



Photothermal phase change materials for wearable thermal management and intelligent healthcare

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Abstract

Photothermal phase change materials (PCMs) are emerging as one kind of multifunctional wearable energy materials that integrate latent-heat storage with solar-to-thermal conversion, electrothermal heating, radiative regulation, and intelligent sensing. Unlike conventional PCMs, wearable photothermal PCMs should simultaneously satisfy thermal performance, flexibility, breathability, leakage resistance, cycling stability, and skin compatibility. We summarize recent progress in photothermal PCMs for wearable thermal management and intelligent healthcare, focusing on material systems, energy-conversion mechanisms, and application scenarios. Shape-stabilized solid-liquid composites, intrinsically flexible solid-solid/polymeric PCMs, photothermal-filler-enhanced composites, and phase-change azobenzene (PC-Azo) molecular solar thermal (MOST) systems are discussed. Their applications in personal thermal management (PTM), solar-thermal/optically switched heat release, wearable thermotherapy, intelligent healthcare, wearable electronics, and self-powered systems are highlighted. Finally, key challenges and future opportunities are proposed, including human-centered evaluation standards, multimodal thermal regulation, epidermal phase-change hydrogels, phase-change solar thermal textiles, and AI-guided material design.

Keywords: Phase change material, photothermal, wearable, thermal management, intelligent healthcare

1. Introduction

Thermal homeostasis is essential for comfort, normal physiological activity, and health. However, the thermal microenvironment next to the body is often unstable because of changing weather, outdoor work, and the increasing use of skin-mounted electronic devices. Conventional heating and air-conditioning systems regulate the entire surrounding environment rather than the individual body, resulting in high energy consumption and limited adaptability to personal thermal demands. Personal thermal management (PTM), by contrast, aims to regulate heat exchange close to the body through clothing, patches, textiles, or flexible devices, thereby improving thermal comfort with much lower energy input^[1-3]. PTM materials maintain the skin/clothing microclimate within a thermally comfortable range by controlling heat conduction, convection, radiation, evaporation, and heat storage/release around the body. Thermal insulation aerogels^[4], radiative cooling textiles^[5], moisture-responsive fabrics^[6], and electrothermal heaters^[7] have therefore been developed for heat retention, daytime radiative cooling, moisture transport, or Joule heating-based warming. However, many of them mainly function through one dominant heat-transfer pathway and often provide either cooling or heating under a specific condition. For example, radiative cooling materials are effective for heat dissipation but may be less suitable for cold environments, while electrothermal materials offer rapid heating but depend on a continuous power supply. In this context, phase change materials (PCMs) are particularly attractive because their reversible phase transitions allow them to absorb excess heat, store thermal energy as latent heat, and release it when the ambient or skin temperature decreases, thereby stabilizing the human-body microclimate without continuous external energy input^[8,9]. Thus, PCMs can address a central challenge of PTM related to providing long-lasting, localized, and low-energy thermal regulation under dynamically changing environmental and physiological conditions.

Despite these advantages, the direct use of conventional organic PCMs remains limited by liquid leakage, low thermal conductivity, poor solar absorption, insufficient flexibility, and weak integration with soft and breathable wearable substrates^[9-12]. These limitations have inspired the design of PCMs, in which latent-heat storage is coupled with solar-to-thermal conversion, electrothermal heating, radiative heat exchange, or molecular photoisomerization to achieve more adaptive thermal regulation. The



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scientific basis of photothermal PCMs lies in the coupling of heat storage and energy conversion across multiple length scales. At the molecular level, crystallizable chains, alkyl segments, or azobenzene (Azo) photoswitches determine phase-transition temperature, latent heat, and light-triggered energy storage^[13–16]. At the mesoscale, polymer networks, porous scaffolds, microcapsules, fibers, aerogels, hydrogels, and Janus architectures stabilize the phase-changing components while providing mechanical compliance and interfacial compatibility^[17–22]. At the device and textile scale, photothermal fillers such as carbon nanotubes, graphene, MXene, polydopamine (PDA), metal nanoparticles, and metal-organic frameworks (MOF)-derived carbons convert light or electricity into heat and promote heat transfer into the PCM domains^[23–29]. The material problem is therefore not simply to maximize latent heat storage, but to simultaneously optimize phase-transition behavior, optical absorption, thermal conductivity, mechanical softness, water-vapor permeability, washability, and long-term cycling stability.

The application landscape of photothermal PCMs is also expanding from passive thermal buffering toward intelligent, interactive, and health-oriented wearable systems^[30–32]. In PTM, PCM-integrated textiles and films can delay overheating or overcooling, while photothermal and electrothermal components provide active heating under sunlight or low-voltage input^[19–21,33]. In wearable healthcare, flexible PCM composites and hydrogels can deliver more stable thermotherapy, photothermal therapy, skin-conformal heat regulation, strain sensing, and motion monitoring, thus linking thermal management with physiological signal acquisition and therapeutic intervention^[34–38]. In wearable electronics, PCMs can serve as thermal buffers to reduce local overheating, protect temperature-sensitive components, and improve skin comfort during long-term device operation^[39–42]. These applications place more stringent demands on material performance than conventional thermal energy storage technologies, because wearable PCMs must operate under bending, stretching, sweating, washing, skin friction, and prolonged body contact. Therefore, photothermal PCMs should be understood as human-interfacing energy materials rather than only as thermal storage media.

Several recent reviews have discussed flexible PCMs^[11], form-stable PCMs^[43], PCM-based wearable devices^[9], radiative thermal-management textiles^[11], MXene-based PCM composites^[10], and Azo solar thermal fuels^[8]. Although these reviews provide valuable insights, most of them focus on either PCM material preparation, thermal-energy storage performance, textile/device configurations, radiative thermal regulation, or a specific functional component such as MXene or Azo. In contrast, this review focuses specifically on photothermal PCMs for wearable thermal management and intelligent healthcare, presenting a comprehensive framework that spans material preparation, energy-conversion mechanisms, wearable integration, and healthcare-oriented applications. Rather than treating PCMs only as passive latent-heat reservoirs or discussing wearable devices only by application location, we emphasize how molecular design, structural stabilization, photothermal/electrothermal conversion, and soft-device integration jointly determine wearable performance (Figure 1). By bridging materials chemistry, thermal-energy conversion, textile engineering, and healthcare-oriented wearable systems, this review seeks to clarify the design principles, current challenges, and future opportunities of photothermal PCMs for next-generation personal thermal regulation and intelligent health management.

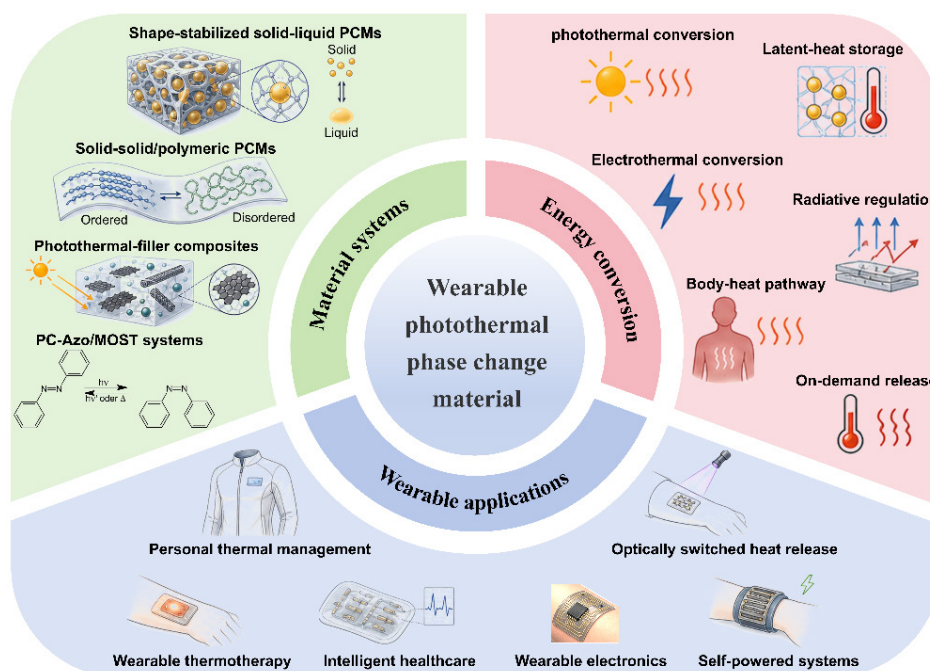


Figure 1. The material categories, energy conversion, and application scenarios of wearable photothermal PCMs. PCMs: phase change materials; PC-Azo: phase-change azobenzene; MOST: molecular solar thermal.

2. Material Systems And Energy Conversion Mechanisms

PCMs for wearable thermal management are no longer limited to passive thermal buffers. Recent studies have increasingly focused on integrating energy conversion, intelligent responsiveness, and multifunctionality into PCMs, enabling dynamic thermal regulation under diverse environmental and physiological conditions^[44,45]. From the perspective of preparation, the key question is how to retain the high enthalpy of organic PCMs while solving leakage, rigidity, low thermal conductivity, weak light absorption, and poor wearability. Based on this logic, this section covers shape-stabilized solid-liquid phase-change composites, intrinsically flexible solid-solid or polymer-mediated PCMs, photothermal-filler-enhanced phase-change composites, and phase-change Azo (PC-Azo)/molecular solar thermal (MOST) fuel systems.

2.1 Shape-stabilized solid-liquid phase-change composites

Shape-stabilized solid-liquid phase change composites represent the most studied class of wearable PCMs. Their design is governed by the challenging trade-off among high PCM loading, flexibility, and leakage resistance. Conventional solid-liquid PCMs, such as paraffins, fatty acids, alcohols, and polyethylene glycol, can store considerable latent heat but lose macroscopic shape after melting^[46,47]. Therefore, the preparation strategy has evolved from simple porous impregnation toward polymer confinement, core-sheath fibers, nonwoven networks, laminated fabrics, and flexible insulating films. A broad review summarized that form-stable phase-change composites are usually prepared by chemical modification, porous confinement, polymer networks, or functional additives to overcome challenges like leakage, low thermal conductivity, phase separation, and supercooling^[48].

A clear representative of this category is the chemically cross-linked elastomeric PCM^[47]. The authors developed polymer-based PCMs using a dual three-dimensional crosslinked network of olefin block copolymers (OBC) and styrene-ethylene-butylene-styrene (SEBS) within paraffin wax (PW). Building on this concept, paraffin was immobilized in an ultraflexible polymer network (Figure 2a). The resulting composites showed high latent heat of about $176 \text{ J} \cdot \text{g}^{-1}$, excellent flexibility, stable compression behavior, and scalable preparation from gram-level to kilogram-level batches. More importantly, the material could maintain a comfortable thermal range of approximately $39\text{--}42^\circ\text{C}$ for wearable thermotherapy after short-term charging. The energy-conversion mechanism remains governed by the melting/crystallization of paraffin, while the elastomeric network transforms this leakage-prone latent-heat material into a mechanically robust and wearable platform. In this sense, chemical cross-linking functions as both a shape-stabilization method and a bridge between thermal storage and wearable mechanics.

