

Multifunctional Aerogel Fiber Radiative Cooling Fabric for Outdoor Personal Thermal Management

Corresponding Author: Professor Rufan Zhang

This file contains all reviewer reports in order by version, followed by all author rebuttals in order by version.

Version 0:

Reviewer comments:

Reviewer #1

(Remarks to the Author)

In this manuscript, the authors present a significant breakthrough in developing multifunctional aerogel fiber fabrics for passive daytime radiative cooling (PDRC). The work addresses the issue that traditional aerogel fibers are inherently fragile and prone to structural collapse due to stress, reducing their cooling efficiency. They provide an innovative method for the continuous production of radially gradient porous bacterial cellulose (BC) aerogel fibers (GP-BCAFs) fabrics. The multilevel gradient micro- and nano-porous structures achieve an optimal balance between strong mechanical properties and excellent PDRC performance. The GP-BCAF fabrics exhibit a tensile strength of 50 MPa, a solar reflectivity of 94.7%, and a mid-infrared emissivity of 97.3%. Additionally, they also fabricate dense and smooth BC aerogel fibers (DS-BCAF), further validating the enhancement in PDRC and mechanical properties conferred by the gradient porous structure. The flexible GP-BCAF fabrics outperform the DS-BCAF fabrics by over 42.8% in impact resistance. In outdoor tests, the GP-BCAF fabrics exhibit excellent PDRC performance with a temperature of 8.5 °C and 1.8 °C lower than conventional cotton fabrics and DS-BCAF fabrics, respectively. The integrated structure-properties-function design approach provides valuable inspiration for next-generation intelligent thermal management textiles. I am highly impressed by the novelty and impact of this work and consider it suitable for publication after minor revisions.

1. The font size of the numbers appearing in each combination figure should be further standardized to give the best possible presentation.
2. To ensure reproducibility, the outdoor human cooling experiment should include supplementary information regarding the ambient temperature and humidity conditions during testing.
3. It is suggested that the author incorporate the color codes from Figure 5f into the textual descriptions of the voltage signals, such as "During repetitive motions (purple), the voltage output displayed regular waveforms in which no output occurred during rest (yellow)."
4. The grammar of this manuscript needs to be further checked to avoid spelling errors.

Reviewer #2

(Remarks to the Author)

Radiative-cooling textiles for personal thermal management have attracted substantial attention, driven by their potential to reduce overheating risks amid accelerating global warming. Their ability to passively dissipate heat without external energy input positions them as promising materials for next-generation wearable cooling solutions. In this work, the authors report the fabrication of BC aerogel fiber fabrics with a wrinkled porous shell and porous core via wet spinning. The textile exhibits commendable mechanical strength (50 MPa) and strong passive daytime radiative cooling performance, with a solar reflectivity of 94.7% and MIR emissivity of 97.3%, suggesting potential use in self-powered sensing applications.

My major concern is: While these results are promising, the manuscript—when evaluated from material design, structural concept, and application perspective—offers limited innovation relative to the existing literature. Similar cellulose aerogel fibers for radiative cooling, including architectures closely resembling those presented here, have already been documented (e.g., comment 1). More specifically, a major claim of the manuscript is that the proposed structure resolves the fragility of traditional aerogel fibers and the associated cooling-performance degradation due to stress-induced collapse. Based on current understanding and available reports, this assertion appears inaccurate. In addition, several key properties highlighted by the authors—such as flexibility, waterproofing, and environmental robustness—are insufficiently supported by experimental evidence.

Given these issues, the manuscript in its current form does not yet meet the technical rigor and level of novelty expected for publication in Nature Communications. Strengthening the scientific justification, clarifying novelty, and providing more comprehensive characterization would be necessary before the work can be considered further.

