Multi-modal textiles for passive hygrothermal regulation

Ranwenbin Yu,[1,2] Yaru Zhi,[1,2] Yang Li,[2,*] and Xiao Chen[2,*]
[1]School of Materials Science and Engineering, North University of China, Shanxi 030051, China
[2]School of Physics and Astronomy, Beijing Normal University, Beijing 100875, China
*Correspondence: younglee@pku.edu.cn (Y. L.); xiaochen@bnu.edu.cn (X. C.)
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Maintaining thermal homeostasis is crucial for human health and work efficiency. Against the backdrop of rising global temperatures and increasingly frequent heatwaves which pose significant threats to public health and socioeconomic stability, radiative cooling textiles have emerged as a promising solution for personal thermal management.[1] These textiles function by reflecting solar radiation and simultaneously emitting mid-infrared radiation from the human body. However, even state-of-the-art radiative cooling materials face limitations in complex environments such as high temperature and high humidity conditions.[2] Their cooling power proves inadequate in demanding scenarios from intense indoor workouts and sauna-like humidity to sweltering industrial workshops. Specifically, the temperature gradient between the body and ambient environment narrows, reducing driving force for radiative heat dissipation. Concurrently, increased humidity elevates atmospheric water vapor content, which absorbs infrared radiation and attenuates atmospheric transmission window, thereby further impairing radiative cooling.[3] Conventional radiative cooling fabrics, which rely solely on solar reflection and mid-infrared emission, suffer from significant performance degradation under high humidity. Similarly, fabrics that excel in moisture transport lack radiative cooling capability, while phase-change or thermally responsive textiles often face limitations in durability, response speed, and sustained cooling performance.

To broaden their applicability, researchers are developing multifunctional textiles that integrate multiple heat-transfer modalities: radiation, conduction, convection, and evaporation. This integrated approach is critical because it overcomes the bottlenecks of single-mode systems by enabling synergistic and sustained cooling across diverse environments. For instance, combining radiative cooling with conductive dissipation and evaporative regulation can maintain performance even in humid conditions, as demonstrated by materials that achieve lower surface temperatures than cotton under solar exposure and significantly cooler temperatures than bare skin in field tests. Moreover, integrating high thermal conductivity with superior moisture evaporation enables faster thermal equilibrium and perceptual dryness than conventional wicking or conductive fabrics, while avoiding the transient limitations of phase-change materials. While initial progress has been made in functional integration, existing systems often fall short in achieving synergistic enhancement across these mechanisms. Key challenges include the inherently low thermal conductivity of conventional fabrics, leading to heat accumulation and delayed cooling response, which increases the risk of overheating.[4] Moreover, inadequate moisture-wicking and evaporation capacity often results in perceptual discomfort and elevated thermal stress. Therefore, the fundamental scientific and technological challenge is how to realize dynamic, adaptive personal thermal regulation under complex ambient conditions through truly synergistic multi-mode heat management.

In this regard, Ding Bin's team[5] has engineered a multi-modal supercooling textile (MST) through a three-dimensional encapsulation strategy. This design effectively integrates radiative, conductive, and evaporative cooling mechanisms into a synergistic system, achieving efficient personal hygrothermal regulation across diverse scenarios (Figure 1). While state-of-the-art radiative cooling fabrics primarily rely on solar reflection and mid-infrared emission, they often degrade under high humidity and temperature due to limited non-radiative dissipation. MST advances the field by overcoming this fundamental limitation: it maintains efficient heat dissipation even in complex, humid environments where conventional radiative coolers underperform. Compared to contemporary textiles that excel in only one modality, MST demonstrates superior and sustained cooling performance under harsh real-world conditions, such as high ambient humidity and intense solar exposure.

Specifically, MST fabrication involves creating a macroporous, fluffy fiber aerogel via humidity-induced electrospinning to serve as a 3D scaffold, followed by ultrasonic treatment to tightly encapsulate boron nitride nanosheets (BNNS) onto the individual fibers. The cooling functionality of MST originates from rationally designed architecture, which leverages the 2D nature and high refractive index of BNNS to provide strong solar reflectance. Simultaneously, synergistic vibrational coupling between B-N bonds and polymer matrix enhances mid-infrared emissivity, thereby enabling efficient heat dissipation. Scanning electron microscopy corroborates the integration of BNNS within the fibrous network, where the formation of thermally bonded junctions at the fiber-fiber and fiber-nanosheet interfaces ensures effective three-dimensional encapsulation, thereby guaranteeing the multimodal cooling efficacy. Compared with conventional cotton, MST exhibits boasts a solar reflectance of 97.30% and a mid-infrared emissivity of 91.22%, along with significantly enhanced thermal conductivity and moisture evaporation rate. Its superior cooling performance is further confirmed by infrared thermal imaging, which consistently reveals lower surface temperatures under various challenging conditions, including high temperature, high humidity, intense irradiation, and simulated sweating during physical activity.

