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REVIEW ARTICLE

Bioinspired Materials: From Distinct Dimensional Architecture to Thermal Regulation Properties

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Abstract
The structural evolutions of the organisms during the development of billions of years endow them with remarkable thermal-regulation properties, which have significance to their survival against the outer versatile environment. Inspired by the nature, there have been extensive researches to develop thermoregulating materials by mimicking and utilizing the advantages from the natural organisms. In this review, the latest advances in thermal regulation of bioinspired microstructures are summarized, classifying the researches from dimension. The representative materials are described with emphasis on the relationship between the structural features and the corresponding thermal-regulation functions. For one-dimensional materials, wild silkworm cocoon fibers have been involved, and the reasons for unique optical phenomena have been discussed. Pyramid cone structure, grating and multilayer film structure are chosen as typical examples of two-dimensional bionics. The excellent thermal performance of the three-dimensional network frame structures is the focus. Finally, a summary and outlook are given.

Keywords Bioinspired · Microstructure · Thermal regulation · Dimension

1 Introduction

Experiencing with epochal evolutions in nature, lots of species have been developed astonishing properties to adapt to the survival environment [1–6], which can be generally achieved through the reasonable construction of macro/micro/nano structures from organisms by utilizing the basic components, including chitin, protein and cellulose [7–11]. Achieving impressive multi-functions from given organic elements, rather than calling assistance from intricate chemical compositions outsides, incidates the significant contributions of their unique structures within their bodies after millions years of development. Currently, biomimetic engineering has become a rapidly emerging and potential strategy to satisfy the practical application requirements under the exploration and guidance from biology, emerging as one of the frontiers in the intersection of Materials, Physics, Chemistry, and Biology [12–15]. Significant efforts have been developed to design and synthesize bioinspired materials with specific properties there have been 7702 articles relating to the bioinspired and biomimetic topic during last five years. For instance, the mechanical performance of structural materials could be inspired by seashells, bone and teeth [16–18], the superhydrophobic and superhydrophilic properties are tailored by imitating the structure of Lotus leaves and fish [19–23], optical functional devices are designed under the inspiration from butterfly wings and beetles [24–26], while the microstructures of feathers and skins can be adopted to design materials with thermal management abilities[27].

Thermal radiation phenomenon is ones of the thermal transfer behaviors (the other two are thermal conduction and thermal convection) in nature, emitting electromagnetic wave with different wavelength in most of the objects that higher than 0 K. After absorbing the radiant energy, the thermal energy can be spread freely through vacuum without any medium, therefore requiring efficient and effective utilization of the thermal energy in both military and civil fields, including energy storage and transform, passive radiative cooling, solar steam generation, radiative heat dissipation,

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infrared stealth or detection, etc. In recent years, there has been a lot of attention to the design of materials, including thermal interface materials, thermal greases, phase change materials, and thermally conductive gap filling materials, showing great significance in transferring, dissipating, or storing excess heat at high temperatures. However, the concern of the structures has been limited, which facilitates radiation selective regulation and thereby achieving radiative temperature control by modulating solar radiation [28–30]. The ability of adaptive thermoregulation is significant among plants and animals during various bio-related properties, endowing them the body temperature self-regulating behaviors to prevent overheating or hypothermia phenomena. Theoretically, the thermal properties (including thermal convection, thermal conduction, and thermal radiation [31–33]) can be tailored by changing their nano/micro/macro-structures, thereby influencing the emissivity, reflectivity and absorptivity behaviors toward electromagnetic waves in specific regions [34–37]. For example, the the silk fibers display high broadband optical scattering and IR emission effects, enabling the natural white silk cocoons with excellent radiative-cooling property [38]. The silver ants can reduce their body temperature in hot desert environment through efficient interaction between the triangular hairs and the electromagnetic wave [39]. Therefore, it is essential for us to concern the role of the microstructrue of the organisms towards the thermal responding behaviors when selecting and designing materials with customized performances in practical application environment. Inspired by multiple architectures during years of evolution, various methods have been established and developed in recent years for designing and fabricating thermal-regulating materials with bioinspired structures, including inheriting the structure or modifying with carbonization process from natural biomaterials [40], 3D printing [41, 42], self-assembly [43]. The development of the designing strategies promotes the utilization and application of bioinspired materials in both military and civil fields with thermal-related performances, including daytime radiative cooling [44–47], solar steam generation [48–50], thermal insulation [51, 52], energy storage and transform [53–55], and infrared (IR) stealth or detection [56–60].

A number of comprehensive reviews have been reported previously discussing the thermal-regulating materials and devices, which mostly focus on the regulation of infrared light by the organism [35], the construction of thermal photonics [54], and dynamic thermal radiation regulation [61]. To the best of our knowledge, the classifications based on dimensions and the corresponding construction of thermal-regulation materials with bioinspired structures have been rarely put forward. Actually, the geometry of the biomaterial was found to play a key role in determining the thermoregulatory behaviors. Therefore, to classify the bioinspired structure in the view of configurations and to uncover the direct relationship between the common configurations and the corresponding thermal-regulating performances, this review provides an overview of the latest developments of thermal-regulation materials with bioinspired architectures, ranging from one dimension to three dimension. This review focuses on several typical research cases, such as the one-dimensional structure of silkworm cocoon fibers [62], the typical triangular cross-sectional two-dimensional structure of desert silver ant hair [39], and the three-dimensional structure inspired by polar bear hair [63], which is shown in Fig. 1. These meaningful works promise to guide the preparation and device assembly of next-generation materials with thermal-regulation properties. Finally, the existing difficulties is analyzed, along with providing future development tendency.

2 One-dimensional Bionic Microstructure

Biomaterials having a high length-to-diameter ratio (typically greater than 50–100) are classified as one-dimensional biomaterials. There are numerous one-dimensional biological materials with special functions and structures in nature such as silkworm fiber, polar bear hair and poplar leaf hairs. One-dimensional biostructures have garnered substantial interest among diverse structures and have potential uses in current heat management technologies from their high structural anisotropy, which permit the combination of multifunctional properties including self-warming clothing,

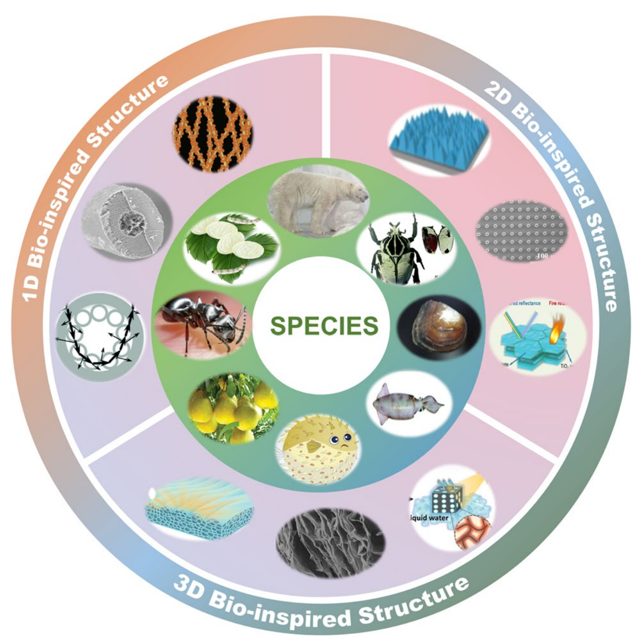

Fig. 1 Bioinspired microstructures realize optical and thermal control

motion-detecting skin, stealth and camouflage against infrared surveillance [64–66]. This section presents various bioinspired 1D materials that mirror the unique architectures and exceptional thermal characteristics of natural archetypes.

2.1 Silkworm Fiber

Silkworm cocoon fibers are extraordinary natural materials with ultralight and exceptional fineness, which are generated by the coagulation of silk liquid during cocooning (Fig. 2a). Importantly, silk fibers play a role in protecting silkworm pupae from predator attacks and sudden temperature changes [67]. Natural white silk cocoons display high broadband optical scattering and high IR emission inside the silk fibers, enabling the cocoons with excellent radiative-cooling property. Currently, the thermal applications of bioinspired silk fibers mainly focus on radiation cooling and personal thermal management, which will be discussed in detail in following.

The scattering phenomenon is caused by hundreds of tightly packed parallel fibrillar nanovoids running along the fiber axis inside each fiber (Fig. 2b–c), while the high IR emission is attribute to the robust and broad absorption of chemical bonds of fibroin proteins. Inspired by the amazing optical properties of silk fibers, Han [38] reassembled the raw silk into fibrous films with regulated fiber diameters by electrospinning method, characterizing the optical properties and analyzing it by optical anisotropic diffusion theory, along with the temperature variation performance throughout the day. The result showed that, the restructured silk fibrous films can display even more optical scattering than

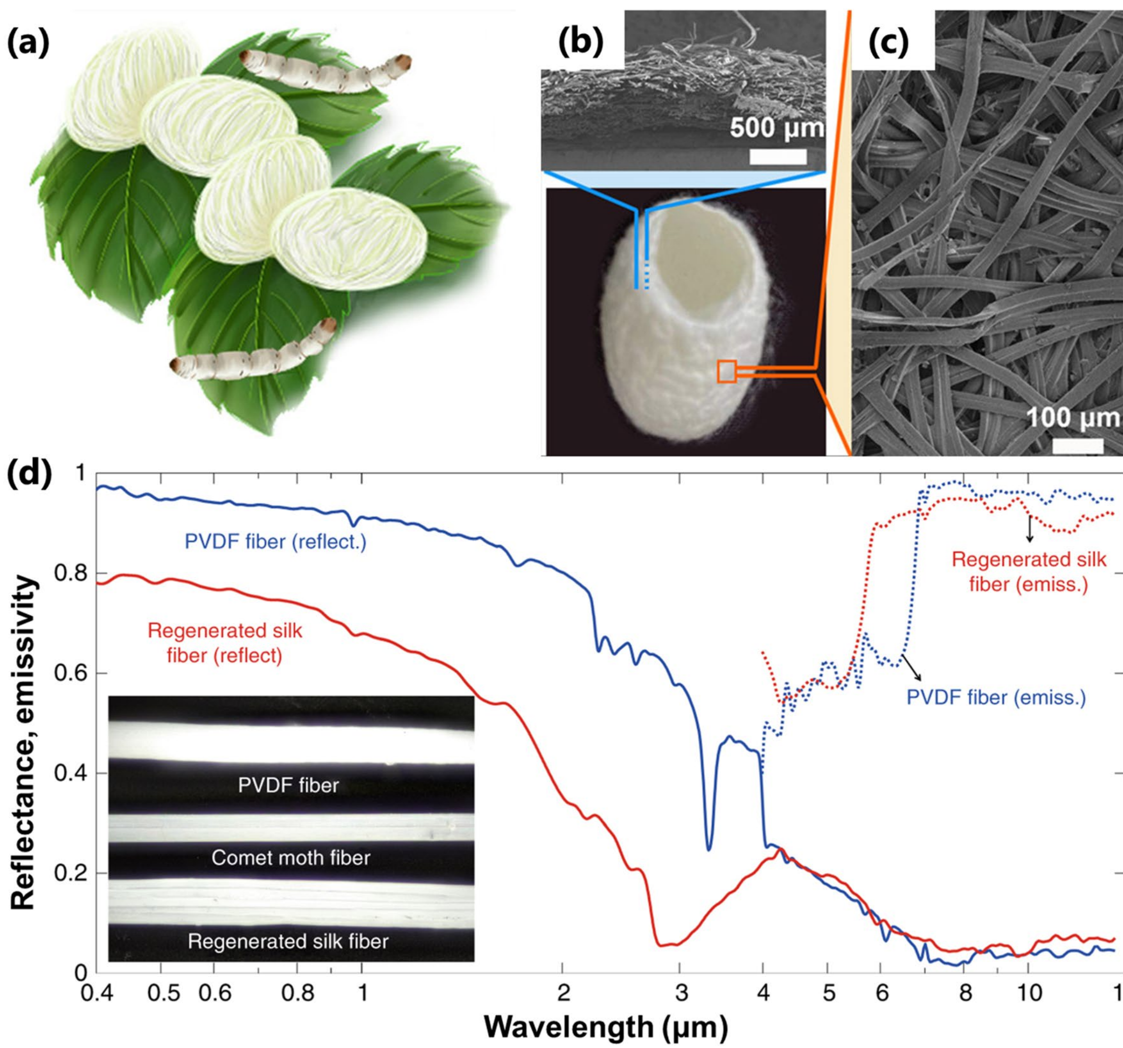

Fig. 2 **a** Schematic of the *B. mori* and its silkworm cocoon. Micrographs showing the top-section view **b** and cross-sectional view **c** of silkworm cocoon [68]. **d** Integrated hemispherical reflectance and emissivity spectra of regenerated silk fibers and a single PVDF fiber from the visible to the mid-infrared region. Inset shows photograph of a different fibers [67]

wild silk when the average diameter of silk fibers is 0.25 µm. Reflection across a wavelength range of 0.4–0.9 µm is maximized among a diameter range of 0.25–1.76 µm, resulting in improved cooling performance compared to a nonwoven raw silk fabric. The fibrous film reaches a lower average substrate temperature than raw silk by 7.5 °C. The Optimization of structural factors in the electrospun silk, may improve optical scattering even further. Starting from the randomly stacked microstructure of silk fibers of *Bombyx mori*, melt-blown polypropylene (MB-PP) is fabricated using a large-scale melt-blown manufacturing process [68] to meet the effective radiative cooling. The cross section and diameter of the fibers is adjusted based on finite-difference-time-domain (FDTD) calculation, followed with modifying polydimethylsiloxane (PDMS) coating on the surface of the MB-PP film to enhance the thermal emittance. The SMB-PP exhibits sub-ambient temperature drops of 4 ℃ during the day and 5 ℃ during the night owing to ~95% solar reflectance and ~0.82 thermal emittance.