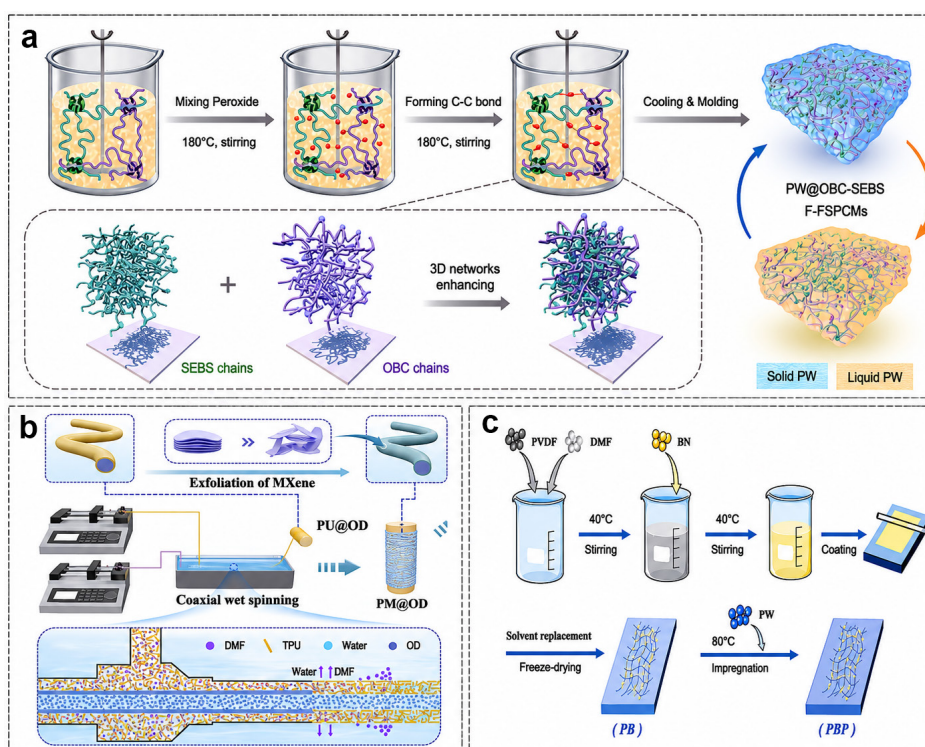


Figure 2. (a) Free radicals induced polymerization for OBC-SEBS networks and leading to encapsulation of PW. Reproduced from reference^[17]. CC BY 4.0; (b) Schematic illustrations of fabrication of PM@OD fabrics seamed with thermochromic fibers for smart thermoregulatory textiles. Reproduced with permission from reference^[49]. Copyright © 2024 Elsevier B.V; (c) Schematic of the synthesis of the PVDF/BN/PW (PBP) composites. Reproduced with permission from reference^[50]. Copyright © 2024 Elsevier Ltd. OBC: olefin block copolymers; SEBS: styrene-ethylene-butylene-styrene; PW: paraffin wax; OD: octadecane; PVDF: polyvinylidene fluoride; TPU: thermoplastic polyurethane; BN: boron nitride; F-FSPCMs: flexible form-stable phase change materials; PU: polyurethane; DMF: N,N-dimethylformamide.

Fiber and textile architectures further translate shape-stabilized solid-liquid PCMs into garment-compatible forms. Wu *et al.* designed a trimode thermoregulatory fibrous membrane by coaxial electrospinning, in which the phase-change core stores latent heat ($106.86 \text{ J}\cdot\text{g}^{-1}$) while photothermal and electrothermal components provide active heating inputs^[51]. Liu *et al.* constructed a graphene-boron nitride (BN) phase-change nonwoven by wet spinning and subsequent vacuum impregnation of paraffins, achieving high enthalpy ($206.0 \text{ J}\cdot\text{g}^{-1}$), anti-leakage behavior, and water-vapor permeability suitable for all-season wearable thermal management^[52]. A flexible composite fabric with integrated thermal energy storage, photothermal conversion and thermochromic responsiveness was fabricated through coaxial wet spinning followed by dip coating with thermochromic microcapsules (Figure 2b)^[49]. In this design, polyurethane (PU) served as the sheath material, MXene functioned as the solar absorber, and octadecane (OD) acted as the phase-change core material. The resulting PM@OD fabrics exhibited a melting enthalpy of $121.64 \text{ J}\cdot\text{g}^{-1}$ and a crystallization enthalpy of $121.44 \text{ J}\cdot\text{g}^{-1}$. By further introducing photothermal and thermochromic functions, this design also shifts PCMs from passive temperature buffering to smart thermoregulatory textiles.

Flexible films and insulating composites provide another important route for solid-liquid PCMs in wearable electronics. Silk-fiber-based and microcapsule-modified fabrics demonstrate that biocompatible substrates, waterborne binders, and textile finishing can incorporate PCMs into daily wearable systems^[53,54]. As shown in Figure 2c, a flexible insulating phase-change composite film was reported^[50], in which PW was integrated into a polyvinylidene fluoride (PVDF)-BN film architecture to provide thermal buffering while retaining electrical insulation and mechanical flexibility. The obtained flexible composite PCM film exhibited a superior melting enthalpy of $105.63 \text{ J}\cdot\text{g}^{-1}$, along with an improved thermal conductivity. Such systems are valuable for wearable electronics and skin-contact devices since the PCM controls temperature fluctuation and the insulating matrix prevents electrical risk.

Overall, shape-stabilized solid-liquid composites usually prevent PCM leakage through porous scaffold confinement^[17], core-sheath encapsulation^[49], polymer-network immobilization^[50] and microencapsulation^[54]. These methods are used to confine the PCM and limit its migration during melting and over repeated thermal cycles. At the material level, high latent heat usually comes from maximizing the crystallizable PCM content to ensure the phase-change domains remain connected and accessible inside the composite. However, excessive loading can reduce air permeability, flexibility, tensile durability, and skin comfort. Thus, for wearable applications, the ideal composite must strike a balance, i.e., maximize accessible latent heat per unit area or per unit mass while retaining an interconnected pore structure and sufficient mechanical resilience for real use. From a manufacturing perspective, different fabrication methods still face distinct industrial bottlenecks. Electrospinning is effective for producing porous fibrous PCM membranes with controllable morphology, high surface area, and good flexibility, but its large-scale application is restricted by low production capacity, slow deposition rate, solvent consumption, and difficulty in preparing thick, mechanically robust membranes. Wet spinning and coaxial spinning are more suitable for continuous fiber production and wearable PCM textiles, yet they require better control over PCM encapsulation uniformity, leakage resistance, and fiber strength during weaving, washing, and repeated deformation. Coating and impregnation methods are compatible with existing textile-finishing and roll-to-roll processes because of their low cost and mature processing basis. However, the mechanical and laundering durability of PCM-coated textiles should be evaluated for each specific coating system and end-use condition. Therefore, future efforts should integrate material design with scalable processing, placing greater emphasis on production throughput, environmental impact, interfacial adhesion, fatigue resistance, wash durability, and compatibility with industrial textile manufacturing.

2.2 Intrinsically flexible solid-solid and polymer-mediated PCMs

Intrinsically flexible solid-solid and polymer-mediated PCMs address the leakage problem at a more fundamental level. Instead of physically retaining molten PCMs within porous supports, they eliminate macroscopic liquid flow by incorporating crystallizable polymer segments, cross-linked soft networks, or fiber-forming polymer matrices that maintain structural integrity throughout the phase transition^[55,56]. Their central advantage is the absence or reduction of free liquid PCM during operation, which makes them attractive for skin-conformal films, stretchable fibers, smart textiles, and wearable electronics. The trade-off is that solid-solid systems often show lower enthalpy than high-loading solid-liquid composites, so recent work has focused on increasing crystallizable content while maintaining flexibility and mechanical integrity.

To translate this concept into wearable architectures, researchers have increasingly developed fiber- and textile-based solid-solid PCM systems. For example, solid-solid phase-change fibers were fabricated through coaxial wet spinning followed by ultraviolet (UV)-induced polymerization and crosslinking (Figure 3a(i))^[14]. In this system, a thermoplastic polyurethane (TPU) solution and a polymerizable polyethylene glycol (PEG) solution were employed as the outer and inner spinning layers, respectively. During the spinning process, solvent diffusion promoted the rigid aggregation of TPU macromolecules from their initially dissolved state (Figure 3a(ii)). These resulting core-sheath fibers exhibited high flexibility, good tensile properties, and excellent reusability, with a high latent-heat density of $122.5 \text{ J}\cdot\text{g}^{-1}$. In a related textile direction, Liang *et al.* fabricated multifunctional phase-change textiles with electromagnetic-interference shielding and multiple thermal-response characteristics by constructing a self-cross-linked PEG-based solid-solid phase-change coating on polyethylene terephthalate (PET) textiles (Figure 3b(i))^[15]. The functionalized PEG, serving as the phase-change component, enhanced the interfacial interaction with Ag nanowires (AgNWs) and the textile substrate (Figure 3b(ii)),

thereby enabling the formation of a robust layered structure with long-term operational stability. The resulting textile, with a thickness of only 0.26 mm, exhibited an energy-storage density of $86.6 \text{ J} \cdot \text{g}^{-1}$ together with multiple thermally responsive functions, including high Joule-heating efficiency, efficient heat storage and release, effective heat dissipation capability, and infrared anti-counterfeiting behavior. These studies demonstrate that solid-solid PCMs can move beyond thin films and become processable fibers or coated textiles, which is crucial for realistic wearable use.

Beyond externally structured fibers and coatings, intrinsically flexible and multifunctional solid-solid PCMs further broaden the design space of wearable thermal-management materials. Soft-matter and conductive solid-solid systems further broaden this category. Kou *et al.* developed an intrinsically flexible phase-change film through molecular design, where the phase-change units were incorporated into a self-supporting polymeric film^[13]. The film can be easily tailored into different and complex customized shapes (Figure 3c). The film was constructed through molecular design of crystallizable phase-change segments within a deformable polymeric matrix, enabling a solid-solid transition without macroscopic leakage. Its phase-transition temperature could be tuned in the range relevant to personal thermal comfort, and the film retained flexibility after repeated heating-cooling cycles. From an energy-conversion viewpoint, this material mainly performs thermal-to-latent-heat conversion through reversible segmental crystallization, but its film form allows coupling with external photothermal or electrothermal layers. Compared with capsule-based or porous-support systems, this approach provides a cleaner design principle for wearable patches. The material can be thin, deformable, leakage-free, and directly integrated with photothermal or electrothermal layers.

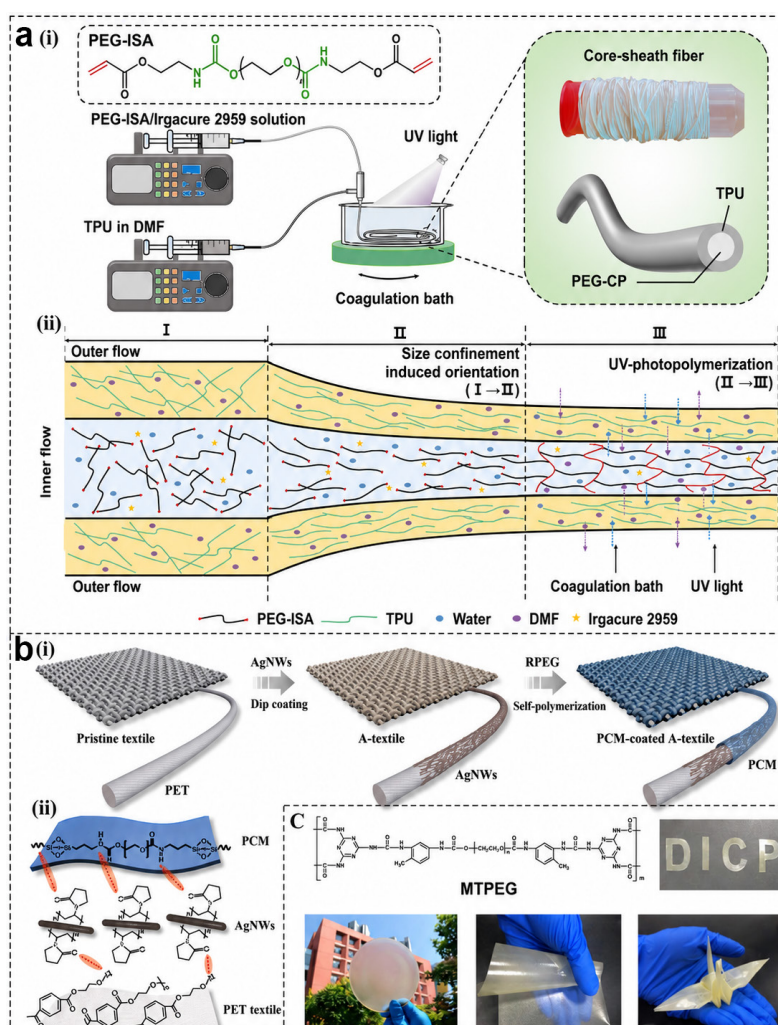


Figure 3. (a) Scheme illustrating (i) the procedures for the core-sheath fibers preparation and (ii) the formation of the fibers through nonsolvent-induced phase separation and polymerization-crosslinking. Reproduced with permission from reference^[4]. Copyright © 2023 Elsevier Ltd; (b) Schematic illustration of (i) the fabrication process of the PCM textile and (ii) the various interfacial interactions within the composite structure. Reproduced with permission from reference^[15]. Copyright © 2023 Elsevier B.V.; (c) Chemical structure of MTPEG film and their customized shapes. Reproduced with permission from reference^[13]. Copyright © 2020 Elsevier B.V. PCM: phase change material; TPU: thermoplastic polyurethane; UV: ultraviolet; PET: polyethylene terephthalate; AgNWs: silver nanowires; DMF: N,N-dimethylformamide; PEG-ISA: polyethylene glycol-2-isocyanatoethyl acrylate; PEG-CP: polyethylene glycol-crosslinked polymer; RPEG: reactive polyethylene glycol; MTPEG: melamine-toluene-2,4-diisocyanate-polyethylene glycol.