The exceptional thermal conductivity of MST originates from three-dimensional encapsulation architecture with BNNS. This robust fiber encapsulation is driven by multifarious interfacial interactions, including π–π conjugation, hydrogen bonding with the polyurethane matrix, and potential hydrophobic forces. Furthermore, the notable mass gain per unit area observed in isopropanol/water mixtures confirms effective encapsulation. Superior to simple blending, this design strategy simultaneously enhances thermal conductivity, optical reflectivity, moisture evaporation efficiency, and mechanical robustness. The post-treatment hot-pressing strategy was implemented to mitigate pilling, forming physical welds that significantly boost mechanical integrity and thermal transport without compromising wash fastness or causing BNNS detachment. Finally, optimized hot-pressing preserves adequate breathability and moisture permeability.

MST demonstrates hierarchically integrated hygrothermal regulation capabilities. Its Janus-type architecture (hydrophilic top and hydrophobic bottom) enables remarkable unidirectional moisture transport, achieving a moisture management index of -1080% and 1536% with performance retention even after 100 laundering cycles. Combined with significantly accelerated moisture evaporation, MST sustains efficient evaporative cooling under high-temperature conditions, outperforming conventional fabrics such as cotton and Coolmax. Thermally, MST exhibits exceptional conductivity, reaching thermal equilibrium on a hot plate markedly faster than reference materials while maintaining near-zero temperature differential between its inner and outer surfaces to ensure efficient heat dissipation. This outstanding thermal transport complements radiative cooling characteristics: BNNS-induced backward scattering via high refractive index and 2D morphology, together with multiple reflections within the electrospun fiber network, synergistically enhance solar reflectance. Meanwhile, the coupling between B-N bond vibrations and polymer absorption peaks significantly boosts mid-infrared emissivity. Systematic validation confirms the practical advantages of MST. Field tests conducted in Shanghai showed a temperature drop of approximately 15°C under cloudy conditions, while under clear skies the temperature decrease reached around 17°C. In wearable trials, MST demonstrated a 3.6 °C lower surface temperature than conventional cotton after 30 minutes of solar exposure, highlighting its exceptional personal thermal management capability in real-world scenarios.

Overall, this multi-modal super-cooling textile integrating radiative cooling, conductive dissipation, and evaporation regulation represents a critical