While diffuse reflection in randomly structured materials is common in nature, light reflection with the high degree of specularity found in moth cocoon fibers is unusual for a natural biological system. The wild silkworm cocoons fiber can be regarded as an important natural application of the Anderson optical positioning theory, in which the light transmission is suppressed in the disordered systems, resulting in a greatly improved reflectivity in the visible to near-infrared (Vis–NIR) regions, along with high emissivity of the biomolecules of silk in IR radiation, resulting in a significant passive cooling effect as 'natural' metamaterials [62].

The radiative-cooling properties of silk are limited both by material absorption and void density in the solar spectrum. Following the Anderson localization effect, A biomimetic nanostructured fibers from comet moth (*Argema mittrei*) was fabricated adopting wet-spinning method based on regenerated silk fibroin and polyvinylidene difluoride (PVDF) [67]. As shown in Fig. 2d, the solar reflectivity of nanostructured PVDF fibers is enhanced to 0.93 when compared with 0.73 of the regenerated silk fibers, while the thermal emissivity is improved to 0.91 from 0.90 in the mid-infrared (MIR) range (electromagnetic wavelength of 8–13 µm), exhibiting remarkable thermal properties for efficient radiative-cooling devices. It is worth noting that the filamentary air voids with high density are distributed randomly throughout the fiber cross section but remain invariant along the fiber, enabling the highly directional scattering and presenting a highly reflective sheen. Similarly, the molecular vibrations of PVDF fibers and the phonon polariton resonance of Al_2O_3 can be integrated to construct PVDF/Al_2O_3 fibers by electrospinning method. The fibers perform excellent radiative-cooling performance under various weather conditions, exhibiting a temperature drop of upwards to 4.0 ℃ [69].

Although natural silk has high reflectivity in the visible region, absorption in the ultraviolet (UV) range should be reduced for efficient radiative cooling. In addition, abrasion resistance and comfort need to be considered when natural fabrics clothing is used for personal thermal management. A molecular bonding design strategy along with scalable coupling reagent-assisted dip-coating technique are used to nanoprocessing of silk [70]. The nano-processed silk with enhancing UV reflectance is depicted in Fig. 3a, exhibiting a lower temperature than natural silk and cotton (Fig. 3b). Stand-alone nano-processed silks have a temperature of 3.5 °C below ambient under direct sunlight. When covered with nano-processed silk as opposed to natural silk, the temperature of a simulated skin may be reduced by 8 °C without compromising its wearability and comfort. In addition, to meet the thermal comfort of human body, a passive cooling meta-fabric with moisture-wicking property and good wearability is fabricated, achieving effective temperature and moisture management [71]. Moreover, a silver-coated polyamide PA textile for thermal management could be used in multiple environments [72]. And colored textiles with thermal management have been developed [73–75], which could have both excellent antibacterial and anti-UV properties.

The continuous nanoporous polyethylene (nanoPE) microfibres with impressive wearability and durability can be constructed by large-scale and industrial extrusion process [76], which can scatter visible light efficiently to make it opaque while maintaining the MIR transparency, exhibiting a great cooling capacity as reducing the skin temperature by 2.3 ℃. In practical life, it is often desirable to dynamically adjust whether to keep warm or dissipate heat according to the actual ambient temperature. By coating carbon nanotubes as conductive materials on the triacetate-cellulose bimorph fibers [77], the metafiber can respond to the change of the relative temperature or humidity, realizing the dynamic infrared gating effect in textile yarns by distance-dependent electromagnetic coupling between adjacent fibers, thereby controlling the infrared emissivity and promoting the radiative cooling. Effective modulating more than 35% of the infrared radiation, this IR-adaptive textile can be served as intelligent wearable localized thermal management systems in the future.

The concept of tailoring natural materials via accessible and scalable procedures may give a sustainable energy-saving approach to personal thermal control and inspire new routes for developing passive cooling materials and technologies.

2.2 Polar Bear Hairs

Polar bears are mammals that can live in extreme settings, mainly in areas with floating ice near the Arctic Ocean. They can keep themselves warm in an extremely

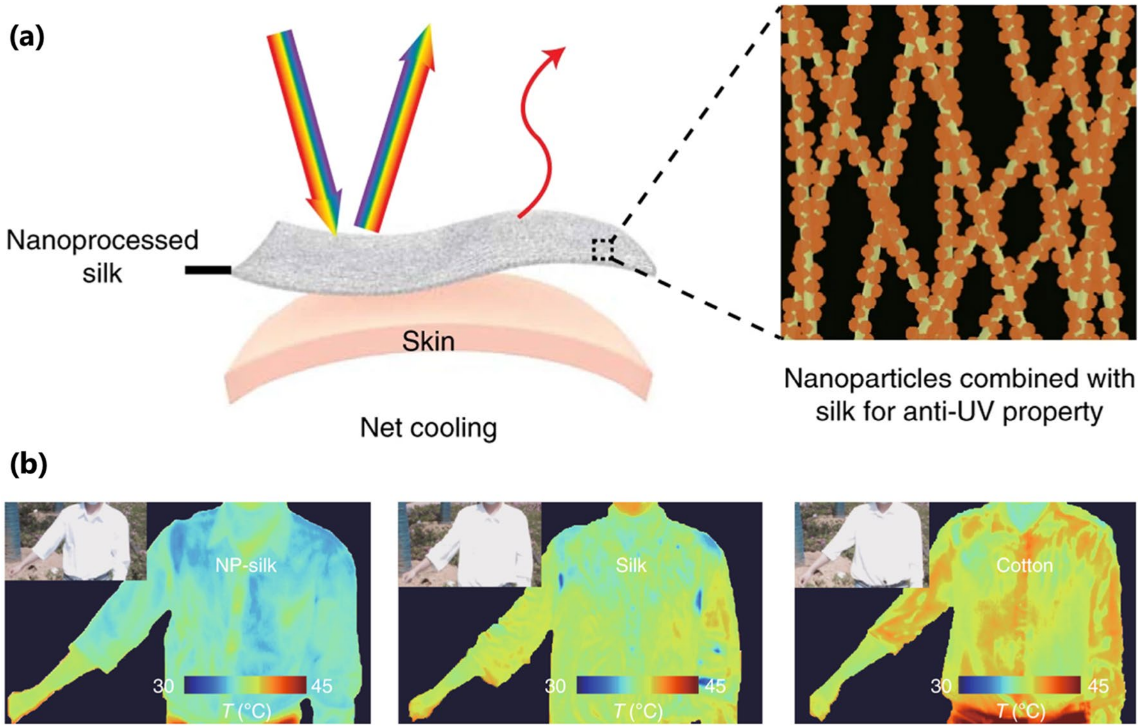

Fig. 3 **a** Schematic of the net cooling performance of nano-processed silk by enhancing UV reflectance. **b** Infrared images and optical photographs (insets) of a human wearing shirts made from nano-processed silk, silk and cotton under sunlight in Nanjing [70]

cold environment by effectively reflecting infrared emission from their bodies, attribute to their thick fat fur with hollow-porous hairs, as shown in Fig. 4a–c [78]. Capturing air within and among the hollow structure of the hairs, the heat radiation can go through while the convection and conduction of the heat are impeded, thereby managing the heat transfer and preventing heat loss. Fibers that mimic the structure of Polar bear hairs is a focus of attention as human thermal management devices.

Drawing inspiration from the microstructure of the polar bear hair as natural radiative-cooling fibers, a continuous and large-scale "freeze-spinning" technique is adopted to fabricate aligned-porous-structure fibers into textile woven with high porosity (87%) [78]. Figure 4g illustrates that biomimetic textiles have an average reflectance of 70–80%, higher than that of typical commercial textiles. Besides, biomimetic textiles exhibit an excellent thermal insulation property as well as great breathability and wearability, possessing more effective thermal stealth properties than commercial polyesters (Fig. 4f–g). After doping carbon nanotubes as electro-heating materials, the textile present electrothermal conversion ability with fast thermal response and uniform temperature distribution, which can be served as a wearable heater. Zhu et al. [79] used a scalable electrostatic spinning process to produce a hierarchically designed Polyethylene oxide (PEO) nanofiber-based film for high-performance all-day radiative cooling.

Except for achieving the radiative cooling and thermal insulating properties by mimicking the porous and hollow structure from polar bear hairs, the multifunctionality should be utilized, which play indispensable roles in wearable smart devices. Yue and coworkers [80] synthesized a nanofibrous membrane inspired by the sunlight absorption and thermal radiation reflection of polar bear pelt. The nanofibrous membrane could work as wearable devices with thermal-regulation properties along with self-electro-heating performance from high electrical layer. In addition, the incorporation of thermal insulation and the ability to sense the surface of the skin into wearable devices is a challenging task. Stretchable hollow-porous thermoplastic polyurethane (TPU) fibers with excellent thermal insulation property and ultra-high stretchability (1468%) are designed. The absolute temperature value difference achieves 68.5 ℃. Furthermore, after decorating