Soft-matter and conductive solid-solid systems further expanded this category toward multifunctional wearable platforms. Highly flexible GO-PU solid-solid phase-change composites have been developed, in which a cross-linked PU network provides mechanical strength, while graphene oxide enhances photothermal conversion and solar thermal storage efficiency^[57]. Highly flexible phase-change films based on *n*-eicosane, silicone networks, and multiwalled carbon nanotubes (MWCNTs) also illustrate how polymer matrices can combine thermal storage with motion sensing^[22]. Recent reviews on PU solid-solid PCMs further emphasize that hydrogen bonding, soft/hard segment regulation, and cross-linking density are key parameters for tuning enthalpy, shape memory, and flexibility^[43]. Collectively, these studies represent a clear transition in wearable PCM design, i.e., from passive physical confinement toward molecular- and polymer-network engineering.

2.3 Photothermal-filler-enhanced phase-change composites

Photothermal-filler-enhanced PCMs represent the predominant class of photothermal PCMs because they directly integrate solar energy harvesting with latent heat storage. Most organic PCMs have weak solar absorption and low thermal conductivity, so fillers such as CNTs, graphene, MXene, polypyrrole, PDA, metal nanoparticles, BN, and MOF-derived carbon networks are introduced to absorb light, generate heat, accelerate heat transfer, and sometimes provide electrical conductivity^[24,27,58-60]. The basic energy pathway is: photon absorption by the filler, nonradiative conversion into heat, thermal conduction through the filler network, melting of the PCM for latent-heat storage, and delayed heat release during crystallization.

A representative example of this category is a flexible wearable phase-change composite^[61], in which a poly(ethylene vinyl acetate) (EVA)/poly PEG composite layer was sandwiched between two films of waterborne polyurethane (WPU)/CNTs (Figure 4a(i)). PEG and EVA are highly compatible, allowing PEG to be evenly distributed within the EVA matrix, which effectively encapsulates the PEG (Figure 4a(ii)). At a PEG loading of 50 wt%, the composite exhibits a melting enthalpy of $71.45 \text{ J}\cdot\text{g}^{-1}$ and a crystallization enthalpy of $65.79 \text{ J}\cdot\text{g}^{-1}$. These enthalpy values are lower than those of net PEG, indicating the inevitable trade-off for acquiring shape stability by encapsulation during the phase transition. The material integrates electrothermal and photothermal heating with phase-change energy storage, allowing PTM under both solar and electrical inputs. This dual-input strategy is especially relevant for all-weather wearables, because solar heating is intermittent and electrical heating is controllable but energy-consuming. Related dual-mode systems, such as PEG/carbon cloth (CC) @Co/CNT composites, use MOF-derived Co/CNT heterostructures on breathable carbon cloth to provide high solar-thermal and electrothermal conversion, while PEG stores the converted heat as latent energy^[26].

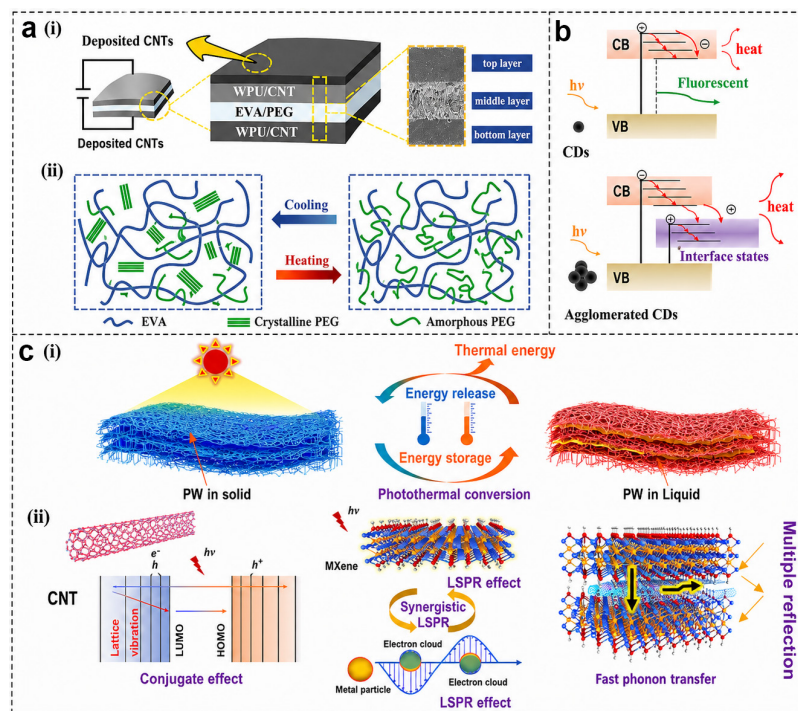


Figure 4. (a) Schematic diagram showing the sandwich-structured composites (i) and the phase-transition behavior of PEG confined within the EVA matrix (ii). Reproduced with permission from reference^[61]. Copyright © 2024 Elsevier B.V; (b) Schematic illustration of the effects of interface states on band gaps of CDs within with PCMs. Reproduced with permission from reference^[62]. Copyright © 2022 Elsevier Ltd; (c) Illustration of (i) the photothermal conversion process in composite PCMs and (ii) the multiple synergistic effects contributing to enhanced light absorption, heat generation, and thermal transport. Reproduced with permission from reference^[25]. Copyright © 2024 Elsevier B.V. PEG: polyethylene glycol; EVA: ethylene vinyl acetate; CDs: carbon dots; PCMs: photothermal phase change materials; CNTs: carbon nanotubes; WPU: waterborne polyurethane; PW: paraffin wax; LSPR: localized surface plasmon resonance; CB: conduction band; VB: valence band; $h\nu$: photon energy.

Carbon- and MXene-based systems highlight the importance of filler architecture in photothermal PCM design^[24,27,63]. The incorporation of carbon dots (CDs) promoted sunlight harvesting and photothermal conversion through interfacial states with reduced band gaps formed at the CD interfaces, as illustrated in Figure 4b^[62]. Under the optimized mass ratio of CDs and PEG, the resulting photothermal conversion efficiency was 13.7% higher than the theoretical value. The overall energy-conversion process can be described as sequential light absorption by conjugated carbon domains, nonradiative conversion of photon energy into heat, heat conduction through the conductive network, and subsequent latent-heat storage within the PCM matrix. The incorporation of MXene sheets can form anisotropic thermal pathways and improve solar/electrical responsiveness^[24]. Gao *et al.* reported a multidimensional collaborative strategy for achieving efficient photon and electromagnetic-wave absorption within magnetic CNT-bridged MXene/CoNi-based composite PCMs^[25]. In this work, the CNT-bridged MXene structures acted synergistically as photothermal sites, where abundant π electrons could be excited to generate heat through nonradiative relaxation processes, thereby enabling ultrahigh light-absorption capability across the entire solar spectrum (Figure 4c(i)). The synergistic localized surface plasmon resonance (LSPR) effect between MXene nanosheets and CoNi nanoparticles facilitated efficient photon trapping and rapid phonon transport (Figure 4c(ii)). Related MXene review literature further suggests that bioinspired porous structures and interface engineering are useful for improving shape stability, conductivity, and energy conversion efficiency^[10]. These studies collectively indicate that the primary challenge is not simply increasing filler loading, but constructing continuous thermal and electrical transport pathways while maintaining low filler content and structural flexibility.

Photothermal fillers also enable advanced wearable functions beyond heating. Phase-change hydrogels with PDA-modified MXene (PDA@MXene) combine latent-heat regulation, tunable adhesion, strain sensing, and photothermal therapy, showing how photothermal PCMs can become intelligent healthcare interfaces^[34]. Janus phase-change films integrate radiative cooling and solar heating by asymmetric structural design, allowing the same material to switch between cooling and heating modes depending on orientation or environmental demand^[20]. Therefore, photothermal-filler-enhanced PCMs should be understood as energy-conversion composites rather than simple filler-reinforced PCMs. Their performance is determined by the coupled design of optical absorption, thermal conduction, latent-heat storage, mechanical softness, and interfacial compatibility.

2.4 Phase change-azo solar thermal fuel systems

PC-Azo systems, a representative class of MOST materials, are one of the most distinctive types of PCMs because they store energy through molecular photoisomerization rather than only through melting and crystallization^[64]. In Azo-based systems, light converts the stable trans isomer into a metastable cis isomer, storing photon energy in molecular strain and chemical configuration. Subsequent thermal, optical, or catalytic triggering drives the cis-to-trans back-isomerization and releases heat^[65–67]. When this MOST process is coupled with phase transition, the material can co-harvest isomerization energy and phase-change enthalpy, offering a promising route toward lightweight, rechargeable, and on-demand solar thermal materials.

From a preparation and design perspective, PC-Azo systems are fundamentally different from photothermal-filler-enhanced PCMs^[8,68–70]. In carbon-, MXene-, or metal-based photothermal PCMs, solar energy is immediately converted into heat by fillers and then stored as latent heat in the PCM matrix^[71,72]. In contrast, PC-Azo systems store part of the solar energy at the molecular level before heat release. Therefore, their molecular design must balance several competing factors: strong solar absorption, high photoisomerization conversion, long cis-state lifetime, sufficient crystallinity for phase-change enthalpy, low-temperature heat release, and processability into films, coatings, fibers, or fabrics^[38]. This balance is challenging because strong molecular packing favors high phase-change enthalpy but may restrict trans-cis isomerization, whereas loose packing facilitates photoisomerization but often decreases crystallization enthalpy and long-term energy density.

An important mechanistic foundation for PC-Azo/MOST systems was provided through work on photochemical phase transitions^[38]. In this system, two forms of energy are simultaneously stored during the trans-to-cis conversion process, while the cis-liquid releases two streams of heat during discharge (Figure 5a(i)). Rationally designed small-molecule azo switches achieved gravimetric energy densities of 0.3–0.4 MJ·kg^{−1} together with long-term storage stability (Figure 5a(ii)). Here, molecular switching is coupled with phase transition, allowing both photon energy and thermal energy to be accumulated within the material. Light drives trans-to-cis isomerization, while the accompanying phase behavior enables additional thermal-energy storage and release. This mechanism differs from conventional photothermal filler systems. In filler-enhanced PCMs, absorbed light is immediately converted into heat and stored as latent heat. In PC-Azo systems, however, light first generates a metastable molecular state, enabling delayed and on-demand heat release. A review of Azo-based solar thermal fuels further clarifies the structural parameters that govern this behavior, including absorption wavelength, photoisomerization efficiency, energy density, thermal half-life, and cycling stability^[8].

A rechargeable MOST system has been reported that can operate under low-temperature conditions relevant to outdoor and wearable thermal regulation^[39]. This capability is particularly important for applications such as winter clothing, outdoor heating, and body-temperature maintenance, where energy storage and release must function efficiently in cold environments. The work employed 4-methoxyarylazopyrazole photoswitches with tunable photostationary states under 400 and 532 nm irradiation (Figure 5b(i)). The system was able to simultaneously harvest visible-light energy and low-temperature ambient heat, followed by on-demand release as high-temperature heat (Figure 5b(ii)). The study demonstrated that Azo-based MOST systems could

be charged and discharged below 0 °C, indicating that molecular photoswitching remains effective even under conditions where many conventional PCMs exhibit slow crystallization or unsuitable phase-transition temperatures. Liu *et al.* also reported optically triggered synchronous heat release of phase-change enthalpy and photo-thermal energy at low temperatures, showing that photoisomerization and phase transition can be coordinated to generate higher heat output^[40]. Building on this, a further strategy involves co-harvesting phase-change enthalpy and isomerization energy by controlling crystallization of alkyl-grafted Azo molecules, which directly addresses the central design conflict in PC-Azo systems: strong crystallinity increases latent heat but may restrict molecular switching^[42].