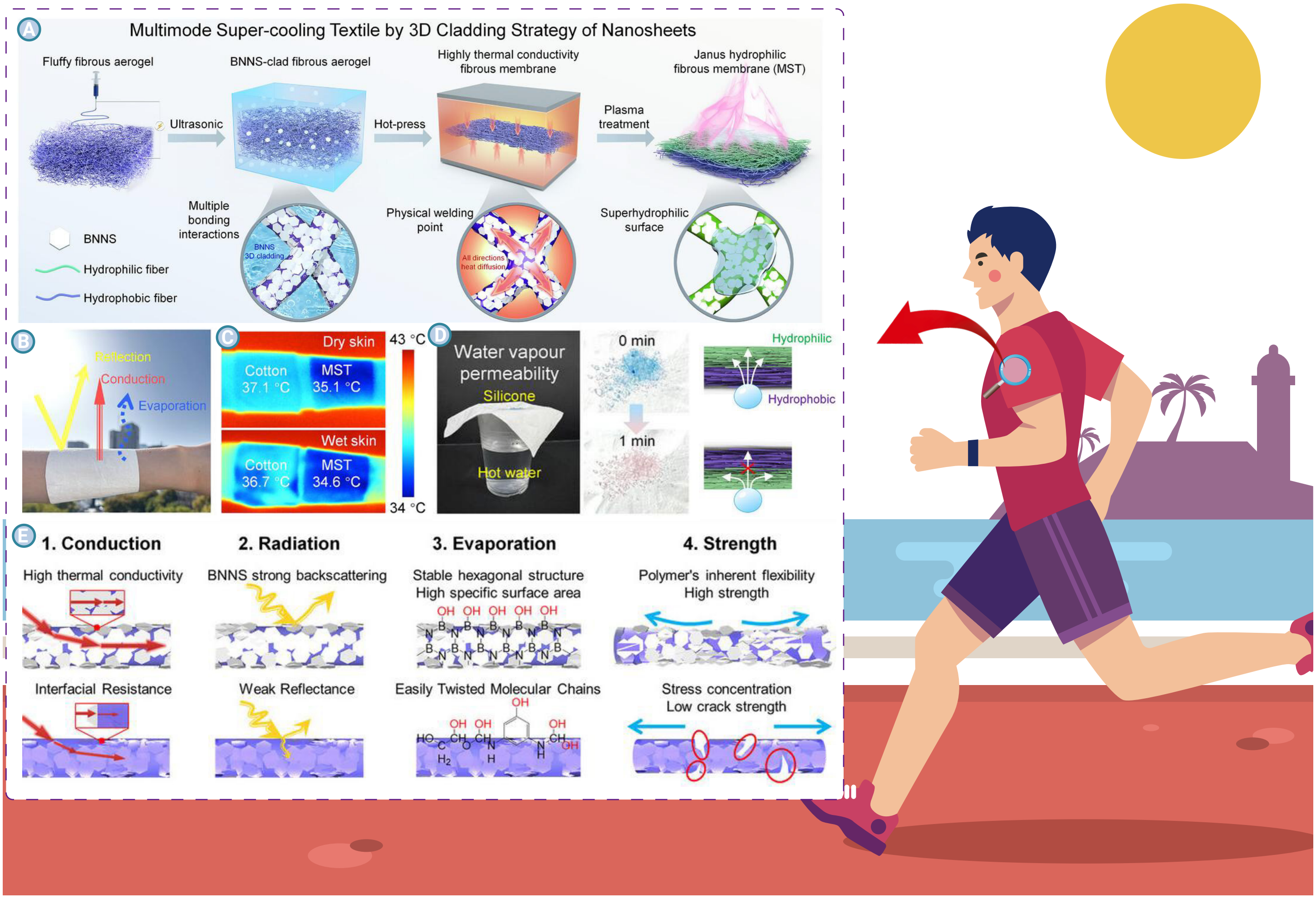

Figure 1. Multi-modal textiles for passive hygrothermal regulation. (A) Diagrammatic representation of multimode super-cooling textile production process. (B) Photograph of multimode super-cooling textile. (C) Cooling effects of super-cooling textile and cotton fabric on dry and wet skin under. (D) Demonstration of the air and moisture permeability and unidirectional liquid transport. (E) Schematic diagram of the performance enhancement mechanism in terms of conduction, radiation, evaporation, and mechanics.

advancement toward adaptive, multi-scenario thermal regulation materials. However, several key challenges and potential directions for future development remain as follows. Firstly, scalable manufacturing presents a major bottleneck for practical implementation. Current ultrasonic-hot pressing continuous production method requires significant optimization to reduce equipment costs, shorten processing cycles, and ensure uniform, consistent fiber encapsulation at an industrial scale. Additionally, the high cost of synthesizing high-quality BNNS and the complexity of achieving uniform, defect-free three-dimensional encapsulation remain key challenges. These factors directly impact both material affordability and the consistency of thermal and optical performance in mass production. Furthermore, integrating additional functionalities such as antibacterial or UV-blocking properties without compromising cooling performance requires synergistic design and evaluation to ensure they do not interfere with thermal dissipation mechanisms. Attention must be paid to the interfacial compatibility between functional additives and the BNNS-polymer matrix, as introduced agents may disrupt π–π conjugation and hydrogen bonding, increasing interfacial thermal resistance. Long-term durability under complex environmental conditions also remains critical, necessitating strategies to strengthen fiber-matrix interfacial bonding and enhance resistance to humidity, thermal stress, and mechanical wear. Future work should focus on in situ functionalization or surface-modification approaches that preserve intrinsic thermal transport pathways while incorporating secondary functionalities. Finally, the incorporation of smart sensing technologies could enable a shift from passive to adaptive thermal management. Embedding microsensors for real-time monitoring of temperature and humidity, combined with feedback-controlled cooling mechanisms, may allow for dynamic and personalized thermal comfort regulation tailored to individual needs and specific environmental scenarios. Such developments would unlock new possibilities for next-generation intelligent thermoregulatory textiles.

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DECLARATION OF INTERESTS

The authors declare no competing interests.