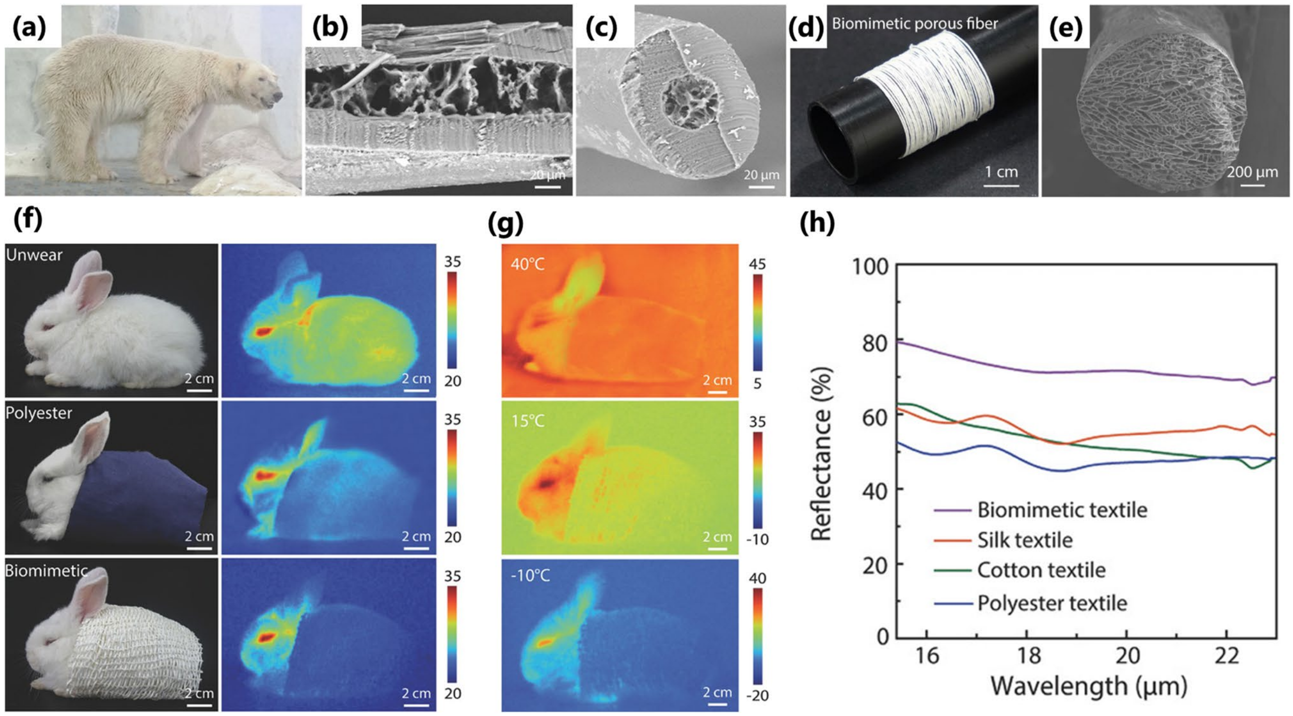

Fig. 4 **a** Photograph and (**b**, **c**) SEM images of polar bear hair. [78] **d** Optical image and (**e**) SEM image of biomimetic porous fiber [83]. **f**–**g** Thermal stealth properties biomimetic textiles. **h** Infrared light reflectance measurement of different textile [78]

with AgNP/polydopamine (PDA)/CNT as conductive filler by coaxial wet spinning and in-situ reduction processes, the conductive composite fibers achieved electrical heating, strain sensing, temperature sensing and pressure sensing properties [81]. By constructing a smart reconfigurable hairy skin based on a hair-patterned shape memory polymer (SMP) with hierarchically porous micro/nanostructures, the dynamic management of temperature and camouflage from infrared surveillance abilities are demonstrated. The programmable form of the hairy SMP allows the irreversible and adaptable reconfiguration of the hair morphology in response to external environments, resulting in more than 61.4% dynamic control of thermal insulation [82]. Superhydrophobic surface treatment of the textile with porous microstructure (Fig. 4d–e) allows for promising a superior thermal insulation in both air and water ambient, paving the way for the bioinspired thermal insulating materials in both air and underwater [83]. In addition, biomimetic thermal-regulation textiles can also have stretchability, high strength, flame retardancy, and acid and alkali resistance [84].

2.3 Other

In addition to the fibers and hair from animals discussed above, there are surprising one-dimensional structures present in specific portions of plants and insects, which have been imitated to realize effective thermal management.

Poplar leaf serves as an excellent natural prototype and the poplar leaf hairs protect the poplar leaves from being burned by strong light with hollow fibers structure. Coaxial electrospinning technology is used to synthesize white hollow polystyrene fiber, achieving a highly reflectivity as ''cool roof'' in visible and infrared wavelengths, while the super-hydrophobicity property enable the film as insulation layer, resisting the damage and erosion from water [85]. The White beetles *Goliathus goliatus* with structural whiteness can live in high-temperature tropical woods due to the evolution of the delicate shell/hollow cylinder structure shown in Fig. 5a–b. Fan [86] found out that the lower equilibrium temperature of elytra of *Goliathus goliatus* is determined to two thermoregulatory effects: synergetic structural effects coming from thin-film interference, Mie resonance, and total reflection in the visible domain dramatically improved broadband omni-directional reflection. Thin film interference in the shell and voids in the scales are responsible for the omni-directional reflective property, shown in Fig. 5c. Besides, the anti-reflection properties of hollow cylinders are superior than shell/hollow and solid cylinder structures (Fig. 5d). Moreover, the white scales with gradient refractive

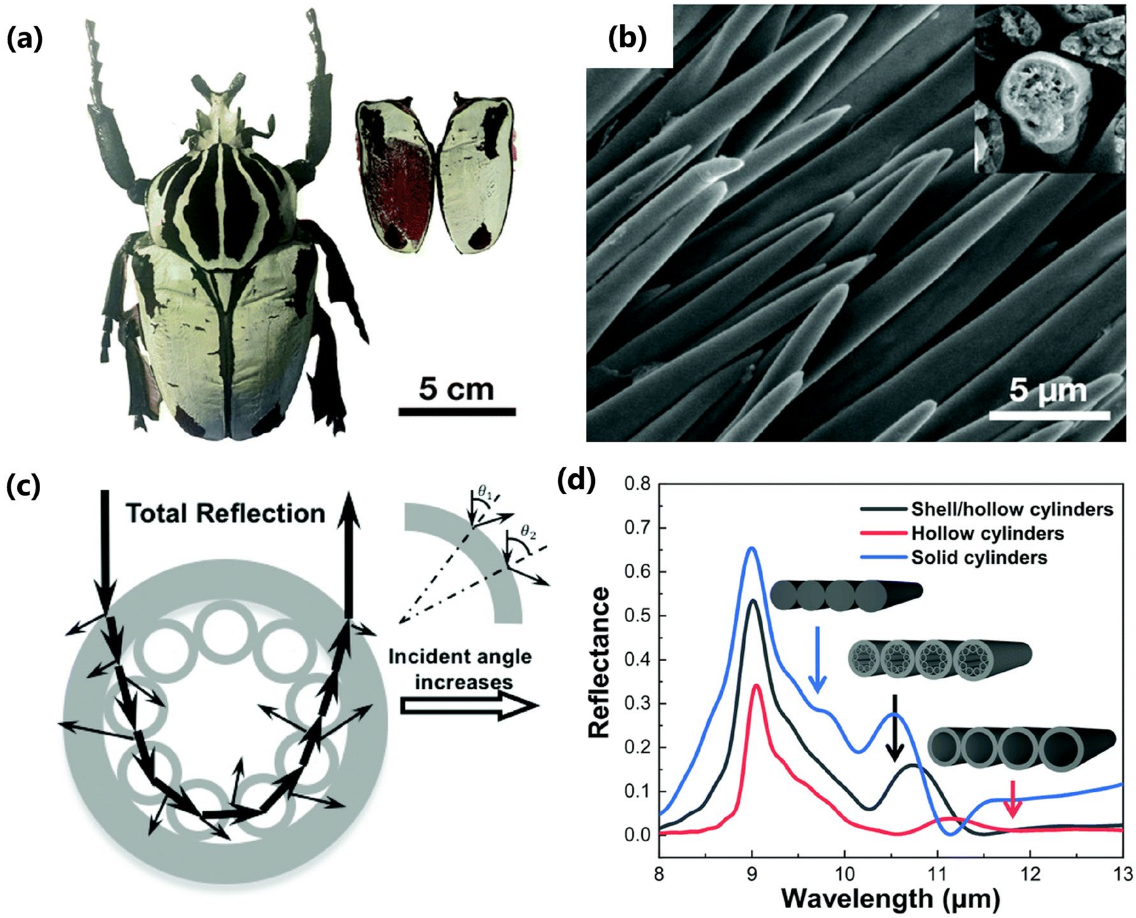

Fig. 5 **a** Photograph of a male *Goliathus goliatus*. **b** SEM image of the central part of white scales. Inset: cross-sectional image. **c** Schematic illustration of total reflection in the scattering system. **d** Simulated reflectance spectra of shell/hollow cylinder structure, hollow cylinders and solid cylinders in the MIR range [86]

index operate as antireflective layers to increase the emissivity in the MIR range. A temperature reduction of ~ 7.8 ℃ in air implies that the biological thermoregulation strategies aid in the development of passive radiative-cooling coatings.

Combining the excellent one-dimensional configuration design of natural bio-fibers and the strong component properties of artificial materials, future research will have more application prospects in the fields of wearables and textiles. Large-scale production and research on adaptive wearable local thermal management systems will become a hot spot for sustainable energy-saving solutions. These all-in-one integrated strategies from bioinspired materials promote the advancement of the next-generation thermal management applications, including self-warming clothing, thermal therapy garment, motion-detecting skin, energy-efficient windows, stealth and camouflage against infrared surveillance. Due to the limitations of the fibers itself and the structural parameters of the one-dimensional structure, the thermal management efficiency is limited, requiring higher dimensional structures to achieve efficient thermal management performance.

3 Two-dimensional Bionic Microstructure

The cross-sectional characteristic parameters has brought inspiration for 2D microstructure with a higher degree of freedom, compared with the one-dimensional configuration. Better thermal performance can be achieved by controlling the 2D-related parameters such as geometric configuration and size. For example, the triangular cross section of the desert silver ant hair has made an indelible contribution

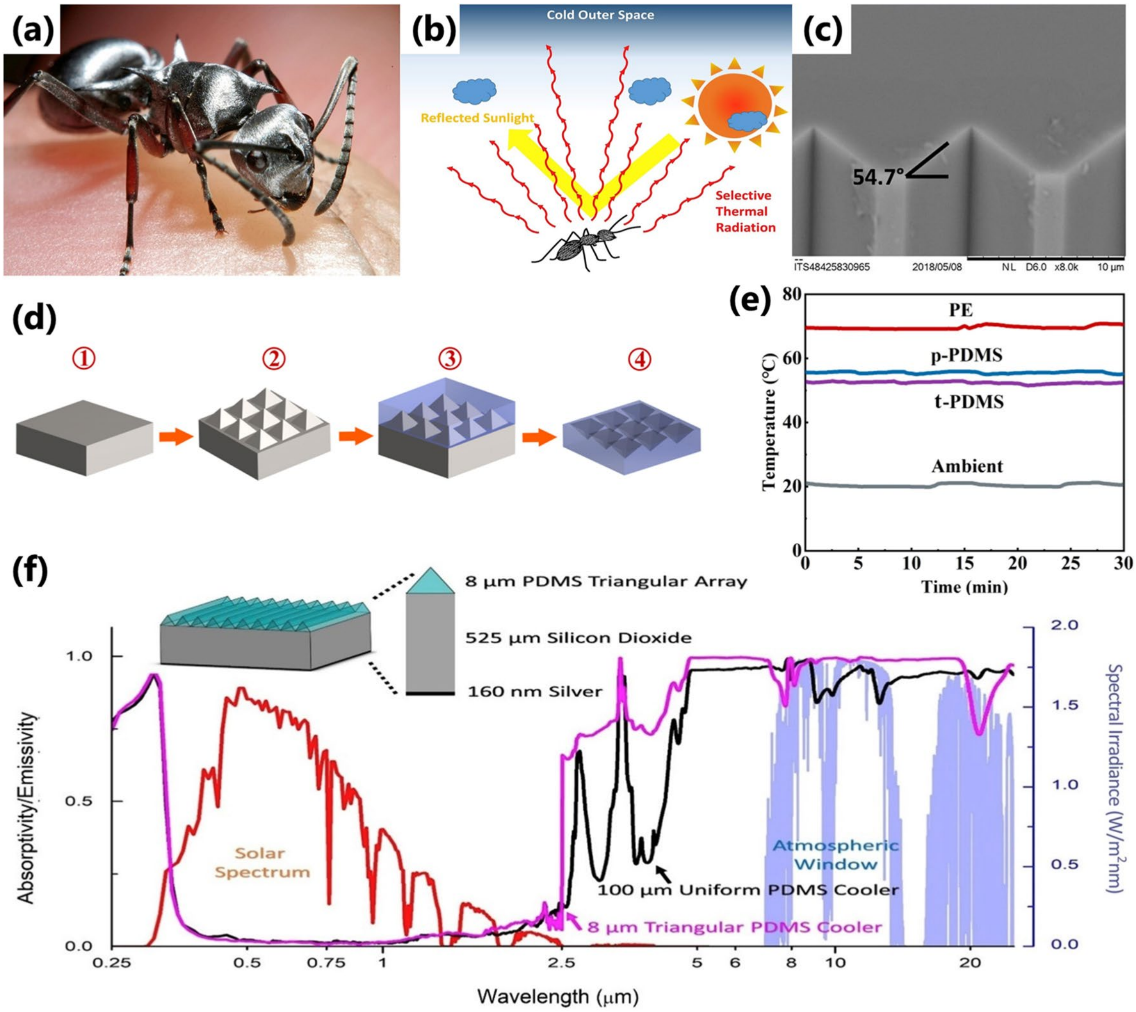

Fig. 6 **a** Photograph of Saharan silver ant, Cataglyphis bombycine. **b** A schematic diagram of thermoregulatory effect discovered in the Saharan silver ant. **c** SEM image of the fabricated silicon mold with 8 μm characteristic length triangular arrays [91]. **d** Schematic diagram of the preparation of PDMS films; **e** The temperature under the sunlight of solar cells with different coatings [93]. **f** Measured full emission spectrum of the uniform 100 μm thick PDMS-SiO_2-Ag [91]

to improving its thermal control [39]. The planar pyramid structure and the conical structure designed after imitating the triangular cross section retain their original structural features and still give full play to the structural advantages [87, 88]. Besides, 2D periodic structures, such as reflective gratings and gradient index structures, can be processed by surface patterning process, improving the efficiency of the radiation surface and regulating electromagnetic waves in a wide range of angles [89, 90].