1. Numerous studies have reported that aerogel fibers are not brittle and can be freely bent and woven into textiles. only a small amount of literature were listed: Nano-micro Letter, 2025, 7, 1605–1614. Advanced Functional Materials, 2025, e10747. Advanced Functional Materials, 2025, 35, 2413361. Advanced Functional Materials, 2025, e2506968. Matter, 2025, 8, 102155. Advanced Science, 2025, 12, e05306. Another, the wrinkled porous shell and a porous core is not a novel structure for aerogel fiber. Simultaneously, cellulosic aerogel fiber for radiative cooling application has also been reported, such as Nano Energy, 2025, 136, 110688. ACS Nano, 2025, 19, 34596–34605. The uniqueness of this work compared with these works are essential.
2. The aerogel fiber usually have low thermal conductivity, which used in warmth applications, such as Science, 2023, 382, 1379-1383. But the author applied the BC aerogel fiber for radiative cooling and test the thermal management efficacy in practical wear scenarios. These two targets using similar materials seem contradictory. A clear analysis and justification regarding why the material can be used for both cooling and warming is required. In addition, measuring the skin temperature under different fabrics would better illustrate the body's thermoregulation.
3. In the current title, “radiative cooling” is presented as one of the fiber’s “multifunctional” properties. As a result, the term “radiative cooling” is unnecessarily repeated.
4. According to Figure S12, the core-layer fiber models of DS-BCAF and GP-BCAF are identical, but their simulated tensile behaviors exhibit distinct characteristics. What is the underlying reason for this discrepancy?
5. Although the authors claim the textile is flexible and suitable for wearability, no relevant characterization is provided—particularly softness measurements, which are essential in textile research. Tensile strength alone does not sufficiently represent flexibility, and no comparative flexibility data are presented.
6. The manuscript describes the BC aerogel fiber textile as environmentally friendly. However, the material contains polyethylene glycol and siloxane particles, and the preparation steps shown in Figure 1a remain incomplete.
7. The BC aerogel fiber exhibits a mechanical strength of 50 MPa, which the authors state is adequate for outdoor use. Please specify the reference standards or benchmarks supporting this assertion.
8. The authors claim excellent waterproof performance, yet no hydrostatic pressure data are provided to substantiate this point.
9. A water-wash resistance test should be included to further demonstrate the practical durability and usability of the textile.

Reviewer #3

(Remarks to the Author)

This manuscript by Feng et al. presents a route to a new type of passive radiative cooling material with convincing and comprehensive characterization. The study is well written and concisely presented, and it is interesting for the wide readership of Nature Comm. However, major revisions are necessary before it can be fully recommended for publication.

1. The surface area of the material must be characterized and quantitatively compared with the state of the art materials. The authors should assess as to what extent the surface area contributes to the apparent high performance of their material.
2. The effect of the calcium counterion with the carboxylate on the IR vibrational frequency is interesting. Is it an effect of cross-linking or molecular weight of the ion which should directly cause a shift in the vibrational spectrum? You can find this out by trialing different monovalent alkaloid metals as counterions (e.g., Li, Na, K, Cs), which do not cross link, and different divalent earth alkaloid metals (e.g., Mg, Ca, Sr, Ba) which do cross link. Can you then tune the radiative cooling response with the selection of the counterion?
3. How do the XPS results indicate that the “silane modification occurred throughout the fiber structure rather than being confined on the surface”? XPS only extracts information from the very surface of the material.
4. Please compare your mechanical properties quantitatively with other existing PDRC materials, not just the DS-BCAF fabrics.

Reviewer #4

(Remarks to the Author)

This work developed a continuous production method to fabricate bacterial cellulose aerogel fiber fabrics with a radially gradient porous structure. This work addressed the long-standing trade-off between mechanical properties and passive daytime radiative cooling performance in traditional aerogel fibers. The integration of self-powered sensing capabilities for real-time monitoring of physiological activities is a powerful boost to the applicability for future smart wearable devices. I will be glad to recommend for publication after addressing a few minor questions.

1. The integration of triboelectric nanogenerator improves functionality. Please comment on the change of voltage signal when the user is sweating and whether encapsulation is needed to stabilize the detecting signals.
2. Was the different morphology of GP-BCAF and DS-BCAFs due to the different free-drying procedure, or the coagulation bath? It wasn't very clear in Figure 1 and Experimental section.
3. The label for Figure 1f seems unclear. It is recommended to enlarge the text in the images to improve clarity and readability.
4. I suggest combine Fig 2a and 2b if they are from the same spectra.
5. To provide convincing, visual proof of the continuous production process described for the fibers, I suggest that the

authors consider adding a supplementary video demonstrating this fabrication step.