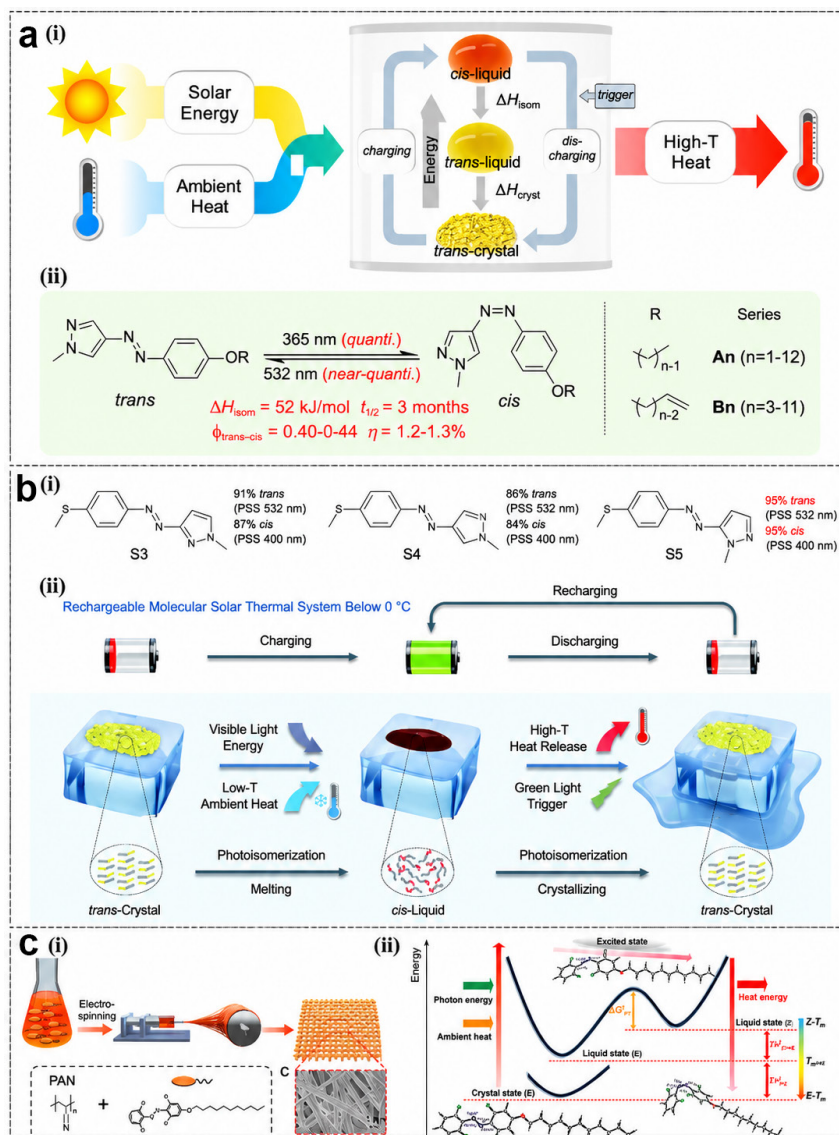


Figure 5. (a) An illustration of a thermal battery that is charged with solar energy and ambient heat and releases heat upon Azo-switches (i) and Photochemical properties of two series of Azo derivatives (ii). Reproduced with permission from reference^[38]. Copyright © 2020 American Chemical Society; (b) Structures of Azo compounds and their photostationary states at 400 nm and 532 nm (i) and schematic representation of a rechargeable PC-Azo system below 0 °C (ii). Reproduced with permission from reference^[39]. Copyright © 2022 The Royal Society of Chemistry; (c) Fabrication of PC-Azo fabrics (i) and energy-storage concept upon geometric structure changes (ii). Reproduced with permission from reference^[73]. Copyright © 2024 Wiley-VCH GmbH. Azo: azobenzene; PC: phase-change; PAN: polyacrylonitrile.

Recent work is pushing PC-Azo materials toward wearable solar-thermal fabrics. An early demonstration of textile-integrated MOST systems was designed by incorporating a photoliquefiable Azo derivative into a flexible fabric template, enabling solvent-free photocharging and heat release^[74]. Building on this concept, a robust MOST fabric was constructed by azopyrazole-containing microcapsules with a deep-UV-filtering shell^[75]. This microencapsulation improved the retention and durability of MOST agents in fabrics, enabling repeated charging, rubbing, and washing without a substantial loss of thermal-storage capability. In another approach, flexible fabric composites, composed of Azo-containing dendrimers, PDA, and a cotton substrate, were designed to enable energy storage and release in low- or room- temperature^[76]. Similarly, PC-Azo molecules have been integrated into textile

architectures to realize solar energy storage and controllable high-temperature heat release (80–95 °C) at room temperature and cold environments^[73]. As illustrated in Figure 5c(i), azo monomers were uniformly immobilized on polyacrylonitrile (PAN) fiber surfaces through electrospinning. The fabric could be charged with green light and discharged with blue light, the released heat originated from the combined contributions of Z-to-E isomerization, phase-transition enthalpy, and photothermal heating (Figure 5c(ii)). Importantly, it retained flexibility and thermal-storage performance after prolonged storage, repeated bending, washing, and soaking. In this system, Azo units act as photo-rechargeable thermal-storage components, whereas the textile substrate provides flexibility, air permeability, and body-contact compatibility.

More recently, high-energy Azo fabrics^[44], elastic solar-thermal fibers^[77], and coaxially electrospun core-shell textiles^[78] have further shifted the field toward higher energy density, body-conformal deformation, direct sunlight charging, and leakage-resistant wearable operation. Nevertheless, challenges including synthesis cost, limited visible-light utilization, fatigue resistance, molecular leakage, and scalable manufacturing still restrict practical applications. Their long-term value lies in enabling programmable and triggerable solar-thermal management beyond conventional latent-heat storage systems.

3. Applications

3.1 PTM

PTM is one of the main applications for wearable photothermal PCMs. Compared with building-level heating and cooling, PTM regulates heat at the individual level, improving thermal comfort while reducing unnecessary energy consumption. Thermal comfort is essential because human thermoregulation directly affects health and well-being. Core body temperatures above 37.5–38.3 °C (hyperthermia) or below 35.0 °C (hypothermia) pose serious, potentially fatal risks^[79,80]. From a materials perspective, the main challenge is not only to increase latent heat storage, but also to integrate PCMs into wearable systems that are soft, breathable, washable, mechanically durable, and compatible with textile manufacturing processes^[53,54]. Therefore, recent studies have gradually shifted from bulk PCMs and rigid composite blocks to fibers, textiles, films, and nonwoven structures. These wearable architectures are complementary in both structure and function: fibers and textiles enable direct garment integration, films provide conformal thermal-buffering interfaces, while nonwoven networks balance PCM loading, breathability, and large-area processability^[31,81–84]. In recent studies, the design focus has moved from simple heat storage toward multi-mode energy management, where latent heat storage is coupled with photothermal conversion, solar thermal fuel chemistry, electrothermal heating, moisture permeability, and anti-leakage structure design^[13].

Fiber- and textile-based materials represent one of the most direct pathways for integrating energy harvesting/storage materials or PCMs into practical wearables^[85–89]. Wu *et al.* reported a trimode thermoregulatory flexible fibrous membrane constructed using a hierarchical core-sheath fiber architecture^[51]. Coaxial electrospinning was used to encapsulate PW within the fiber core (Figure 6a(i,ii)), while the sheath and outer conductive/photothermal coatings established a multifunctional interfacial network and provided additional solar-heating and Joule-heating functions (Figure 6a(iii)). This hierarchical design simultaneously addresses multiple issues, including suppression of PW leakage, enhancement of interfacial stability, preservation of mechanical flexibility and textile compatibility, and facilitation of efficient photothermal and electrothermal energy conversion. The textile-based material exhibited a latent-heat enthalpy density of 106.9 J·g⁻¹ and reached a surface temperature of 70.5 °C under 1 sun irradiation. As a wearable textile, it could further achieve a surface temperature of 73.8 °C under a low voltage of 4.2 V through Joule heating (Figure 6a). In addition, the material could operate in a “pre-charging/energy-releasing” mode, buffering rapid temperature fluctuations within the clothing microclimate while also providing active heating under solar or electrical stimulation (Figure 6a(v)). This study therefore marks a transition from single-mode PCM textiles to multi-source-driven wearable thermal systems.

Solar energy storage fabrics provide another logical route for PTM, especially for outdoor and cold-environment applications where sunlight can be harvested during use. One such development is a visible solar storage fabric (VSSF), created by coating cotton fabric with Azo-PCM@polystyrene (PS) nanocapsules and Cs_{0.32}WO₃ nanoparticles^[90]. In this system, the Azo-PCM component stores energy through coupled photochemical isomerization and thermally induced phase transition. As illustrated in Figure 6b, UV irradiation induces the trans-to-cis conversion of Azo units within the nanocapsules, leading to molecular conformational changes and variation of intermolecular binding energies, thereby enabling storage of photon energy in metastable cis states. Subsequent blue-light irradiation triggers the reverse cis-to-trans transition and releases the stored energy as heat. Meanwhile, Cs_{0.32}WO₃ nanoparticles efficiently harvest visible and near-infrared light and convert it into heat, broadening solar-spectrum utilization beyond conventional UV-responsive Azo systems. Compared with conventional Azo MOST systems that mainly rely on UV light, this fabric broadens solar-spectrum utilization across UV-Vis-NIR wavelengths. The PS shell prevents PCM leakage and volume-change problems, while the Azo unit provides photochromic behavior that allows real-time monitoring of the energy-storage state through color change. Under sunlight, the VSSF achieved a solar energy utilization efficiency of approximately 4.8% and a heat-release temperature of 83 °C. Demonstrations such as a self-heating wrist guard and a photothermally driven lifter indicate that this material is not merely a passive warm fabric; rather, it functions as a wearable solar energy management platform that combines solar capture, thermal storage, heat release, and visual feedback.

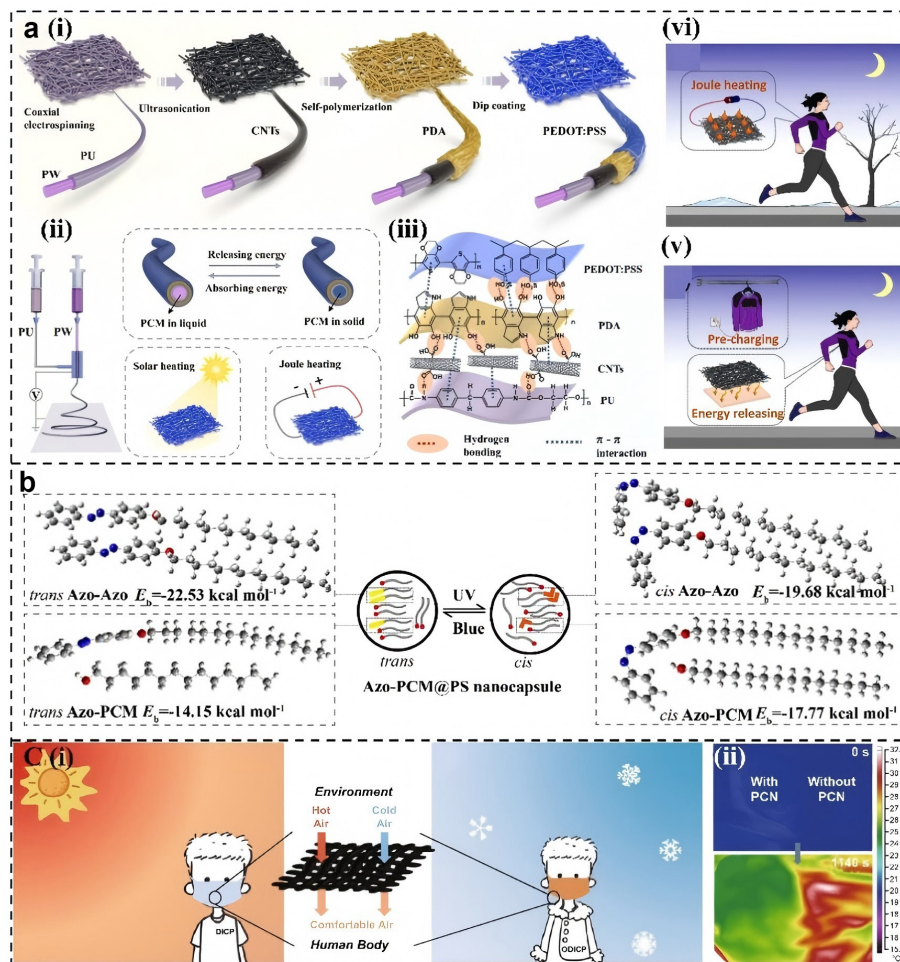


Figure 6. (a) Trimode thermoregulatory fibrous membrane based on a hierarchical core-sheath architecture: (i) fabrication process, (ii) coaxial electrospinning, (iii) multifunctional interfacial network, (iv) Joule heating effect, and (v) operating modes. Reproduced with permission from reference^[51]. Copyright © 2022 American Chemical Society; (b) DFT-simulated configurations of Azo-PCM in the *trans* and *cis* isomeric states under by UV and Blue-light irradiation. Reproduced with permission from reference^[90]. Copyright © 2021 Elsevier B.V.; (c) Wearable thermal management in face masks: (i) schematic illustration of GB-PCN for face-mask thermal management, (ii) simulated performance shown by IR images at 0 s and 1,140 s at 38 °C (left side represents the functionalized face mask, while the right side represents a conventional unfunctionalized face mask). Reproduced from reference^[52]. CC BY 4.0. DFT: density functional theory; Azo: azobenzene; PCM: photothermal phase change material; UV: ultraviolet; GB-PCN: graphene-boron nitride phase change nonwoven; IR: infrared; PW: paraffin wax; PU: polyurethane; CNTs: carbon nanotubes; PDA: polydopamine; PS: polystyrene; PEDOT:PSS: poly(3,4-ethylenedioxythiophene);poly(styrenesulfonate).