3.1 Desert Silver Ants' Hair

Some insects in the desert can reduce body temperature by reducing the absorption of solar radiation and enhancing infrared emission in extremely hot environments such as Saharan silver ants (*Cataglyphis bombycine*), shown in Fig. 6a, while Fig. 6b displays the thermal-regulation effect of silver ants.

Confronting to the foraging behavior of silver ants under high temperature in African desert, Yu's team reported [39] that the internal two thermoregulatory effects of desert silver ants are attributed to the dense array of triangular hairs which behaves conspicuous silvery appearance. The reflectivity in the Vis–NIR range can be enhanced by Mie scattering from the triangular cross-section hair. The gradient index layer of the hair structure can provide broadband, wide-angle anti-reflection properties in the MIR where the solar radiation reaches pinnacle, thereby efficiently dissipating heat back to the environment through blackbody radiation in daylight circumstances. The thermoregulatory strategies by mimicking the structure of the silver ants lead to the design of biomimetic coatings for passive radiative cooling [91]. The design of prismatic structure on the PDMS could be optimized by FDTD simulations and printed using silicon molds with triangular arrays (Fig. 6c). The average emissivity in the MIR range of spectrum is increased to 0.98 by the gradient refractive index effect, along with the average reflectivity in the Vis-MIR spectrum to 0.95. Figure 6f shows the emissivity in the wavelength range from UV to IR. The optimized bioinspired polymeric reaches a highest temperature drop of 6.2 ℃ lower than the ambient air temperature in a tropical region.

The hundreds of nanometers thick air gap between silver ant hair and epidermis also plays a key role in enhancing visible light reflection and mid-infrared radiation. Flexible hair-like photonic structures on PDMS are fabricated, which involved the triangular air gap (TAG) and bridge air gap (BAG), resulting the enhancement of the optical reflection and mid-infrared emission by 17% and 4%, respectively, thereby enabling the maximum temperature drop of 6.7 ℃ [87]. Similar, Song et al. [88] mimicked the hierarchical feature structure of the hairs of silver ants, fabricating and modifying the flexible corrugated triangular cross-section photonic architectures (FPA) on PDMS, which exhibited a large emittance (0.98) at atmospheric window wavelengths, and the record-high transmittance (96.72%) in the wavelength range of 0.3–1.2 µm. As a consequence of improved light harvesting properties, this device has appealed to photovoltaic systems for maximizing solar absorption and minimizing parasitic heat. Besides, Zinc oxide micro-crystal-bar (MCB) composite is synthesized to fabricate a unique solar heat shielding fabric by imitating silver ants [92]. The textile coating with MCB composite could achieve 95% solar reflectance and the temperature dropped by 7.6–17.7%. Moreover, the coating results in improvements of the thermal conductivity as well as the mechanical property.

Regarding the exploration of desert ants and their biomimetic materials, the unique prismatic structure shows great advantages in thermal management. The natural design idea could increase the knowledge of complicated biological processes and inspire the invention of new technology.

Analogous to sliver ants, longicorn beetles contain triangular cross-section microstructures and dual-scale hairs, which help to regulate bogy temperature. Inspired by the longicorn beetles, a flexible hybrid photonic material with high throughput for passive radiative cooling was fabricated [94]. The micro-pyramid arrays of the PDMS matrix can reflect sunlight (~ 95% solar irradiance) and emit heat radiation (IR emissivity > 0.96), leading to an efficient cooling power of ~90.8 W/m^2 and a temperature drop of 5.1 ℃ under direct sunlight. Integrating with the hydrophobicity, outstanding flexibility, and strong mechanical strength, the film exhibits great potential for designing and fabricating wearable devices with thermal management properties.

Apparently, the design of pyramid structure could improve the cooling efficiency. Through designing multilayer films of all-dielectric micro-pyramid structure with alternating Al_2O_3 and SiO_2 layers, the weakness of poor MIR selectivity in planar photonic structures and the disadvantage of high solar absorption in metal/dielectric metamaterials can be solved out, which achieved excellent selective emissivity in the MIR region as well as extraordinarily low absorption over the entire solar spectrum, thereby presenting a net cooling power of more than 122 W/m^2 at ambient temperature [95]. Also, a random inverted pyramid-like light-trapping structure can be textured on the surface of the PDMS film by low-cost coating and embossing process, exhibiting the enhancement of the transparency and radiative-cooling performance by 2.1% and 2.7%, respectively, which is more suitable for applying as outdoor radiative-cooling emitters [93]. Similarly, an ultra-wideband versatile pyramid structure is prepared by sol–gel imprinted method to achieve radiative cooling and light regulation via the interaction with geometric, diffractive, and optical effects [96].

3.2 Moth-eye

The moth-eye structure has developed to be more effective at capturing light, allowing them to avoid predators and find food. The nano-tapered structure inspired by the moth's eye exhibits excellent performance in anti-reflection and photo-thermal management. The micro-nano feature traps within the moth-eye surface presents the hierarchical structures, which can trap the light effectively by concentrating the light energy through multi-reflection and absorbing behaviors. Specifically, the moth's eye presents protuberances with hexagonally close-packed configurations, creating structurally profile with graded refractive index through sub-wavelength tissue, thereby transparentizing the interfaces between the air and the eye. The Fresnel reflection and diffraction can be eliminated due to the little discrepancy of the graded refractive index value between the air (1) and the eye tissue (1.4), leading to hardly reflection of light. Therefore, fabricating by nano-patterning, 3D printing, and selected-etching strategies, the omni-directional anti-reflection properties could be included in the moth-eye-inspired structure, achieving broadband wavelength range [97, 98].

The bioinspired moth-eye structured surface could improve the photovoltaic thermoelectric hybrid system's solar energy utilization efficiency through photon and thermal management methods. Optimized by FDTD, the reflection of the full solar spectrum photons can be suppressed while the transmission for photons with energy below the band-gap of PV cells can be enhanced simultaneously, thereby achieving better utilization of solar spectrum energy under AM1.5 and AM0 illumination with the average reflectivity decreased from 28.64 to 3.02% and from 29.70 to 3.37%, respectively, ultimately increasing total power output [99]. Besides, the black titania (BT) nanocomposites can be fabricated on carbon cloth by mimicking the nanostructure of moth's eye, which produce clean water by solar steam generation and photocatalytic degradation [100]. The nanoarray of BT can trap the light by extending the effective transmission path and increasing the scattering effect, achieving outstanding light absorption of 96% in the full spectrum, thereby presenting solar steam efficiency of 94% under 1 kW/m^2 simulated light of and high degradation efficiency of 96% toward rhodamine B. Facing the large-scale processing, the antireflective topographies inspired by moth-eye structure can be fabricated through roll-to-roll thermal nanoimprint lithography methods [101], while the relationship between the process parameters and the optical/mechanical properties can be established to satisfy the practical application environment requirement with optimal performance.

3.3 Skin

The animal skin is an important organ for thermal regulation, which is able to adjust the body temperature in response to the change of external environment and excess heat generated inside. A growing number of skin-inspired thermal management products have been developed in recent years.

3.3.1 Human Skin

Human skin plays an important role in regulation, induction and protection [102]. The naturally wrinkled human skin structure is shown in Fig. 7a–c. The self-adaptive temperature regulation ability of human skin is demonstrated by enhancing or depressing sweat evaporation during different temperature environment. Also, skin can be regard as an emission surface, and ~60% heat is lost through thermal radiation. As shown in Fig. 7d, the average emissivity of the human body can achieve 91.5% in 8–13 μm band. These characteristics have inspired the development of adaptive temperature regulation devices.

Inspired by the dynamic thermal-regulation processes of human skin, a solar-driven evaporation system with

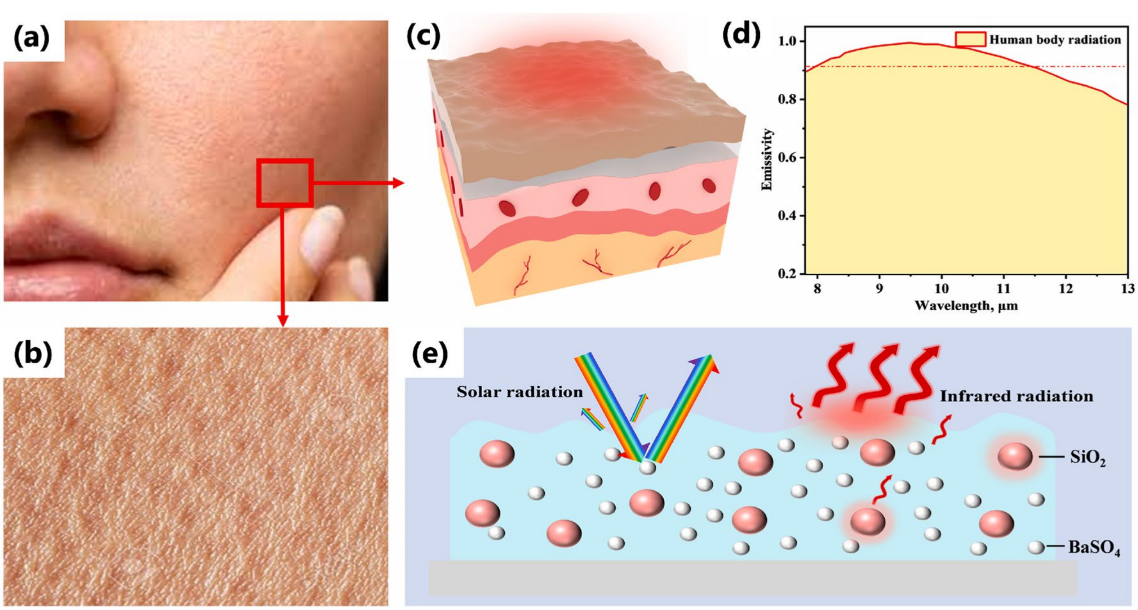

Fig. 7 **a** Photo, **b** Locally enlarged view, and **c** Schematic of human facial skin. **d** Emissivity of the human body at 8–13 μm. **e** Basic working principle and schematic of the Bio-RC coating [104]

self-adaptive temperature adjusting functions at the interface is designed to harvest the solar energy [103]. The bioinspired interface system is based on thermochromism temperature regulator, which is composed of tungsten-doped vanadium dioxide nanoparticles and a PVDF pyroelectric thin film, achieving a self-adaptive temperature oscillation with a maximum temperature differential of about 7 ℃ under the simulated solar irradiation with 1.1 kW/m^2 power density. Similar, Chen et al. [104] achieved efficient optical property regulation by mimicking the natural wrinkle structure of human skin with optimized $BaSO_4$ and SiO_2 particles into synthesizing a large-scale radiative-cooling coating (Fig. 7e). This ~ 100 µm thick coating showed high solar reflectivity of ~ 95% and emissivity of ~ 96% at "atmospheric window", thereby presenting the average effective cooling power of ~ 89.6 W/m^2 and the maximum sub-ambient temperature decrease of 8.1 ℃, while the maximum average interior air temperature of the building coated with the coating can be reduced by 6.2 ℃.

