering heat dissipation,

while the PLCL zone was cooled through heat release. This resulted in a temperature differential between the TE generator regions, leading to the generation of power (as shown in [Figure 6H](#)). The proposed system showed outstanding performance compared with relying solely on radiative cooling. The system can maintain performance during stretching and generate energy throughout the day to ensure the viability of eco-friendly energy harvesting when coupled with a TE generator system.

CONCLUSION AND OUTLOOK

In this review, recent advances in thermodynamic technology that make it possible to manage thermal conditions efficiently for external/interfacial wearable devices on the skin of users are summarized, ranging from microstructures/nanostructures to dynamically changing materials. With the advances in wearable devices, the progress in this field has been rapidly evolving over the past decade, resulting in many promising achievements, along with new ideas and strategies. Thermal management schemes offer a variety of potential pathways toward efficient thermal management of wearable devices through the modification and optimization of structures or properties to improve performance based on each thermal mechanism. Highly beneficial applications have been demonstrated both conceptually and experimentally, including structured thermal conductors, passive radiative coolers, evaporative textiles, PCM-based coolers, and TE devices. Nonetheless, thermal management technologies for wearable devices are in their infancy, limited to laboratory settings, and must mature to meet the demands of practical and industrial applications. This entails addressing material and manufacturing issues for thermoregulators and wearable devices that have not yet received adequate attention.

Wearable device applications require careful consideration of a variety of biomedical needs, including nontoxic/nonirritant qualities, breathability, regulatory compliance, and aesthetics. Because past studies have been few, interdisciplinary collaboration and rigorous clinical testing are necessary to assess these requirements. The growth of wearable applications requires low-cost mass production and ongoing basic research. Population diversity and operating conditions must be considered in comprehensive studies, especially studies of heat transfer into and out of human skin^[140]. Other than conventional thermal conductors, such as heat sinks, there is still a lack of well-tested and proven thermal management structures in practical, field-tested devices. During long-term, repetitive device operation in various thermal environments, thermoregulator-integrated wearable devices should be tested to ensure that they can provide users with practical monitoring and information. Most thermal management schemes previously introduced have been conceptually demonstrated in limited settings, depending only on one of their thermal management mechanisms. In reality, thermal structures in outdoor/indoor thermal environments cannot operate solely as independent thermal mechanisms but are affected by the interaction of multiple thermal mechanisms. Convergence studies in materials and structures covering complex thermal mechanisms are necessary to manage the thermal conditions of wearable devices realistically. Active thermal management is a promising field for fundamental research. The potential for thermal diodes, thermal transistors, and other innovative thermal control devices to provide exciting opportunities is evident; however, there is currently a lack of conceptual designs for practical and versatile solid-state thermal control devices^[140]. The exploration of novel concepts and physical mechanisms that extend beyond established TE processes is a rich area for investigation.

In conclusion, with the recent rapid development of thermodynamics and manufacturing technology, wearable electronics based on thermoregulators have become an advanced platform for practical/future applications but still have limitations. Further technological advances are necessary to meet industry demands, such as high-efficiency thermal management, fast thermal modulation, cost-effective manufacturing, active thermal management, and fully integrated multifunctional devices.

Researchers should weigh the benefits and downsides of different thermal management techniques to fix problems and encourage the development of cooling technologies. The future of thermal management research for wearable devices is promising, and ongoing technological improvements can lead to the development of even more inventive solutions. Wearable devices that generate heat can be uncomfortable and even dangerous, so enhancing their thermal management can make them safer and more useful. Wearable devices frequently rely on batteries, which can be damaged by heat; research on thermal management can increase battery efficiency and extend battery lifespan. In addition, heat management can affect the accuracy and reliability of sensors as well as the durability of wearable devices that are susceptible to bending and flexing. With the rapid development of micro/nano materials and electronics manufacturing technology, fundamental analysis of the thermal characteristics of materials/devices, advanced integration of materials and devices, and innovative thermal management mechanisms, thermal management schemes can be applied to various multifunctional wearable devices worn on various parts of the body to provide users with a better daily experience.

DECLARATIONS

Authors' contributions

Literature review, the outline of the manuscript structure, and writing of manuscript draft: Yun JH, Yoo YJ

Revised the manuscript: Yun JH, Yoo YJ, Kim HR

Supervision, writing - review & editing, project administration: Song YM

All authors have read the manuscript and approved the final version.

Availability of data and materials

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Conflicts of interest

All authors have declared that there are no conflicts of interest.

Ethical approval and consent to participate.

Not applicable.

Consent for publication

Not applicable.

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