Nonwoven structures further improve the practicality of PCM-based PTM by combining textile-like permeability with high latent-heat capacity. Liu *et al.* reported a thermoregulatory flexible phase-change nonwoven, assembled from wet-spinning graphene/BN hybrid fibers followed by paraffin impregnation^[52]. The interconnected graphene-BN fibrous framework provided mechanical support, thermal transport pathways, and structural stability, while the impregnated paraffin served as the primary latent-heat storage component. As a result, the obtained graphene-boron nitride phase change nonwoven (GB-PCN) material exhibited a high latent-heat enthalpy of $206.0 \text{ J} \cdot \text{g}^{-1}$ together with excellent anti-leakage capability and outstanding thermal reliability, retaining 97.6% of its original thermal-storage performance after 1,000 heating-cooling cycles. Owing to the synergistic combination of thermally conductive fillers and porous nonwoven architecture, the GB-PCN material could dynamically regulate heat exchange between the human body and surrounding environment, helping maintain a more comfortable microclimate under both hot and cold conditions (Figure 6c(i)). Infrared thermal imaging further demonstrated that the PCN-containing textile exhibited markedly enhanced thermal buffering behavior compared with the control sample, maintaining a more stable surface temperature during prolonged thermal exposure (Figure 6c(ii)). As a result, the porous nonwoven structure also maintained water-vapor permeability comparable to that of cotton, which is critical for long-term wearable comfort, as demonstrated in clothing and face-mask systems.

These representative studies illustrate the development of photothermal PCMs for PTM. Core-sheath fibers enable trimode thermoregulation, solar storage fabrics expand energy input and on-demand heat use, and phase-change nonwovens improve wearing comfort and large-area textile applicability. The real performance of PCM-based PTM system isn't determined just by latent

heat and phase-transition temperature. It also depends on the rate of heat absorption and release, photothermal/electrothermal energy input, thermal conductivity, material thickness, contact area, and the local skin-clothing microclimate. Future PTM materials should therefore be evaluated not only by their latent heat, but also by their solar-spectrum utilization, leakage resistance, breathability, long-term cycling stability, thermal conductivity and garment-level integration. Recent progress in super-stretchable PCMs has further expanded the applicability of PCM-based PTM from relatively static garments to highly deformable wearable patches, epidermal devices, and intelligent healthcare systems. Unlike conventional form-stable PCMs that mainly emphasize leakage resistance and latent heat capacity, super-stretchable PCM composites must maintain phase-change enthalpy, thermal buffering capability, and structural integrity under repeated stretching, bending, twisting, and skin motion. To this end, elastic polymer networks, chemically cross-linked matrices, hydrogel frameworks, elastomer/PCM hybrids, and dynamic interfacial bonding have been introduced to confine phase-changing domains while preserving large deformation tolerance. For example, highly stretchable PCM composites have been developed for simultaneous thermotherapy and physiological monitoring, demonstrating the possibility of coupling latent-heat regulation with strain sensing^[35]. Ultraflexible polymer-based PCM composites prepared through chemical cross-linking also show scalable processability and stable wearable thermal management performance^[17]. These studies indicate that super-stretchability is not merely a mechanical advantage, but a key requirement for real PTM scenarios where PCM devices must operate reliably on moving joints, soft skin, curved body surfaces, and long-term wearable electronic platforms.

3.2 Optically controlled thermal storage and on-demand heat release

Optically controlled thermal storage and on-demand heat release are important applications of wearable photothermal PCMs because they separate solar energy collection from heat utilization^[64]. Conventional organic PCMs can store and release latent heat through melting and crystallization, but their heat release is mainly controlled by passive cooling from the surrounding environment. This limitation is particularly important for wearable applications, where solar energy can be collected during daytime exposure but heat is needed later under nighttime, indoor, or cold conditions. Azo-based solar thermal fuels and PC-Azo systems provide a molecular-level solution to this temporal mismatch^[73]. Upon light irradiation, trans-Azo undergoes photoisomerization into a metastable cis-state, thereby storing photon energy in the form of chemical potential energy. When this reversible isomerization is coupled with solid-liquid phase transition, the material can simultaneously store photoisomerization energy and phase-change enthalpy. Subsequent back-isomerization can be triggered when heat release is required, enabling controlled thermal output on demand. Therefore, PC-Azo systems are not only photothermal materials, but also thermal storage systems that combine molecular solar-energy storage, latent heat storage, and light-triggered heat release^[8].

The conceptual foundation for PC-Azo based on-demand heat release was clearly demonstrated by incorporating a photoresponsive alkyl-grafted Azo into tetradecane to construct a photosensitive crystallization barrier^[40]. This strategy addressed a long-standing limitation of conventional PCMs. Once the environmental temperature falls below the crystallization point, latent heat release becomes difficult to regulate and cannot be triggered on demand. In the Azo/tetradecane composite, trans-cis photoisomerization modulated molecular packing and crystallization behavior, giving the composite controllable supercooling of 4.04–8.80 °C. More importantly, under light irradiation, the system synchronously released phase-change enthalpy together with photothermal/photoisomerization energy, delivering a high heat output of 207.5 J·g⁻¹ at relatively low temperatures ranging from -1.96 to -6.71 °C. As illustrated in Figure 7a, the proof-of-concept annular system could undergo a reversible light-controlled energy-storage/release cycle, including UV-light charging at room temperature (i), low-temperature energy storage in the metastable red-liquid Z-isomer state (ii), blue-light-triggered heat release (iii), and recovery to the yellow solid E-isomer state at low temperature (iv). The optically-triggered heat release produces a temperature increase of approximately 4 °C in a -5 °C environment. This work represents a transition of PCMs from passively temperature-responsive materials to optically addressable thermal-release systems, thereby establishing a direct strategy for low-temperature wearable warming and distributed thermal-energy utilization.

Building on this principle, Gao *et al.* further clarified how molecular crystallization and photoisomerization can be co-optimized in PC-Azo systems^[42]. The authors designed two series of alkyl-grafted Azo molecules, with and without methyl substitution, and demonstrated that the heat output of PC-Azo materials depends not only on photoisomerization energy, but also on how molecular crystallization can be selectively activated at different temperatures. By tuning side-chain structure, they established three distinct exothermic modes in which crystallization enthalpy and photothermal/photoisomerization energy could be released either independently or synchronously. Distributed thermal-energy utilization systems were constructed based on PC-Azo materials. As illustrated in Figure 7b, the PC-Azo material enabled reversible light-driven thermal transport and spatially controlled heat delivery through a multistep photoisomerization/crystallization cycle: (1) energy collection and transport, (2) first heat release, (3) photoenergy storage, (4) low-temperature transport, (5) second heat release, (6) thermal reset. The optimized alkyl-grafted azobenzenes (Azo-g) molecules achieved high heat outputs of 275–303 J·g⁻¹ over a broad temperature range from -79 to 25 °C, while a distributed thermal-delivery device produced a temperature increase of 6.6 °C at -8 °C. Compared with the earlier Azo/tetradecane composite system, this work advanced the field from empirical component blending toward molecularly programmed thermal release. More importantly, it demonstrated that crystallization is not merely a side effect to be suppressed, but can instead function as a secondary energy reservoir and a temperature-selective gate for controllable heat delivery.

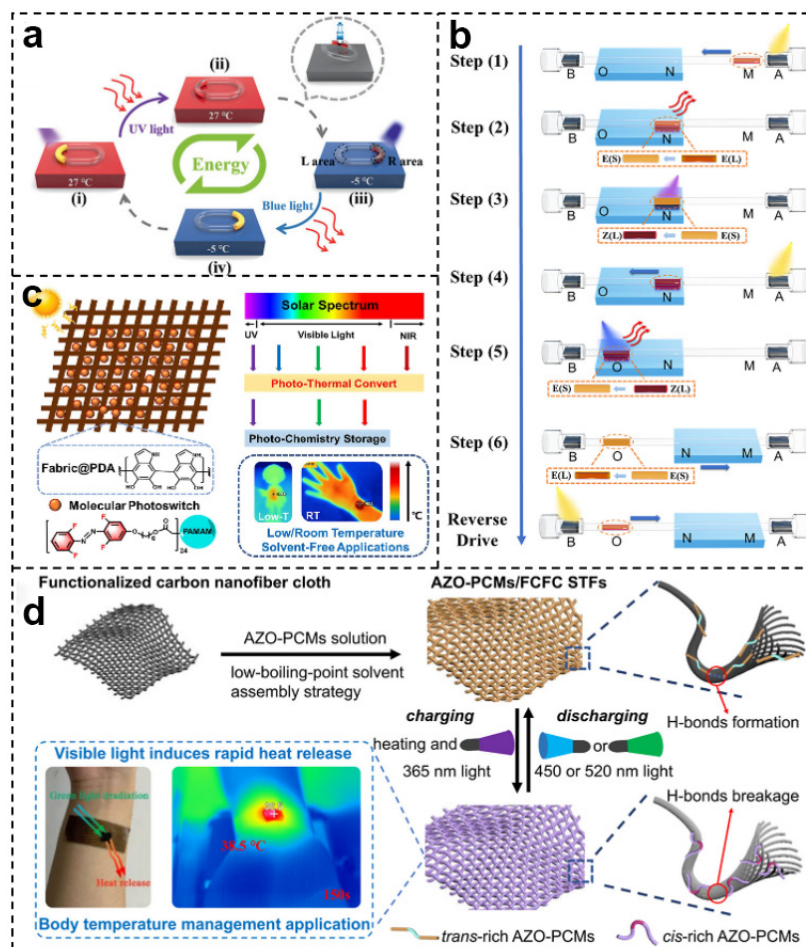


Figure 7. (a) Schematic illustration of the distributed energy utilization system using an annular device, including (i) UV-light charging, (ii) low-temperature storage in red-liquid Z-isomer, (iii) blue-light irradiation for latent heat release, and (iv) formation of yellow-solid E-isomer at low temperature. Reproduced with permission from reference^[40]. Copyright © 2020 Wiley-VCH GmbH; (b) Schematic illustration of a distributed energy utilization system consists of six steps: (1) movement at 20 °C, (2) first heat release at 0 °C, (3) heat storage through photoisomerization at 0 °C, (4) movement at -8 °C, (5) second heat release at -8 °C, and (6) heat storage through melting at 20 °C. Reproduced from reference^[42]. CC BY 4.0; (c) Schematic diagram of the composition of the flexible wearable fabrics and their solar-energy harvesting, storage and application under various light environments. Reproduced with permission from reference^[76]. Copyright © 2023 Elsevier B.V.; (d) Schematic diagram of optically controlled, high-energy flexible AZO-PCMs/FCFC solar thermal fabrics for effective body-temperature management, featuring reversible trans-cis photoisomerization under 365 nm irradiation and visible-light-triggered heat release. Reproduced with permission from reference^[41]. Copyright © 2025 American Chemical Society. UV: ultraviolet; Azo: azobenzene; PCMs: photothermal phase change materials; FCFC: functionalized carbon nanofiber cloth; NIR: near-infrared; PDA: polydopamine; RT: room temperature; STFs: solar thermal fabrics; H-bonds: hydrogen bonds.

The transition from molecular PC-Azo systems to practical wearable devices was further advanced by the development of flexible wearable fabrics composed of Azo-containing dendrimers, PDA, and cotton textiles^[76]. This design addressed several practical limitations of earlier MOST fuels, many of which required UV irradiation, solvent assistance, or operation near room temperature. In this system, σ -fluoro Azo dendrimers broadened light absorption through red-shifted $n\text{-}\pi^*$ transitions, while the dendritic architecture lowered the glass-transition temperature of the fuel to enable low-temperature operation (Figure 7c). Meanwhile, PDA contributed additional photothermal conversion capability and enhanced utilization of the solar spectrum. As a result, the fabric could store UV, green, red, and solar-light energy in a solvent-free state under both room-temperature and low-temperature conditions. The material achieved an energy-storage density of $0.05 \text{ MJ}\cdot\text{kg}^{-1}$ with a storage half-life approaching one month, while blue-light-triggered heat release generated a temperature increase of $11.1\text{--}12.3 \text{ }^\circ\text{C}$. Demonstrations using wrist guards and low-temperature body-warming scenarios further highlighted the wearable potential of this system, and established a direct connection between MOST fuels and practical textile-based thermal-management platforms for human-body applications.