Electronic skin (e-skin) is outperforming skin properties and demonstrates a broad range of applications in a variety of fields [105, 106]. The electronic skin for long-term human thermoregulation is fabricated by constructing Ag and Pt nanofibers networks on silk fibroin composite membranes (SFCMs), exhibiting high thermal stability, temperature sensitivity, along with inflammation-free and air-permeable [107]. However, e-skin with dynamic temperature regulation have rarely been reported. Xiang et al. [108] fabricate a thermoregulating E-skin using phase change material, achieving dynamic thermal regulation through a phase change based on the surrounding temperature. This work provides dynamic temperature regulation to e-skin and establish new prospects for its evolution.

3.3.2 Dynamic Discolored Skin

The dynamic discolored skin of animals provides a wealth of inspiration for the IR adjustment system. Effective IR attenuation is vital for areas including intelligent thermoregulation, adaptive thermal camouflage, and energy-efficient building. Compared to conventional thermal management systems which are mostly statically controlled (such as space blanket) [109], the dynamic systems with active thermal-regulation properties are more desirable in the future application.

Cephalopod skin has an intriguing ability to produce dynamic color changes for camouflage and communication [110]. To reproduce the ability of camouflage in Vis-IR region, a multi-band stealth skin in Vis-IR region is developed recently by controlling the temperature with a bi-functional device which could heat or cool actively [111]. The thermochromic layer endows the device with ability to stealth in the Vis region, by producing various colors according to controlled surface temperature. Moreover, the prepared skin has high resolution to respond to sophisticated background, attributed to the localized control of independent pixels.

Squid is one of the cephalopods and its skin changes in appearance through contracting and expanding of chromatophores. Inspired by squid skin, Leung et al. [112] developed

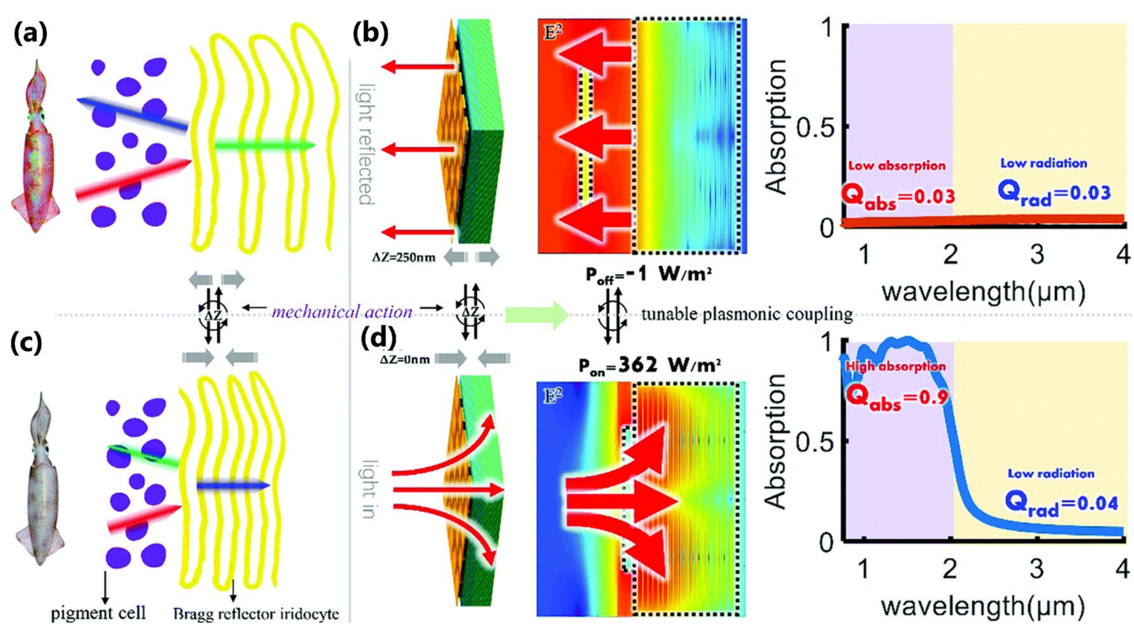

Fig. 8 **a**, **b** Schematics of iridescent colour change from the tuneable coupling of the pigment cells and the iridocytes in squid. **c**, **d** Schematics of the composite structure, which consists of a grating and a hyperbolic structure [113]

a dynamic temperature regulation material composing of an infrared-transparent polymer matrix to simulate the transparent dermal layer of squid, and an overlaid nanoscale copper array to act as embedded pigments to reflect the infrared radiation. The mechanical stretching mode can change the surface microstructure of the material reversibly, thereby tuning the transmission and the reflection towards the infrared radiation. Drawing inspiration by the tunable coupling of the iridocytes and chromatophores of squid skin, an thermoregulatory metamaterial was produced by coupling the grating and multi-layered structure [113] as shown in Fig. 8. The thermoregulatory metamaterial can regulate the solar absorptive quality from 0.9 to 0.03 while maintaining a low radiative quality, with the photonic thermal power density ranging from 362 to 1 W/m^2 under on/off state from FDTD method. In addition, a dynamic IR modulator is developed with Au-styrene-ethylene-butylene-styrene (Au-SEBS) membrane, of which the IR performance changes with mechanical strain, demonstrating a great potential for thermal management and adaptive thermal camouflage [114]. A packaging material with tunable thermal management properties is also strain-driven, having ability to keep the hot beverages in paper cups cool. Importantly, the raw material cost of the composite material is as low as 0.1 US$/$m^2$ [115].

Chameleons can quickly and finely exhibit complex and rapid color shift of their skin color and even skin texture during social interaction, including camouflage, camouflage, communication, and thermoregulation. Teyssier et al. [116] discovered that the color-shifting mechanism of chameleon is attributed to the active tuning of a triangular lattice of guanine nanocrystals spacing within an upper multilayer of dermal iridophores. Deeper population of iridophores cells with larger crystals can broadly reflect a significant part of sunlight, especially in the NIR range of spectrum. Hence, the combination of two functional layer allows the integration of efficient camouflage with different display and thermal protection from solar radiations potentially. Gorodetsky et al. [117] reported a new category of adaptive IR reflecting materials and platforms which presented multi-functionalities, including tunable spectral, adaptive infrared camouflage, wearable thermoregulation with fast response and simple actuation mechanism, along with mechanical stability. The combination of these desired features might open up new opportunities for current technologies that rely on regulating heat radiation transmission. Inspired by the diagnostic thermal-protection properties of the Chameleon, Gonome et al. [118] developed two superposed layers with different functions: the CuO particles imitate the superficial surface for color, while the TiO_2 particles imitates the deep surface to reflect the solar irradiation (NIR range of spectrum). After optical modelling, low reflectance in vis region and high reflectance in NIR region can be achieved, thereby enhancing the thermal-protection performance of the dark-tone coating.

3.4 Other

The cuticles of certain insect wings are patterned to produce natural photonic structures for camouflage and temperature regulation. The coloration of butterfly wing results from a combination of pigmentation and periodic chitin microstructures which provide the scattering effect of optical properties within the visible spectrum [89, 90], helping tailoring the spatial variation of thermal emissivity and hence regulating the temperature of the wing. Besides, the relationship between the periodic structure and the thermoregulatory behaviors in infrared wavelengths can be demonstrated via unit cell approach and thermal computations [119], suggesting the contribution of the butterfly wings grating structure into tailoring the absorption of the sunlight and the emission of infrared ray, thereby producing better spectral selectivity with narrower peaks or depressions of the spectrum. Inspired by the iridescence of the *Morpho didius* butterfly, Didari et al. [120] designed a metamaterial system by modifying the SiC palm tree-like structure with periodical multi-layered film separated by nanoscale-gap. The spectrally selective enhancement, originating from geometric variations, spatial location of the source, and the material characteristics, increased the heat flux in the infrared range of spectrum ultimately.

The planar photonic structures could play a role in multi-bands compatible camouflage with thermal-regulation properties. Therefore, a periodic photonic crystal structure was fabricated [121] by incorporating simple wavelength-scale grating structure into multi-layered structure, along with utilizing thin-film interference to realize the thermal management function. Also, combining pore array/structure with phase change material (SU_8, VO_2, SiO_2) can also realize adaptive infrared camouflage by changing the reflection spectra of the multi-cavity-coupled plasmonic system [122].

Heat-dissipating materials with excellent thermal conductivity are a requirement for electronic packaging and thermal management. Liu et al. [123] produced zebra-skin-like composites consisting of graphene paper and copper, exhibiting ultra-high thermal conductivity of 968 W/m K. Besides, the thermal-related properties of the devices can be tailored through adopting silica photonic crystal as visibly transparent thermal blackbody [124], or retaining the emission in the

Vis–NIR range while suppressing the longer wavelengths by limiting the electron thermal fluctuation at specific region and enhancing the resonance behavior of the intrinsic semiconductor [125], using UV nanoimprint lithography method [126], achieving to efficient radiative-cooling performance.

Natural organisms provide excellent two-dimensional configuration design, such as pyramid structure, multilayer film structure, grating structure, etc. The effect of these structures alone is often not very good in temperature regulation, stealth, camouflage and other fields. It is usually the combination of multiple structures that can exert greater advantages. Manual design can select the required structure according to actual needs. Future research is worthy of attention in dynamic photonic materials and dynamic radiation adjustment.

4 Three-dimensional Bionic Microstructure

Designing the porosity and internal network structures or tailoring the light propagating routes in the hierarchical structures, the gas/liquid adsorption and separation performances can be integrated in the aerogel/hydrogel systems while maintaining remarkable thermal-regulation properties simultaneously in the nature-derived and artificial sophisticated 3D structures. Besides, the arrangement and the construction of the sophisticated 3D structures endows the materials with multifunctionalities, including the self-cleaning and the mechanical properties, over a wide length scale ranging from nanometers to meters.

4.1 Aerogel and Hydrogel

Aerogel represents a kind of 3D materials with high-porous and nano-frameworks structure, possessing low density, large surface area, and low thermal conductivity properties. Therefore, increasing researches have been successfully to meet the practical requirement of multifunctional devices in thermal-regulation devices through designing of the porous structures and tailoring the chemical compositions of the aerogels based on bioinspired strategies.

Drawing inspiration of hollow structure of the polar bear hair, Yu et al. [127] designed a dual-function carbon-nanotube-based aerogels which consisted of two layers: the C/SiO_2/Au aerogel act as a absorption layer with 98% broadband absorption in Vis–NIR range, while the carbon nanotube aerogel serves as a heat insulation layer that effectively resisting the thermal transport from the hollow network structure. This biomimetic aerogel could be utilized directly as the thermal insulation layer for solar steam generators, exhibiting the solar-thermal conversion efficiency of 82.8% under 1 kW/m^2 solar illumination, thereby applying for water evaporation. Although the polar bear hair presents excellent thermal insulation performance, the low UV reflectivity and high Vis–NIR light reflectivity implies disadvantageous effect to heat collecting, daylighting, and human health. To solve out the problem, Du et al. [128] deposited the tetraethoxysilane (TEOS) onto the carbon aerogel via chemical vapor deposition (CVD) method, followed by calcinating into silica nanotube aerogels in air. The construction of the random nanoscale tubular microstructure induces strong Rayleigh scattering effect, contributing to scattering of short wavelengths and resulting to the low UV transmittance and high Vis–NIR range transmittances. Further, the PDMS film with high-scattering PE aerogel are laminated into cooling skin exhibiting flexible, superhydrophobic, and reusable characteristics to imitate the synergistic thermo-optical effect of polar bear fur [63]. By tailoring the pore size (3.8 ± 1.4 μm), porosity (97.9%), and the thermal conductivity (0.032 W/mK), the cooling skin can achieve a high solar reflectance of ~ 0.96 and MIR transparency of ~0.8, leading to a sub-ambient cooling of 5–6 ℃ in a metropolitan environment at midday. The maximum temperature is estimated to be 14 °C under optimal usage circumstances. This is desirable for sustainable thermal management of operable energy-saving cooling materials. The structure of a penguin feathers is comparable to polar bear hairs, which contain micro/nano porous to trap air and provide insulation. Inspired by both of the above animal hairs, Yu et al. [129] devised a biomimetic sponge with interlinked macroporous framework for thermal regulation and macro channels for water transportation. Multiple light reflections can be induced by the 3D isotropic truss structures, allowing for omni-directional light absorption. Therefore, the as-prepared biomimetic hierarchical evaporator can inhibit the thermal diffusion, exhibiting high evaporation rate (2.3 kg/m^{2}h) and high efficiency (93%), along with salt resistance, ions removal properties, endowing it with long-term durability for sewage purification and desalination.