Reviewer #5

(Remarks to the Author)

[Editor's Note: See attached]

Multifunctional Aerogel Fiber Radiative Cooling Fabric for Outdoor Personal Thermal Management

Recommendation: major revisions.

Comments:

The manuscript presents an interesting and well-structured study on the synthesis of porous fabrics based on cellulose aerogel fibers, showing a multilevel gradient from micro- to nano scale. The authors also report a novel methodology for controlling the structure of the bacterial cellulose fibers through gradient coagulation into a hydro-spinning bath, allowing for the production of these fibers at a large-scale. In order to validate the optimal structure, dense and smooth aerogel fibers were also produced for comparison, thus leading to a systematic and thorough study.

The produced material showed high solar reflectivity (94.7%) and tensile strength (50 MPa), as well as high emissivity, thus providing an excellent combination for efficient passive cooling and enabling its use at lower temperatures than conventional commercial cotton fabrics. Moreover, this fabric was tested in wearable garments to monitor human electrophysiological signals during physical activities, maintaining stable signals and high sensitivity. The electrical signals collected can also be transmitted to a smartphone, thereby facilitating user-friendly operation, promoting accessibility for personal use, and opening new opportunities for advancements in wearable sports and health-monitoring technologies. Therefore, this study provides an innovative solution to improve the performance of other fabrics currently employed for thermal management, being applicable to smart textile designs.

Despite being a high-quality study, very complete by the employment of many characterization techniques, there are several issues that should be addressed prior publication:

Results

1) The authors could analyze the dependence of transmittance on wavelength in order to confirm the Mie scattering mechanism and the possibility of having Rayleigh scattering.

2) The pore size provided by nitrogen sorption is likely far from the real value since this technique only measures pores smaller than 100nm, underestimating bigger pores that can contribute with a high percentage. Thus, a more realistic average pore size should be provided by calculating first the real pore volume through the relationship between densities, and then assuming cylindrical pores (see 10.2136/sssabookser5.4.c11).

3) Evaluating the thermal insulation capability of the composite aerogel felt at different temperatures is necessary since the thermal conductivity values and their dependence with temperature will provide relevant information for its performance in human bodies in different months of the year and different environments.

Thermal conductivity should therefore be quantitatively determined using standardized measurement techniques. In particular, steady-state methods are strongly recommended rather than transient techniques, as highly insulating materials typically require steady-state conditions to ensure reliable and reproducible measurements (10.1007/s10971-023-06282-9 and 10.3390/polym14132556).

Version 1:

Reviewer comments:

Reviewer #2

(Remarks to the Author)

The authors have conducted extensive additional experiments and provided a thorough review of the relevant literature. Their efforts have largely resolved the technical issues I raised, which is highly appreciated. However, there are still issues that remain unsolved, especially the overall theme and innovation of the current work (i.e., the first two major issues).

1. The manuscript would benefit from a clearer articulation of the scientific gap and a more tightly aligned statement of novelty. At present, there appears to be an inconsistency between the authors' response—where the brittleness of traditional aerogel fibers is described as largely resolved—and the revised abstract and introduction, which continue to position the work as addressing intrinsic fragility. Clarifying this point would help sharpen the central contribution and ensure that the claimed innovation—a simple strategy for enhancing mechanical robustness—is grounded in a well-defined problem statement.

In supporting the discussion of brittleness, references [19–24] are cited; however, a closer reading of these works suggests several points that may merit reconsideration for accuracy and clarity. First, aerogel fibers and fibrous aerogels represent structurally distinct classes of materials and should not be used interchangeably, as appears to occur in Refs. [19, 21, 22]. Second, aramid aerogel fibers reported in Refs. [20, 24] demonstrate notable flexibility rather than brittleness, which contrasts with the current characterization. Third, while conventional ceramic aerogels are indeed brittle, ceramic nanofibrous aerogels (Ref. [23]) have been shown to exhibit remarkable super-elasticity, an important nuance that could be

incorporated to provide a more balanced perspective. Addressing these points would substantially strengthen the manuscript by improving conceptual precision, reinforcing the validity of the cited literature, and clarifying the true scope and novelty of the work.