Most recently, Peng *et al.* reported optically switched, high-energy wearable solar-thermal fabrics, further advancing PC-Azo systems toward higher energy- and power-density direction^[41]. Instead of incorporating AZO-PCMs into conventional polymer textiles, the authors integrated different AZO-PCMs onto functionalized carbon nanofiber cloth (FCFC), which served as a flexible, lightweight, and thermally conductive substrate (Figure 7d). As illustrated, the system underwent a reversible light-controlled charging/discharging

cycle. Under heating and 365 nm irradiation, the AZO-PCMs were converted into cis-rich states for energy storage, accompanied by disruption of intermolecular hydrogen bonding. Upon exposure to 450 or 520 nm visible light, reverse isomerization induced rapid heat release and reconstruction of hydrogen-bond networks. This architecture enhanced energy-storage capability through strengthened intermolecular interactions, particularly hydrogen bonding, while the high thermal conductivity of FCFC accelerated heat transport and visible-light-triggered thermal discharge. By optimizing molecular structure, PCM loading, and photoexcitation conditions, the solar-thermal fabrics achieved an energy density of $58.44 \text{ Wh}\cdot\text{kg}^{-1}$ together with a thermal conductivity of $3.13 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$. Under green-light irradiation, the power density reached $1,402.56 \text{ W}\cdot\text{kg}^{-1}$, approximately 3,420 times higher than that of spontaneous heat release in the dark. The fabrics also exhibited excellent bending durability, cycling stability, and noticeable body-temperature-regulation performance. Taken together, these studies reveal a clear progression for optically controlled wearable thermal-management systems, moving sequentially from optically gated PCM crystallization, to molecular regulation of coupled enthalpy release, to solvent-free wearable fabrics, and finally to thermally conductive textile platforms for rapid and on-demand heat output.

3.3 Wearable thermotherapy and intelligent healthcare

Wearable thermotherapy is a healthcare-oriented application of PCMs, where the goal is not only to regulate body temperature but also to provide controllable heat for localized treatment, rehabilitation, and physiological monitoring^[91]. Compared with conventional heaters, PCM-based systems can store converted thermal energy and release it within a relatively stable temperature window, thereby reducing abrupt overheating while prolonging therapeutic warmth. This feature is useful for applications such as muscle fatigue, soft-tissue injury, joint discomfort, and rehabilitation, where moderate temperatures, close skin contact, and repeated use are required^[92–94]. In this context, recent wearable PCM devices have evolved beyond simple thermal-storage components into integrated multifunctional platforms that combine electrothermal or photothermal conversion, latent-heat regulation, strain sensing, adhesion control, and skin-conformal mechanics. Such integration enables the same device to simultaneously monitor body motion or physiological deformation, provide on-demand heating, and maintain therapeutic temperatures through phase-change buffering.

A representative example is an electrothermal phase-change composite in which a polypyrrole-decorated melamine foam (PPy@MF) was constructed^[33]. This electrothermal PCM composite converts Joule heat into latent heat during melting, thereby delaying temperature rise and maintaining a relatively stable therapeutic temperature. Specifically, the PPy@MF served simultaneously as a Joule-heating framework and a porous scaffold for confining a binary polyethylene glycol PCM composed of PEG4,000 and PEG200 (Figure 8a(ii)). This design tackled the common conflict between thermal-storage performance and mechanical deformability in wearable PCM systems, since high PCM content generally increases latent-heat capacity but reduces flexibility at low temperatures. By incorporating PEG200 as a plasticizing component, the composite maintained excellent flexibility even at -20°C while preserving a high PEG4000 loading of 74.1% and a latent-heat storage density of $150.1 \text{ J}\cdot\text{g}^{-1}$. As illustrated in Figure 8a(ii), the composite integrated phase-change heat storage, Joule heating, thermal comfort regulation, and flexible thermotherapy into a single wearable platform. Under a low operating voltage of 4.5–6.0 V, the material rapidly heated from 28 to 70°C and subsequently released stored heat to maintain a relatively stable therapeutic temperature. More importantly, the electrothermal response remained stable under curved and repeated bending conditions, demonstrating that the PPy@MF-PEG₄₀₀₀₊₂₀₀ composite could operate reliably under realistic body-motion environments. This work integrates three essential features for portable thermotherapy, i.e., high latent heat, low-temperature flexibility, and robust electrothermal heating.

This concept was further advanced by developing highly stretchable phase-change composites (SPCCs) for simultaneous health monitoring and thermotherapy^[35]. In these stretchable PCM composites, the phase-change domains regulate heat flow and thermal exposure, whereas the conductive network simultaneously converts deformation into electrical signals, enabling thermotherapy and health monitoring within one coupled structure. Specifically, the device employed a dual-functional layered architecture in which a photothermal phase-change layer was created by dispersing island-like MXene-enhanced PEG particles within an elastic polydimethylsiloxane (PDMS) network, whereas a conductive sensing layer was fabricated by incorporating CNTs into a PDMS substrate. This structural design enabled efficient functional specialization while preserving overall mechanical integration. The SPCCs exhibited an energy-storage density of $139 \text{ J}\cdot\text{g}^{-1}$, an elongation at break of 334%, and a gauge factor of 70.8 over a strain range of 0–140%, enabling simultaneous human-motion monitoring and photothermal/electrothermal treatment. The device was further evaluated in a thermotherapy-assisted muscle injury recovery model using Sprague-Dawley (SD) rats. The SPCC patch was attached to the injured region and activated under external light irradiation, generating localized heating for therapeutic treatment (Figure 8b(i,ii)). Infrared thermal imaging demonstrated that the composite could rapidly elevate the wound-area temperature from approximately 34 to 48°C under irradiation while maintaining stable thermal output during treatment (Figure 8b(iii)). This work thereby links material-level thermal regulation with biologically relevant therapeutic outcomes.

Other related studies further reinforce this trend toward multifunctional healthcare-oriented PCM systems. An EVA/PEG layer was sandwiched between two WPU/CNT layers to form a composite that combined electrothermal/photothermal heating, strain sensing, and high stretchability for wearable thermal management and motion detection^[61]. Huang *et al.* reported phase-change hydrogels

based on sodium sulfate decahydrate, polyacrylamide, and PDA@MXene, achieving a suitable therapeutic temperature window of 37–42 °C together with high photothermal conversion efficiency, strain-sensing capability, and temperature-switchable adhesion for painless detachment^[34]. Collectively, these studies suggest that the future of wearable thermotherapy lies in multifunctional material systems capable of integrating stable thermal storage, safe and controllable heat delivery, reliable physiological signal acquisition, soft-tissue compatibility, and adaptive skin-conformal interfaces. Besides future studies should report not only phase-transition temperature and latent heat, but also the actual skin-temperature regulation range, response time, heating/cooling duration, and thermal resistance variation under realistic wearing conditions.

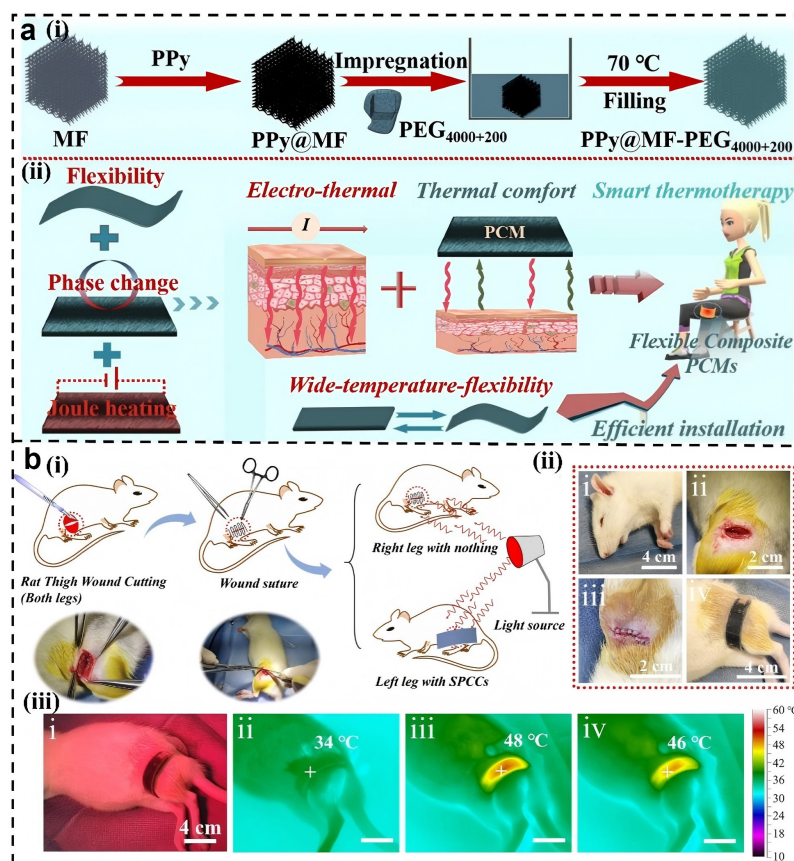


Figure 8. (a) (i) Schematic illustration of the fabrication process of the flexible PPy@MF-PEG₄₀₀₀₊₂₀₀ composite through PPy coating, PEG impregnation, and thermal filling. (ii) Conceptual illustration of the multifunctional wearable platform integrating phase-change heat storage, Joule heating, thermal-comfort regulation, and smart thermotherapy for body-temperature management. Reproduced with permission from reference^[33]. Copyright © 2024 American Chemical Society; (b) Photothermal therapy of SPCCs for muscle wound healing: (i) illustration of a rat muscle injury model with photothermal treatment, (ii) digital images showing a rat muscle injury model, and (iii) digital and infrared images of a rat undergoing photothermal treatment with SPCCs. Reproduced with permission from reference^[35]. Copyright © 2023 Elsevier B.V. PPy@MF-PEG: polypyrrole-decorated melamine foam-polyethylene glycol; SPCCs: stretchable phase-change composites; PCMs: photothermal phase change materials.

3.4 Thermal management for wearable electronics

Wearable electronics present a unique thermal-management challenge because heat is generated and accumulated at soft, curved, and thermally sensitive skin interfaces. Unlike conventional electronic devices that can use rigid heat sinks or forced-air cooling, epidermal devices, electronic textiles, and electronic skins need to manage heat while maintaining mechanical flexibility, breathability, sensing performance, and long-term wearing comfort^[81,95–97]. Localized overheating may lead to skin burns, signal drift, accelerated device degradation, or even functional failure. Consequently, thermal-management materials for wearable electronics are increasingly designed around three coupled requirements: efficient lateral heat spreading to eliminate hot spots, phase-change or high-heat-capacity buffering to absorb transient thermal loads, and skin-like mechanical integration to maintain conformal contact during body motion. In this context, PCMs, thermally conductive fillers, radiative-cooling textiles, and thermoregulatory e-skin architectures are converging into a new class of multifunctional wearable interfacial materials^[98].

A representative example was a strategy for multifunctional wearable thermal management through the design of flexible PCMs for ambient energy harvesting and respiration monitoring^[99]. Inspired by neuronal signal transmission (Figure 9a,b), the authors constructed interconnected conductive and phase-change pathways by integrating PEG, gum arabic (GA), and carboxylated

MWCNTs (cMWCNTs) within a flexible EVA polymer framework. The neuron-like architecture enabled efficient transport of thermal, moisture, and electrical signals throughout the material, while crystalline-to-amorphous phase transition of PEG domains provided reversible latent-heat storage capability. The GA-assisted self-assembly process, combined with ultrasonication, promoted the formation of PEG@GA microcapsules and the targeted distribution of cMWCNTs. This resulted in "neuron-like" conductive pathways and microdome surface structures, which in turn enhanced interfacial responsiveness and moisture capture. The hierarchical network simultaneously enabled multiple wearable functions, including photothermal energy harvesting, moisture-responsive electricity generation, respiration monitoring, and thermal management (Figure 9c,d). The material exhibited excellent flexibility, with an elongation at break of 565.67% and a toughness of $14.88 \text{ MJ}\cdot\text{m}^{-3}$, while maintaining a latent-heat storage density of $71.11 \text{ J}\cdot\text{g}^{-1}$ and a photothermal conversion efficiency of 95.27% under 808 nm irradiation. In addition, the composite demonstrated ultrasensitive humidity responsiveness with rapid response/recovery times of 50.4/50.5 ms, enabling accurate detection of breathing, coughing, sneezing, speech patterns, and long-term respiratory states. This work highlights an emerging trend in wearable thermal-management materials. Rather than relying solely on passive thermal buffering, bioinspired architectures can integrate heat regulation, moisture management, sensing, energy harvesting, and physiological monitoring within a unified adaptive material platform.