Confronting the major mechanical vulnerability and structural processability constraints when creating structure-integrated multifunctional aerogel. Fu et al. [130] assembly the tunable Salvinia-inspired surface topography and intrinsic topology in-situ into programmable binary architectures with function-adaptable surfaces morphologically. The resulting structure-adaptable multifunctional aerogel presented outstanding temperature-endured elasticity, lasting super hydrophobicity, oil absorbency, anti-icing, and thermal insulating (0.075 W/mK) properties. Further, facing the poor interfacial adhesion in fire-retardant polymeric foam as

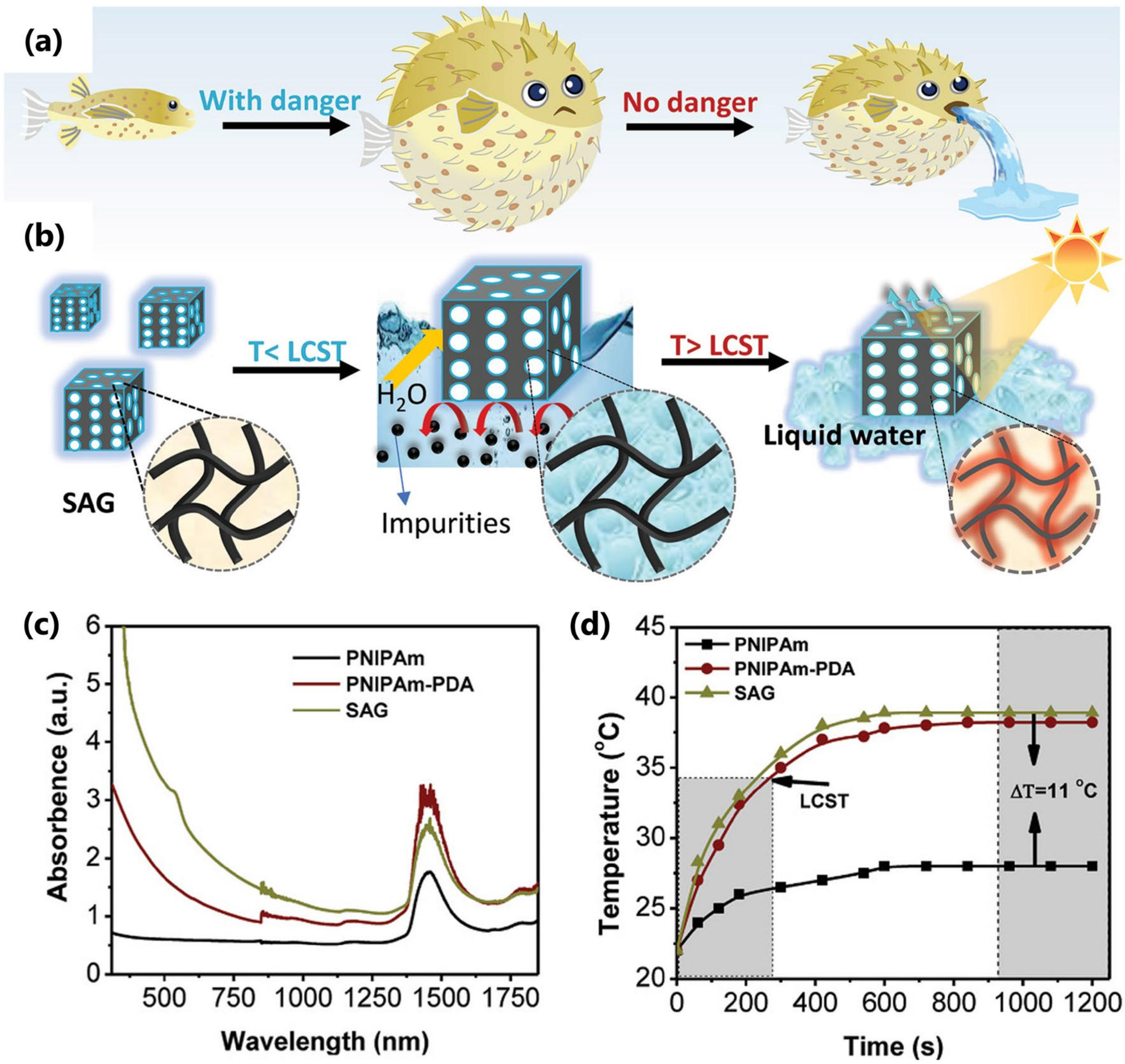

Fig. 9 **a** The shape changes of a pufferfish via the uptake and release of water when threatened. **b** The phase transformation (swelling and de-swelling) of PNIPAm under natural sunlight. **c** UV–vis–NIR absorbance spectra and **d** Surface temperature change under one sun illumination of PNIPAm, PNIPAm–PDA, and SAG [132]

thermal insulation materials, a fire-retardant polymeric coatings with phase-separated micro/nanostructures is developed based on adhesion mechanisms of snails and tree frogs via a facile radical copolymerization strategy approach [52]. The coating exhibits high interfacial adhesion to rigid polyurethane (PU) foam, along with super hydrophobicity, well-preserved thermal insulation, and flame self-extinguishing features with low heat and smoke release.

Compared with aerogel, thermally responsive hydrogels can be adopted in the water-based environment, regulating the water transport in the fields of Solar Evaporation and desalination applications. The sunflower stalk pith has special structural features and possesses a high pumping capacity in dry settings. Motivated by this characteristic, Su et al. [131] design a solar desalination device by coating a porous foam derived from sunflower stalk pith with zwitterionic hydrogel and carbon black. Specifically, the multi-curvature and gradient honeycomb structure provides excellent water transportation channels and thermal insulation, while the water diffusion for steam generation is enhanced by open-pore structure under the capillary force. Inspired by the absorption and release cycle of water from the pufferfish, a high-elastic solar absorber gel (SAG) has been developed through depositing photo-thermal PDA layer and sodium alginate (SA) network at macro-porous thermo-responsive poly(N-isopropylacrylamide) (PNIPAm) hydrogel [132], shown in Fig. 9a–b. The low-temperature light-driven water release from SAG proved by lower eventual surface temperature (Fig. 9d), while exhibiting broad and efficient absorption (Fig. 9c). Absorbing a big amount of clean water after being immersed in polluted water and expelling the clean liquid water when exposed to natural sunlight, the facile operation in sustainable production of clean water can address water scarcity. Further, Keeping up with the rapid evaporation rate and excellent quality of water while deploying at a reasonable cost remains a problem. Yu et al. [133] introduced the metal–organic framework-derived nanoparticles and konjac glucomannan biomass into polyvinyl alcohol networks, developing hydrogel evaporators in a cost-efficient manner. The naturally konjac glucomannan can possess excellent heat insulation property and fast water transport channel under macro-/meso-porous structures. The metal–organic framework-derived nanoparticles can tailor the spatial distribution of the magnetic solar absorbers, thereby reducing the use of solar absorbers and enhancing heat localization at the evaporation surface. The evaporators produce a high evaporation rate (≈90% energy efficiency).

Motivated by mussel adhesion properties and chameleon color shift mechanisms, Zhao et al. [134] added conductive CNTs/PDA filler into PU inverse opal scaffold to fabricate hydrogel-like film. The stable stretchability and brilliant structural color abilities is attributed to the special microstructure and splendid flexibility of the PU layer, while PDA endow the film with high tissue adhesiveness and self-healing capabilities, thereby presenting color-shifting ability that responds to motion as sensor. Similar to the porous structure of the aerogel, through designing the pore size and structure or building micro-void arrays (inverse-opal-like), the solar reflectance and infrared emissivity of the materials can be tailored, reaching up to cutting edge of sub-ambient all-day cooling performance, indicating significant advances toward the design and application of bioinspired devices for outdoor passive radiative cooling [135–137].

4.2 Hierarchically Structure

Different from the disordered nano-framework of aerogel, the hierarchical porous microstructures facilitate the optical properties of the materials, which induces intense sunlight scattering and reflection effect owing to the refractive index mismatch between materials and air. Besides, the Mie scattering in the short wavelengths region is efficiently increased by the multiple reflections in the porous structure, which is benefit to minimizing the solar absorption and resulting in an ultra-white appearance. Furthermore, the super hydrophobicity can be satisfied from the hierarchical rough structures, endowing the materials with self-cleaning performance.

Confronting the decreased radiative-cooling performance from outdoor contamination, Huang et al. [138] adopted a phase separation process to fabricate polyvinylidene fluoride and polydimethylsiloxane porous film with hierarchical structure and superhydrophobic property. Owing to the molecular vibrational modes of PVDF/PDMS and the enhancement of the Mie scattering, the as-prepared film exhibited a high reflectance of 97% in Vis–NIR range and a high MIR emissivity of 96%, thereby yielding excellent cooling performance as average temperature drop of 12.3 ℃ in direct sunlight. Besides, the low surface energy and the hierarchical micro/nano porosity of PVDF and PDMS endow film with self-cleaning properties and durability against different chemicals and UV irradiation. Besides, imitating the structures and functions of the *Cyphochilus beetle*, Saharan silver ant and lotus leaf together, Liu et al. [139] developed self-cleaning coating with hierarchical structure which integrates the optical, thermal, and physiochemical properties. The muti-bioinspired design strategy is shown in Fig. 10. The self-cleaning coating exhibits strong solar reflection, high MIR emission, and excellent anti-contamination properties, presenting sustainable radiative-cooling performance (sub-ambient cooling of 13.8 ℃) with durability at various harsh conditions. Integrating self-cleaning with radiative cooling, these researches provide fresh approaches for advancing energy-free cooling materials into practical applications.

Solar evaporation is seen as a viable solution for dealing with the problem of fresh water shortage. Various attempts have been made to increase solar-thermal conversion efficiency, but developing efficient, cost-effective technologies from easily accessible basic materials remains a problem. Moreover, there are few reports of subsequent structural modifications to the initial biomass framework, which might increase the solar–thermal performance of these material systems. Li et al. [140] adopted direct graphitization process and followed fractal structural design strategy to carbonize pomelo peels (PPs) into low-cost system with intrinsic microscale porosity (Fig. 11), exhibiting high solar spectrum absorption (≈98%), superior evaporation rate ~ 1.95 kg/m^2h, and high photo-thermal efficiency (92.4%). Numerical simulation and experimental analysis were used to identify the light harvesting systems that contributed to the evaporation enhancement. This biowaste-derived materials with biomimetic structures showed tremendous potential in