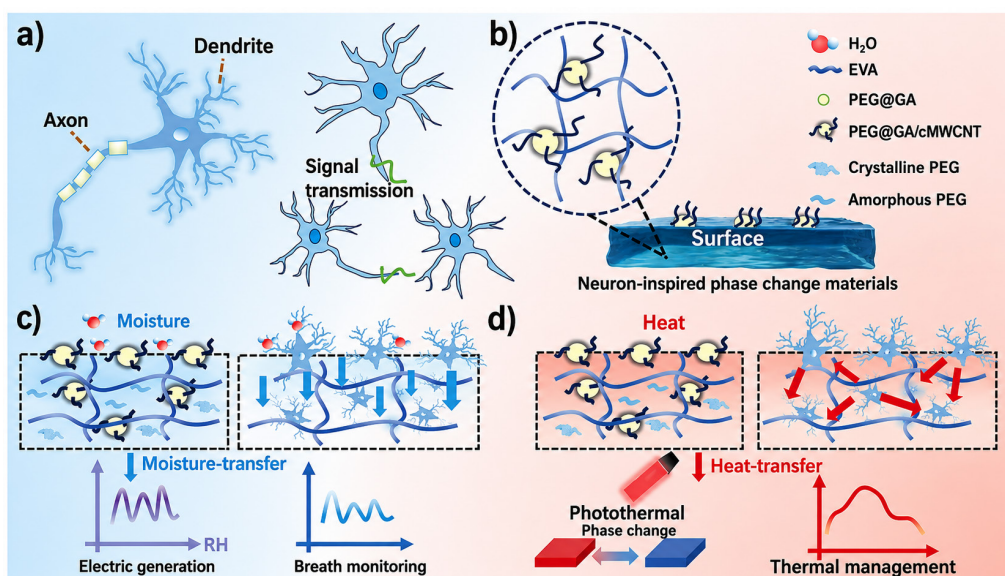


Figure 9. Schematic illustration of neuron-inspired flexible PCMs and their multifunctional applications: (A) biological nerve cells and neurons exhibiting efficient signal transmission; (B) structural design of the PCMs, and (C-D) responses of the PCMs to external stimuli of moisture and heat. Reproduced with permission from reference^[99]. Copyright © 2024 Wiley-VCH GmbH. PCMs: photothermal phase change materials; EVA: ethylene vinyl acetate; PEG: polyethylene glycol; GA: gum Arabic; cMWCNT: carboxylated multiwalled carbon nanotubes; RH: relative humidity.

A more direct phase-change strategy for wearable electronic thermal protection was reported through the development of an advanced thermal skin (ATS) designed as an interfacial layer between electronic devices and human skin (Figure 10a,b)^[100]. The ATS integrated a sodium-acetate-based hydrogel matrix (SAHM), which served as the latent-heat storage component, with a silver-flake/polydimethylsiloxane serpentine structure (SPS) that enabled rapid lateral heat diffusion (Figure 10c). This hybrid architecture addressed the insufficient thermal diffusivity and severe stiffness variation during phase transition commonly encountered in conventional wearable PCM systems. Specifically, the highly thermally conductive serpentine network redistributed localized heat over a broader area, thereby mitigating hotspot formation, while the PCM hydrogel absorbed and stored thermal energy to suppress rapid temperature increases at the skin interface. Meanwhile, the SAHM achieved a mechanical modulus similar to human skin (only 4.8-fold variation across phase states) while maintaining heat-storage capability comparable to conventional PW. This enabled conformal contact with soft and deformable epidermal surfaces, which is essential for stable wearable operation. The ATS successfully protected swine epidermis from thermal damage and maintained stable performance of wearable thermoelectric devices under mechanical deformation. This work redefined the role of wearable thermal-management layers from passive thermal insulation toward dynamic thermal regulation. Rather than simply blocking heat transfer, the artificial thermal skin simultaneously redistributed, buffered, and dissipated heat while preserving mechanical softness and interfacial stability.

Recent studies show that thermal management in wearable electronics is developing toward electrically safe, mechanically flexible, and multifunctional thermal-interface systems. Zhang *et al.* reported a flexible insulating phase-change composite film by incorporating PW into a porous PVDF-BN substrate^[50]. The porous BN network simultaneously enhanced thermal conduction and maintained electrical insulation, while the paraffin component provided substantial latent-heat storage with a melting enthalpy of

105.63 J·g⁻¹. Compared with pure PW, the composite exhibited a 200% increase in thermal conductivity, together with excellent cycling stability and shape-recovery capability, enabling efficient transient thermal buffering for flexible electronic devices. Besides, mechanistic simulations have further revealed that effective thermal regulation arises from the synergy between excessive heat absorption and latent heat release during phase transition, rather than relying on PCMs as stand-alone insulators for skin-safe wearables^[101]. In parallel, thermoregulatory electronic skins are increasingly combining heating, cooling, temperature sensing, and feedback control functions for healthcare monitoring and human-machine interfaces^[98]. Collectively, these studies suggest that photothermal PCMs in wearable electronics are developing from simple heat-storage media into integrated thermal-management interfaces that combine heat dissipation, transient thermal buffering, electrical insulation, moisture regulation, mechanical flexibility, and sensing stability.

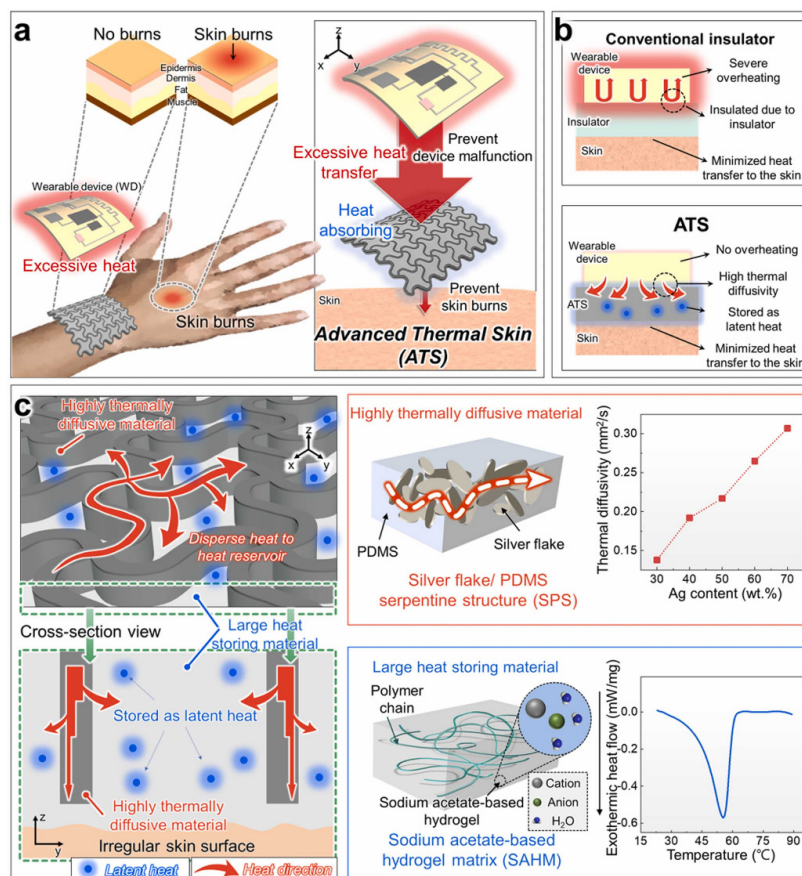


Figure 10. (A) Schematic illustration of ATS and the functional that prevents heat transfer to the skin; (B) Comparison between the conventional insulator and ATS (C) graphical illustration of ATS constituents and their thermal properties. Reproduced with permission from reference^[100]. Copyright © 2022 Elsevier Ltd. ATS: advanced thermal skin; WD: wearable device; PDMS: polydimethylsiloxane; SPS: serpentine structure; SAHM: sodium-acetate-based hydrogel matrix.

3.5 Self-powered and multimodal coupled systems

Self-powered and multimodal coupled systems represent a further development beyond passive PTM because they integrate energy harvesting, thermal regulation, energy storage, and wearable sensing into a unified platform. In these systems, PCMs no longer serve as isolated thermal-storage media, but instead operate as adaptive energy-management components that coordinate thermal flow, temporal energy matching, and device-environment interactions across multiple functional units^[171,102,103]. The design principle is based on energy integration at the system level: photothermal components harvest solar energy^[76], electrothermal units provide active heating under weak illumination^[33], thermoelectric generators convert body heat into electricity^[104], triboelectric nanogenerators harvest biomechanical energy^[102], and PCMs regulate the temporal mismatch between intermittent energy supply and thermal demand^[105]. Such multimodal integration is particularly important for all-weather wearable electronics, outdoor operation, low-temperature environments, and autonomous health-monitoring systems, where thermal comfort, continuous power supply, and stable device performance must be simultaneously maintained.

A representative example of low-temperature self-powered wearable textiles was reported through the development of an Azo-based semicrystalline copolymer with reversible photoinduced solid-liquid transition behavior^[106]. Nylon fabrics were coated with the optimized PAzo_{9:1}-co-PS copolymer (copolymerized at an Azo:styrene molar ratio of 9:1) to fabricate PAzo_{9:1}-co-PS@NF. As illustrated

in Figure 11a(i), UV-light irradiation induced reversible trans-cis photoisomerization of the Azo moieties, enabling photothermal energy storage through light-driven phase transition within the semicrystalline polymer network. The wearable system integrated photothermal energy storage with triboelectric energy harvesting within a single textile platform (Figure 11a(ii)). Specifically, the Azo component enabled controllable light-driven heat storage and release, while the coated nylon-fabric friction interface generated electrical output through triboelectric effects. As a result, the textile could independently operate as a photothermal energy-storage system, a triboelectric generator, or a coupled photothermal-triboelectric platform for simultaneous thermal and electrical energy management. The resulting textile exhibited excellent hydrophobicity, mechanical durability, rapid photoisomerization responsiveness (0.624 s^{-1} under 365 nm UV irradiation), and a relatively high energy density of $70.6\text{ J}\cdot\text{g}^{-1}$. More importantly, the triboelectric performance remained stable across a wide low-temperature range from -20 to $25\text{ }^{\circ}\text{C}$, maintaining an open-circuit voltage of approximately 170 V, a short-circuit current of $5\text{ }\mu\text{A}$, and a transferred charge of 62 nC. When fabricated into gloves and exposed to UV light and friction, the coated finger region became approximately $6.0\text{ }^{\circ}\text{C}$ warmer than the uncoated parts. This work demonstrates that multifunctional wearable systems can simultaneously combine photothermal energy storage, motion-driven electricity generation, and localized thermal regulation, thereby providing a promising strategy for autonomous wearable heating and self-powered operation in cold environments.