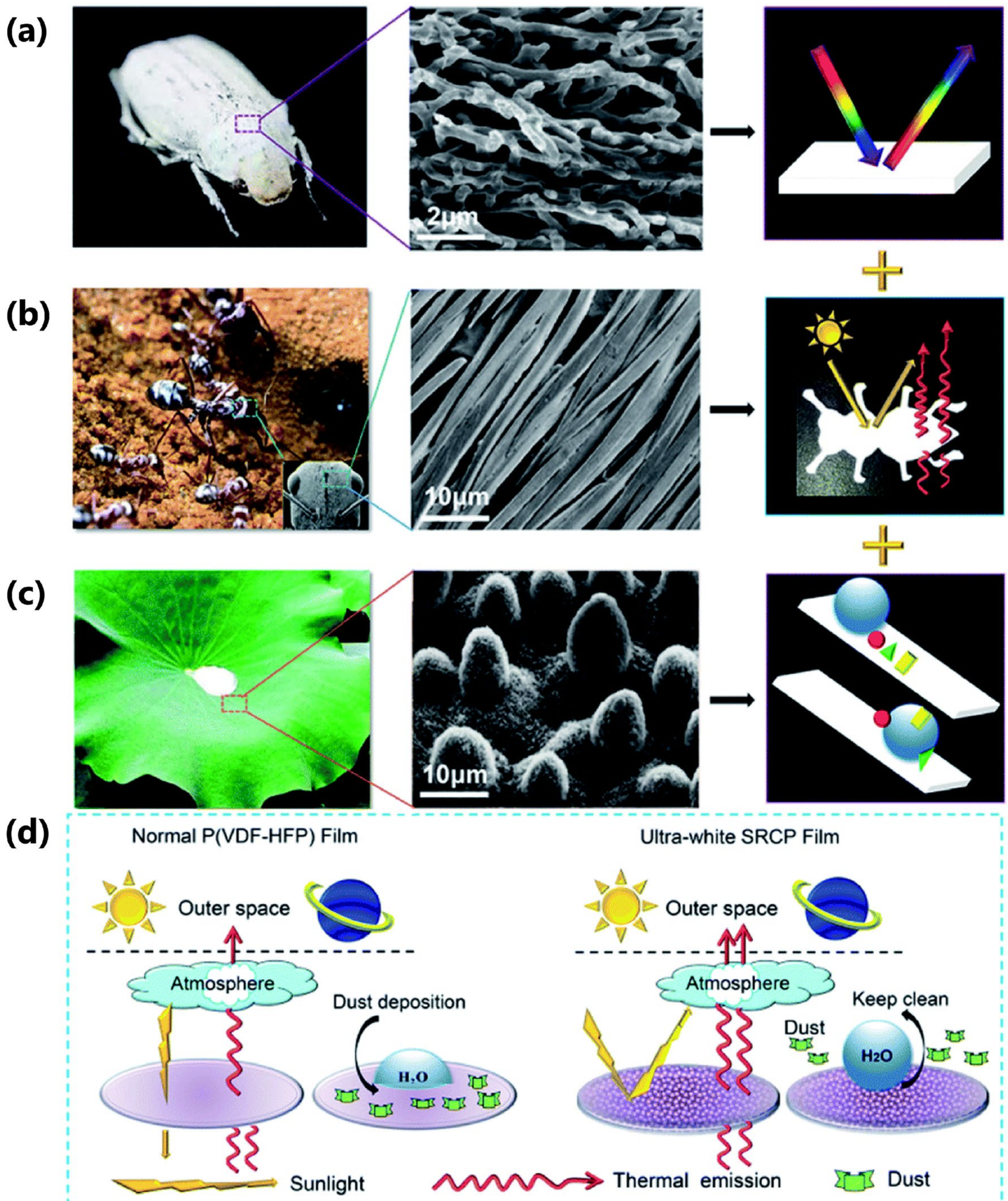

Fig. 10 Muti-bioinspired design strategy. **a** Optical picture of the Cyphochilus white beetle (left), cross-sectional SEM image of its scale (middle), and the schematic diagram of total reflection of visible light (right). **b** Photo of Sahara silver ants (left) and their head (inset) covered with hair microstructures (middle). Schematic diagram of high solar reflection and strong thermal infrared emission (right). **c** Optical photo (left) and SEM image of the lotus leaf (middle) that exhibits self-cleaning properties (right). **d** Working principles of the flat P(VDF-HFP) film and SRCP film [139]

sewage treatment and solar desalination. Besides, a T-shaped synthetic tree is designed [141] to simultaneously achieve solar-thermal efficiency of 75% with high steam productivity (2.03 kg/m^2h), attribute to the ambient energy harvesting, interfacial thermal evaporation and edge-preferential crystallizing properties. Especially, with a consistent collection rate of 59.879 g m^{-2} h^{-1}, the salt may be continually rejected at the evaporator's edge simultaneously without affecting the evaporation of the water.

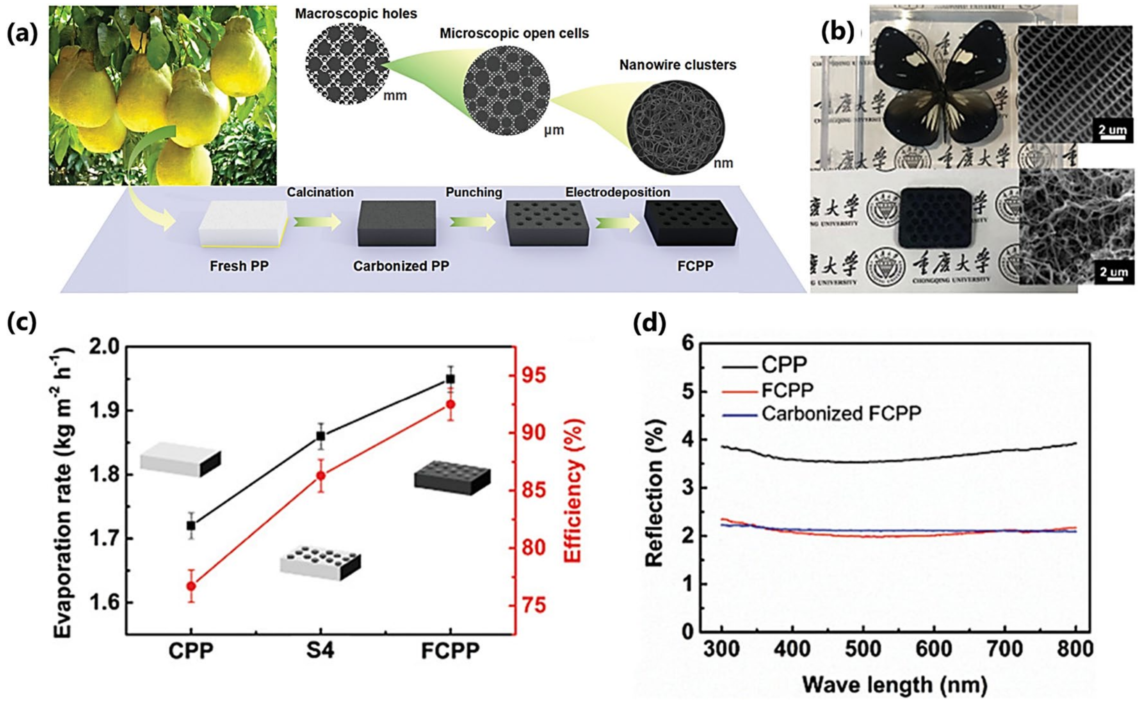

Fig. 11 **a** Schematic illustration of the synthesis route of FCPP. **b** Photos of the overall view of a black butterfly and FCPP. The insets are respective SEM images showing their micro structures. **c** Evaporation rates (left-hand side axis) and corresponding solar–thermal efficiency (right-hand side axis) of samples CPP, S4, and FCPP. **d** Reflections of CPP, FCPP, and carbonized FCPP [140]

Woods serve as bioinspiration for engineering materials since of their exceptional mechanical properties, while the cellulose microstructure is advantageous in the field of passive cooling application. Hu et al. [142] developed a radiative-cooling structural material after delignifying and densifying the natural wood. The multi-scale cellulose structure can serve as effective scattering centers and exhibit strong broadband reflection in Vis–NIR range, while molecular vibration as well as stretching of the cellulose will promote the strong emission of infrared rays. Along with the superior whiteness properties which results from the low optical loss of the cellulose fibers and the disordered photonic structure, this engineered material present continuous sub-ambient cooling effect all-day long, while the mechanical strength can be maintained of 404.3 MPa. Yu et al. [143] adopted self-assembly and thermos-curing strategies to fabricate bioinspired polymeric woods with hierarchical cellular microstructure and pre-designed polymeric matrices, which exhibited superior mechanical performance (compressive yield strength of 45 MPa), desirable preferable acid corrosion resistance, thermal insulation (~21 mW/m K) and fire retardancy performance.

By mimicking the disordered porous network from numerous wrinkled microfilaments within the layer of the *Boehmeria nivea*, Yu et al. [144] adopted electrospinning process to fabricate porous polymeric artificial reflective coatings for light-shielding and optoelectronic applications by visible light scattering effect. Fan's team [145] discovered that the cicada *Cryptotympana atrata* could protect themselves from overheating under hot environment with radiative-cooling properties, attributed to the brilliant golden micro-spikes with nanophotonic porous heart-shaped cross section (Fig. 12a). The finding provides inspiration for the fabrication of biomimetic thermal photonic composite (Bio-PC), consisting of randomly embedded alumina nanoparticles in TPU porous matrix through micro-imprint process and phase separation method (Fig. 12b–c). The Bio-PC exhibits a high reflectivity of solar irradiance (97.6%) and average infrared emissivity of 95.5% (Fig. 12d), due to Mie scattering by microscale pores, antireflection of microhumps, and phonon polarization resonances in MIR range. As a result, a maximum sub-ambient temperature drop of 6.6 °C was experimentally demonstrated in Fig. 12e, along with an outstanding cooling power of 78 W/m^2. By mimicking the dynamic thermoregulation behaviour of butterfly wings [146], the solar-thermal energy can be harvested within flexible form-stable composite phase change

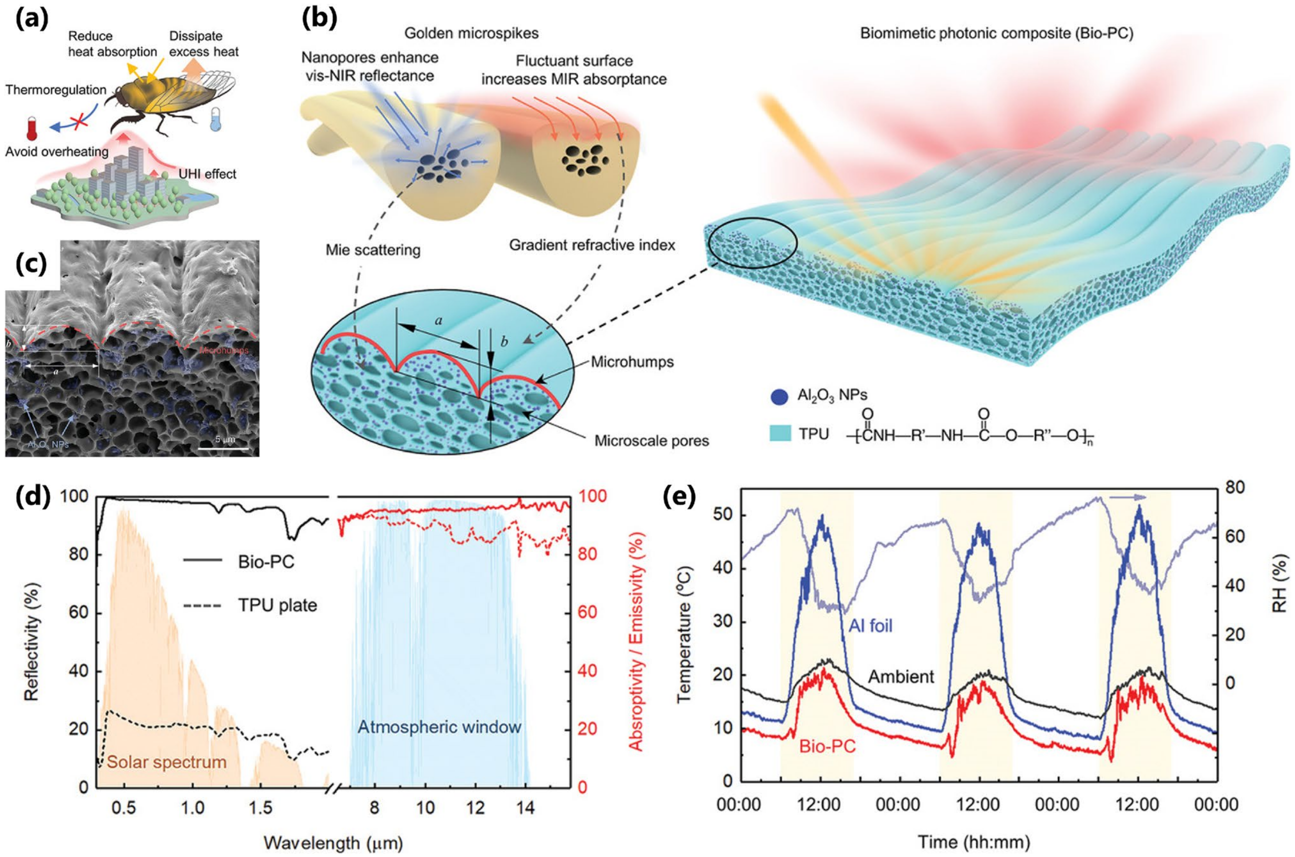

Fig. 12 **a** Thermoregulation behaviour of thermophilic cicadae with intensified UHI effect. **b** Schematic illustration of the biomimetic concept from the microspike to the radiative cooling composite. **c** SEM images, **d** Optical properties, and Recorded temperatures of Bio-PC, ambient and Al foil and RH changing with time [145]

materials, thereby achieving rapid charging performance while the composite sheets are continuously rolled under solar radiation. Inspired by thermal-regulation properties of the butterfly *P. paris*, Tian et al. [147] blended plasmonic Au/TiO_2 porous materials into a crafted 3D hierarchical structure to enhance the photo-degradation performance by utilizing the photo-thermal effect, along with combating the harmful overheating effect simultaneously.