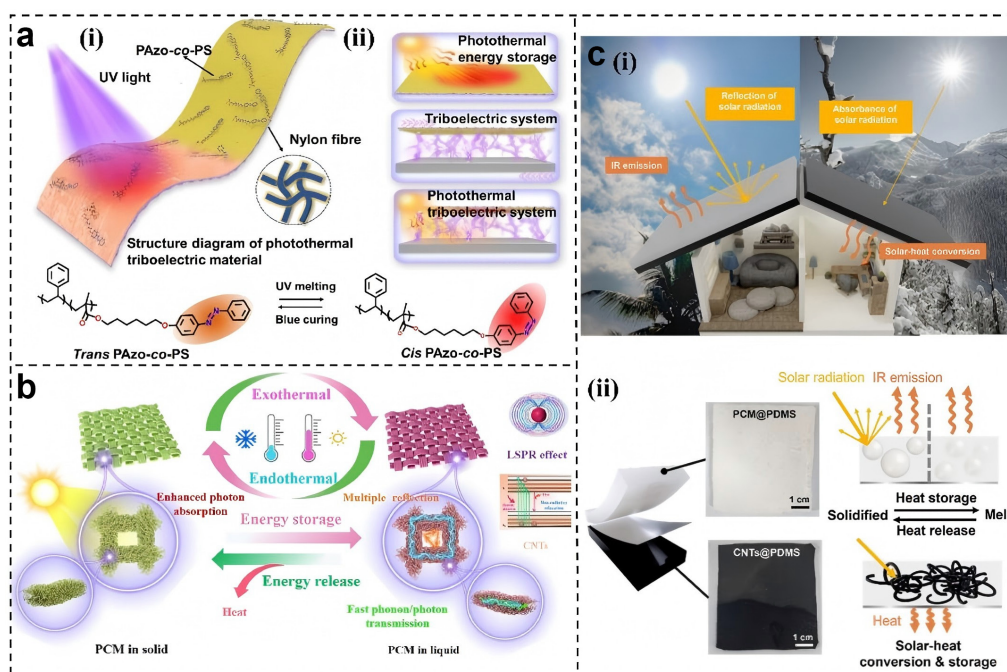


Figure 11. (a) Schematic of the (i) structure and (ii) related mechanism of a photothermal triboelectric material. Reproduced with permission from reference^[106]. Copyright © 2025 Elsevier; (b) Schematic illustration of solar-thermal conversion mechanism. Reproduced with permission from reference^[26]. Copyright © 2024 Elsevier Inc; (c) (i) Schematic of the PCM-enhanced dual-mode thermal management Janus film used as a roof coating in cooling (left) and heating (right) modes. (ii) Photographs and working principle of the dual-mode thermal management Janus film. Reproduced with permission from reference^[20]. Copyright © 2025 American Chemical Society. PCM: photothermal phase change materials; UV: ultraviolet; PAzo-co-PS: poly(azobenzene-co-styrene); LSPR: localized surface plasmon resonance; CNTs: carbon nanotubes; PDMS: polydimethylsiloxane.

Another representative multimodal strategy involves the development of photoelectric dual-mode triggered composite PCMs for all-weather PTM and shape-memory applications^[26]. In this work, ZnCo-MOF nanosheet arrays were first grown in situ on flexible CC and subsequently carbonized to produce Co/CNT-modified carbon cloth (CC@Co/CNT), which was then impregnated with PEG to fabricate PEG/CC@Co/CNT composite PCMs. The interconnected porous carbon-cloth framework enhanced photon absorption and enabled efficient energy-storage/release cycling through reversible PCM phase transitions. Meanwhile, the graphitized carbon/CNT heterostructures together with Co nanoparticles promoted multiple light reflections, LSPR-assisted photothermal conversion, and rapid electron/photon/phonon transport throughout the conductive network (Figure 11b), thereby accelerating both solar-thermal and electrothermal responses. The carbon-cloth scaffold also provided intrinsic flexibility, air permeability, and mechanical robustness, allowing the composite to maintain stable wearable functionality during deformation. As a result, the composite showed a tensile strength of 9.15 MPa , a latent-heat storage density of $114.19\text{ J}\cdot\text{g}^{-1}$, a thermal conductivity of $2.01\text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$, and an electrical conductivity of $1,468\text{ S m}^{-1}$. It also exhibited a high solar-thermal conversion efficiency of 93.7% under $100\text{ mW}\cdot\text{cm}^{-2}$ irradiation and electrothermal conversion efficiency of 94.5% at 2.0 V . By integrating solar heating, Joule heating, thermal storage, breathability, and shape memory into one fabric-like PCM, such designs highlight the development of all-weather thermal management systems that can operate under more complex and changeable environments.

To address the limitation of conventional wearable or building thermal-management materials that usually perform either cooling or heating under a fixed environmental condition, Yu *et al.* developed a PCM integrated Janus film for dual-mode thermal management by coupling radiative cooling, solar heating, and latent-heat storage within one flexible platform^[20]. As illustrated in Figure 11c(i), the PCM-enhanced dual-mode thermal-management Janus film operates as an adaptive roof-coating system capable of switching between cooling and heating modes under different environmental conditions by switching the exposed surface. The film was constructed from a PCM/PDMS layer and a carbon-nanotube-modified PDMS (CNTs@PDMS) layer, giving the two surfaces distinct optical and thermal functions (Figure 11c(ii)). In the cooling mode, the PCM/PDMS surface reflects incoming solar radiation while promoting infrared emission for passive radiative cooling, while the embedded PCM absorbs excess heat through phase transition and suppresses rapid temperature rise. In the heating mode, the CNTs@PDMS side efficiently absorbs sunlight and converts it into heat, which can be stored by the PCM and released later when the ambient temperature decreases. Therefore, the PCM is not simply used as a thermal buffer, but acts as a dynamic energy-storage component that broadens the working window of the Janus thermal-management system. As a result, the introduction of PCM enabled temperature-adaptive thermal management by dynamically regulating both cooling and heating behaviors. During daytime operation, the Janus film maintained a temperature approximately 5 °C lower than that of a conventional radiative cooler at the initial stage, whereas at night it remained up to 2.5 °C warmer due to the release of stored thermal energy. A related passive thermal-regulation concept was reported in the bioinspired multilayer structure for energy-free passive heating and thermal regulation in cold environments, where photothermal conversion, thermal insulation, and directional heat regulation were integrated to reduce heat loss and maintain a warmer local microenvironment without external energy input^[107]. Besides, flexible thermoelectric devices have also shown that PCM heatsinks and stretchable semi-liquid-metal interconnectors can simultaneously provide cooling effects exceeding 10 °C together with power densities of 7.3 $\mu\text{W}\cdot\text{cm}^{-2}$ for self-powered sensing applications^[105]. Overall, these studies suggest that the next generation of wearable PCM systems will be hybrid platforms where heat storage, heat spreading, power generation, motion harvesting, and intelligent triggering are co-designed rather than independently optimized.

4. Summary and Perspectives

Photothermal PCMs have developed from passive latent-heat reservoirs into multifunctional wearable energy materials that can harvest, store, convert, and release heat in a more controllable way. Their value in wearable thermal management and intelligent healthcare comes from the combination of phase-transition behavior with photothermal conversion, electrothermal heating, radiative heat exchange, skin-interfacing mechanics, and sensing functions. Compared with conventional thermal storage materials, wearable photothermal PCMs must work under much more complex constraints: they need to operate near the human comfort or therapeutic temperature window, maintain softness and breathability, survive repeated deformation and washing, remain safe during long-term skin contact, and respond reliably to fluctuating solar, electrical, and body-heat inputs. Therefore, future development should move beyond simply increasing latent heat and focus on system-level designs that integrate thermal performance, wearability, durability, and human-material compatibility.

A first key design principle is to match the phase-transition temperature with the target application. For personal thermal comfort, the phase-transition temperature should match the skin-clothing microclimate, while wearable thermotherapy requires a higher but safe temperature range. In both cases, the latent heat, thermal conductivity, flexibility, and air/moisture permeability need to be balanced rather than optimized separately. Increasing PCM loading can improve thermal buffering but may reduce mechanical strength and breathability. Similarly, adding more photothermal fillers can enhance solar or electrical heating efficiency but may lower latent heat and increase stiffness. Anti-leakage strategies should also be considered together with cycling stability, textile processability, stretchability, and washability. These trade-offs suggest that future wearable photothermal PCMs should be evaluated as integrated wearable systems rather than simply as thermal storage materials.

A second challenge is the lack of standardized evaluation methods for wearable applications. Many studies report latent heat, photothermal conversion efficiency, or cycling stability under simplified laboratory conditions, which may not fully represent real wearing environments. In practical use, wearable photothermal PCMs are exposed to sweat, humidity, skin oils, body curvature, repeated bending and stretching, washing cycles, textile friction, intermittent sunlight, and changing airflow. Therefore, a systematic evaluation protocol should be established at three levels. First, material-level tests should include phase-transition temperature, latent heat, photothermal conversion efficiency, thermal conductivity, leakage resistance, and long-term heating/cooling cycling stability. Second, wearable-structure tests should evaluate cyclic bending/stretching fatigue, abrasion resistance, interlayer delamination, washing durability, sweat/skin-oil resistance, air permeability, water-vapor transmission rate, and mechanical softness. Third, biological and system-level tests should include cytotoxicity, skin irritation/inflammation, sensitization, adhesion fatigue, long-term biocompatibility, and thermal regulation performance on skin models, sweating guarded hot plates, thermal manikins, or human-body simulations under indoor/outdoor conditions. In particular, textile-related standards such as water-vapor resistance/thermal resistance measurements using sweating hot plates and water-vapor transmission tests can provide useful references for quantifying wearing comfort, while recent reviews on PCM-based wearable devices also emphasize the need to connect material thermal properties with application-specific evaluation under real wearing conditions^[108,109]. Such protocols will be essential for comparing different material systems and accelerating the transition from proof-of-concept demonstrations to wearable

products.

A third opportunity lies in the development of multimodal thermal coupling systems. Photothermal PCMs should not be limited to solar heating and latent-heat storage, but can also be combined with radiative cooling, electrothermal heaters, thermoelectric generators, and triboelectric or photovoltaic energy harvesters to achieve all-day and all-season thermal regulation. For example, flexible radiative cooling materials and wearable thermoelectric systems have shown that heat flow can be used not only for cooling or heating but also for self-powered energy generation^[104,110,111]. Incorporating PCMs into such systems may stabilize temperature gradients, prolong useful thermal output, and improve device endurance. However, this requires careful matching of PCM transition temperature, thermal resistance, optical selectivity, and device geometry. Janus multimode thermal-management structures, PCM-assisted wearable thermoelectric devices, and self-powered PCM-based sensors are therefore promising directions.

PC-Azo and MOST fuel systems represent another important research direction. Unlike filler-enhanced photothermal PCMs, PC-Azo materials store solar energy through photoisomerization and release heat when demanded. This approach provides a pathway toward lightweight, rechargeable, and programmable wearable thermal systems. However, PC-Azo materials still face several challenges, including high synthesis cost, limited visible-light response, limited cycling lifetime, molecular fatigue, and difficulties in large-scale textile processing. Future studies should focus on visible-light-responsive photoswitches, supramolecular packing control, polymer immobilization, fabric coating, and hybridization with conventional PCMs. In parallel, epidermal phase-change hydrogels are expected to become important for intelligent healthcare because they combine thermal buffering, adhesion, sensing, and therapeutic heating in one skin-interfacing platform.

Finally, data-driven and AI-guided design may accelerate the future development of wearable photothermal PCMs. Traditional PCM development and device optimization mainly rely on trial and error, but the design space is rapidly expanding in terms of molecular structures, polymer networks, photothermal fillers, textile architectures, and device configurations. Recent reviews have shown that machine learning can contribute to PCM property prediction, system optimization, and operation control in thermal energy storage applications^[112–114]. For wearable photothermal PCMs, AI-guided approaches should be linked to specific and cost-reducing research steps. First, molecular descriptors and machine-learning models can be used to pre-screen organic PCMs, polymeric PCMs, and PC-Azo molecules with suitable phase-transition temperatures, latent heats, crystallization behavior, and photochemical energy-storage density before synthesis, thereby reducing the number of trial-and-error synthetic experiments. Second, data-driven models can help optimize the type, loading, dispersion state, and interfacial compatibility of photothermal fillers such as CNTs, graphene, MXene, PDA, and metal nanoparticles, reducing repeated formulation tests while improving photothermal conversion and thermal conductivity. Third, finite-element simulation combined with surrogate models can predict heat-flow pathways in Janus films, multilayer textiles, porous scaffolds, and core-sheath fibers, allowing device geometry and layer thickness to be optimized before prototype fabrication. Fourth, multi-objective optimization can balance latent heat, leakage resistance, stretchability, breathability, water-vapor transmission rate, wash durability, and skin comfort, which are difficult to optimize simultaneously through conventional experiments. Finally, closed-loop experimental platforms that combine high-throughput formulation, automated thermal/mechanical testing, and active-learning algorithms could further shorten the development cycle from material screening to wearable device validation. Looking forward, major advances are expected to come from the integration of phase-change Azo textiles, Janus multimode thermal management systems, epidermal phase-change hydrogels, PCM-enabled self-powered wearables, and AI-assisted molecular and structural design.

Declarations

Acknowledgments

The use of ChatGPT 5.5 in this work was strictly confined to language polishing. All research content, including study design, data analysis, interpretations, and figures, is original and was not generated using AI tools. The authors are responsible for the accuracy and scientific content of the article.

Authors contribution

He W, Huang L: Conceptualization, writing-original draft.

Nie Q, Zhang F, Zhang Z: Writing-review & editing.

Feng W: Supervision, conceptualization, writing-review & editing.

Conflicts of interest

Wei Feng serves as an Editorial Board Member of *Smart Materials and Devices*. The other authors declare no conflicts of interest.

Ethical approval

Not applicable.

Consent to participate

Not applicable.

Consent for publication

Not applicable.

Availability of data and materials

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