There are relatively few 3D microstructures found in nature and artificial 3D structural materials for thermal radiation adjustment. However, there are enough reasons to believe that there are still many models in nature's treasure house. What has been discovered so far is only the tip of the iceberg, and it is still necessary to continue to explore and discover.

5 Summary and Outlook

In the long evolution process of nature, natural species have developed fine and unique microstructures to cope with the ever-changing environment and solve the thermal-related problems of survival, which provide us valuable example to refer. In this review, the physical mechanism of thermal-regulating properties, the advancement of the heat/light management microstructures, and the corresponding functional devices/systems are revealed under the classification of dimension. Various biological configurations can provide an idea pool for structural design and application of optical and thermal-regulation materials, an overview of typical biomimetic thermal-regulation materials ranging from one dimension to three dimension, along with corresponding applications in recent years are summarized in Table 1, which might illuminate the audiences and facilitate the development of bioinspired thermal-regulating materials.

Although great breakthroughs have been made, there are still challenges to be solved in the nearby future, including uncovering bioinspired micro/macro structure, developing fabrication methods, and integrating several functions into one device.

The first problem is discovering innovative micro/nano structure from nature with outstanding thermal-regulating properties. The natural and artificial optical structures discovered so far are limited, focusing on traditional insects

Table 1 Selected typical bioinspired thermal-regulation materials

Dimension	Typical biological prototypes	Artificial materials	Application	Properties	Refs.
1D	Native silk	Regenerated silk, PVDF fiber	Radiative cooling	R_{solar}[a)] = 0.73, ε_{atm}[b)] = 0.90 R_{solar} = 0.93, ε_{atm} = 0.91	[67]
		PE		Visible opacity ~ 90%, infrared transmittance ~ 70%, ΔT[c)] ~ 2.3 ℃	[76]
		Silk fibroin		Absorptivity = 0.05 (λ = 6um), ε_{atm} ~ 0.97, ΔT = 7.5 ℃	[38]
		Al_2O_3 and silk fibroin		R_{solar} ~ 95%, ε_{atm} ~ 0.9, ΔT ~ 3.5 ℃	[70]
		PP		R_{solar} ~ 95%, ε_{atm} ~ 0.82, ΔT = 3.5 ℃ (day time), ΔT = 4 ℃ (night time)	[68]
		PVDF and Al_2O_3		R_{solar} = 0.97, ε_{atm} = 0.95, P_{cool}[d)] = 82.7 W/m^2, ΔT = 4 ℃(daytime)	[69]
	Polar bear hair	Silk fibroin	Thermal insulation and thermal stealth	Thermal insulation (ΔT ~ 20 ℃), thermal stealth (− 10 to 40 ℃)	[78]
		TPU, CNTs, silver nanoparticles	Thermal insulation, wearable electronics	Thermal insulation (|ΔT| = 68.5 and 44 ℃), electrical heater (40 ℃ in 18 s at 2 V)	[81]
	Hairs in homeothermic animals	PLA, TPU	Adaptive thermal insulation, infrared camouflage	Dynamic control of thermal insulation > 61.4%	[82]

Table 1 (continued)

Dimension	Typical biological prototypes	Artificial materials	Application	Properties	Refs.
2D	Silver ants	SiO_2	Radiative cooling	$\varepsilon_{atm} > 0.96$, T_{solar} e) ~ 0.94	[96]
		PDMS		$R_{solar} = 0.98$, $T_{solar} = 96.72\%$	[88]
		PDMS		$\varepsilon_{atm} = 0.96$, $\Delta T \sim 5.6$ ℃(day time)	[87]
		PDMS, SiO_2, Ag		$\varepsilon_{atm} = 0.98$, $P_{cool} \sim 144$ W/m^2, $\Delta T = 6.2$ ℃	[91]
		ZnO		$R_{solar} > 95\%$, $\varepsilon_{atm} \sim 0.89$	[92]
		Corrugated nickel	Thermal management	R_{solar}: 0.3–0.7, T f): 310–315 K	[148]
	Longicorn beetles	PDMS film distributed particles (Al_2O_3, TiO_2, and ZnO)	Radiative cooling	$R_{solar} \sim 95\%$, $\varepsilon_{atm} > 0.96$, $P_{cool} \sim 90.8$ W/m^2, $\Delta T = 5.1$ ℃	[94]
	Moth-eye	p-$Al_{0.8}Ga_{0.2}$, n-$Al_{0.3}Ga_{0.7}$, GaAs, SiO_2	Photovoltaic–thermoelectric hybrid system	Average reflection loss < 5%, $T_{solar} > 28.1\%$ (AM1.5) and 30.8% (AM0)	[99]
		SiO_2 quasi-periodic air hole arrays	Omnidirectional antireflection	$T_{solar} > 90\%$, $R_{solar} = 2\%$	[149]
		Black titania on carbon cloth	Solar-driven clean water generation	Light absorption: 96%, solar steam efficiency: 94%	[100]
		PMMA	Antireflective flexible films	$T_{solar} \sim 97\%$, $R_{solar} < 4\%$	[101]
	Human skin	$BaSO_4$, SiO_2, N-methyl pyrrolidone, PVDF	Radiative cooling	$R_{solar} \sim 95\%$, $\varepsilon_{atm} \sim 96\%$, $\Delta T \sim 8.1$ ℃, $P_{cool} \sim 89.6$ W/m^2	[104]
		VO_2, PVDF	Self-adaptive temperature regulation	$\Delta T \sim 7$ ℃, evaporation efficiency: 1.43%, electrical power density: 104 μW/m^2	[103]
	Squid skin	Cu, SEBS	Dynamic thermoregulatory material	~ 25 on/off switching ratio for the transmittance, ~ 8 ℃ dynamic environmental set point temperature window,	[112]
		Au, SiO_2, Ti	Selective infrared solar absorber	Tunable solar absorptive quality: 0.9–0.03, photothermal power density = 362 W/m^2 (on state) and − 1 W/m^2 (off state)	[113]

Table 1 (continued)

Dimension	Typical biological prototypes	Artificial materials	Application	Properties	Refs.
3D	Polar bear hair	PDMS, PE	Daytime radiative cooling	R_{solar} ~ 0.96, T_{solar} ~ 0.8, ΔT ~ 5–6℃	[63]
		Silica nanotube aerogels	Light management, thermal insulation	T_{solar} = 53.91% (400–780 nm), thermal insulation, infrared blocking	[128]
		$C/SiO_2/Au$ aerogel layer, CNT-based aerogels layer	Steam generation	98% broadband absorption (250–2000 nm)	[127]
	Sunflower stalk pith	Sunflower stalk pith, carbon black, zwitterionic hydrogel	Solar evaporation	T > 40 ℃ under 1 kW/m^2 illumination, evaporation efficiency ~ 98.8%	[131]
	Raw cotton	Semi-crystalline PP	Radiative cooling	R_{solar} ~ 97%, tunable ε_{atm} (0.81–0.67), ΔT ~ 6℃	[137]
	Cyphochilus beetle, Saharan silver ant and lotus leaf	P(VDF-HFP), PDMS	Radiative cooling	R_{solar} = 96.5%, ε_{atm} ~ 94.3%, ΔT = 13.8 ℃	[139]
	Penguin feathers, polar bear hairs	Ammonium-dihydrogen-phosphate-modified melamine sponge	Interfacial solar steam generation	Evaporation rate: 2.3 kg/m^2 h, efficiency: 93% under 1 sun	[129]
	Wood	Wood	Radiative cooling	P_{cool} = 63 W/m^2 (night) and 16 W/m^2 (day), ΔT > 9 ℃ (day time), > 4 ℃ (nigh ttime)	[142]
		Resins	Thermal insulation and fire retardancy	Thermal insulation: ~ 21 mW m^{-1} K^{-1}	[143]
	Golden cicada	Alumina nanoparticles, TPU	Radiative cooling	R_{solar} = 97.6%, ε_{atm} = 95.5%, P_{cool} = 78 W/m^2, ΔT = 6.6℃	[145]

a) R_{solar}: solar reflectance
b) ε_{atm}: emittance in thermal atmospheric windows (λ = 8–13 um)
c) ΔT: temperature difference
d) P_{cool}: net cooling power
e) T_{solar}: solar transmittance
f) T: temperature

(such as desert silver ant), aquatic organisms (squid), and mammals (such as polar bear), while a large number of natural prototypes are currently waiting to be discovered and utilized. For example, Zhang discovered that the longicorn beetle *Neocerambyx gigas* present highly adaptable ability to areas of hot climate all year round, attributed to the dual-scale triangular-shaped fluffs. Through increasing the reflectivity in the vis–NIR region from total internal reflection and Mie scattering, along with enhancing the MIR emissivity, the body temperature can be decreased. Besides, the relationships between the microstructure and the corresponding thermal-regulation properties should be explained in-depth with more theoretical methods and experimental analysis, which requires exploration by interdisciplinary cooperation. For example, the photonic structures are designed with controllable solar reflection and thermal emission properties by manipulating light–matter interactions at sub-wavelength scales or tailoring the layer or array structures.

The second challenge is the large-scale and low-cost manufacturing method of fabricating micro/nano structure precisely. The thermal-regulating properties of the devices are affected by both the components and their structure, which cannot be normally satisfied under most of the circumstances. It is often difficult to directly copy and paste the natural biological structures bred by nature which have experienced long-time evolution. The subtle microstructures are normally synthesized and fabricated by nanoscale engineering strategies, including electrospinning, selected-etching, nano-patterning, template method, ion beam lithography and so on, which are usually expensive and low yield. A balance between precious fabrication and low-cost manufacturing should be taken into consideration, which is indispensable for practical application. For example, additive manufacturing, known as 3D printing, is an innovative method to efficiently fabricate designated constructions from digital system, which have been broadly applied in bio-engineering fields. The complex 3D microstructures, including porous structure, microchannels, and arrays can be successfully constructed by 3D printing process, facilitating designing and fabricating bioinspired structure with thermal-regulating performances. Besides, roll-to-roll charging method was adopted to fabricate flexible reduced graphene oxide-coated polyurethane sponges phase change composites, which effectively reduce the distance of heat transfer, thereby achieving enhanced solar-thermal energy harvesting properties with uniform temperature distribution.

Finally, Multifunctionality is gradually indispensable when meeting practical environments. In nature, organisms often present thermal-regulation behaviour and other excellent properties that are conducive to their survival, such as self-cleaning, self-healing, mechanical properties. For example, many organisms in nature possess self-repair capabilities when their structure are destroyed, thereby maintaining the optical and thermal-regulating properties. However, the originally expected light and heat regulation functions of the biomimetic materials would be invalid while the as-prepared structure collapse. Therefore, the self-adaptation and self-healing functions are suggested to be integrated in the next-generation bionic materials, which can promote the advancement of the devices with thermal-regulation performances. Besides, the self-cleaning, oil absorption/separation, and thermal insulating can be integrated through programming aerogel by co-assembling strategies. Therefore, the development of devices with multifunctionality offers great potential and opportunity in broader fields.

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Data availability Not applicable.

Declarations

Conflict of interest We declare that there is not any commercial or associative interest that represents a conflict of interest in connection with the work submitted.

Ethical Statement No animals were handled or harmed during this research.

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