2. The authors present comparisons of skin temperature reduction using the aerogel fiber fabric relative to bare skin, cotton, and GP-BCAF. While these comparisons are informative at a phenomenological level, the underlying heat transfer mechanisms within the coupled human–fabric–environment system remain insufficiently resolved. In particular, the manuscript would benefit from establishing a clear functional framework that links radiative cooling (arising from spectral selectivity) with thermal insulation (governing conductive and convective heat transport), and from quantifying the relative contributions of each pathway in determining the net heat flux from the skin to the ambient environment. At present, the specific role of the aerogel fiber's thermal insulation in the overall heat transfer process is not clearly delineated. This raises an important conceptual question regarding material selection: what is the mechanistic rationale for employing a thermally insulating aerogel fiber in a radiative cooling textile? In principle, a highly effective insulating layer suppresses heat transfer between the skin and the fabric's surface, potentially decoupling the radiative exchange at the outer interface from the thermal state of the skin. Reconciling this apparent tension—between minimizing heat conduction and enabling effective heat dissipation—would significantly strengthen the theoretical foundation of the work.

Minor issues:

3. More detailed experimental information, for example, the raw material manufacturers and preparation details, is required for readers to better understand the reported technique. Additionally, please specify whether the material shown in Figure S3 is polyethylene glycol (PEG) or polyvinyl alcohol (PVA).

4. In the textile industry, materials exhibiting hydrostatic pressure below 20 kPa are not considered to possess excellent waterproof properties. According to GB/T 4744-2013 (Textiles – Testing and evaluation for water resistance – Hydrostatic pressure method), a hydrostatic pressure value of 35–50 kPa is classified as “excellent water resistance” (Level 4), while 20–35 kPa is only classified as “good water resistance” (Level 3).

In summary, I will support the acceptance of this nice work with these issues clarified.

Reviewer #3

(Remarks to the Author)

The authors have credibly addressed all points raised by the reviewers. Just one comment: monovalent ions do not cross-link carboxylates. You use this term for the monovalent ions in the response letter, but it requires no revisions as the terms are correct in the actual revised manuscript.

Reviewer #4

(Remarks to the Author)

I recommend for publication.

Reviewer #5

(Remarks to the Author)

The authors have addressed all my comments. Nevertheless, I would like to suggest a more balanced representation in the literature review. Currently, the citations are almost exclusively restricted to Chinese researchers, and diversifying the references with international studies would better reflect the global state-of-the-art and strengthen the paper's theoretical framework.

Reviewer #6

(Remarks to the Author)

I co-reviewed this manuscript with one of the reviewers who provided the listed reports. This is part of the Nature Communications initiative to facilitate training in peer review and to provide appropriate recognition for Early Career Researchers who co-review manuscripts.

Version 2:

Reviewer comments:

Reviewer #7

(Remarks to the Author)

[Editor's Note: This reviewer was asked to evaluate the response to Reviewer #2]

The revised manuscript has addressed many of the comments from Reviewer 2, though there are several follow-up point on the thermal analysis mentioned in comment 2:

2a) First, not enough information is provided on the thermal modeling in Figure S21 for the reader to evaluate or interpret the results. The citation to the details of the thermal model, and the information about all of the inputs to the model, can be

provided in the SI - no information is currently provided.

2b) Second, is higher or lower thermal conductivity better for reducing skin temperature? The current results are presented ambiguously, so I could not tell whether the insulation is desirable or undesirable for achieving low skin temperature at the given conditions. (I imagine if the surface of the fabric achieves sub-ambient cooling, then high thermal conductivity is better for reduced skin temperature to better pull the metabolic heat generation out of the body; if the surface of the fabric is warmer than ambient due to the solar absorption, then low thermal conductivity is desirable to block the heat flow from the surface into the skin). It may be useful to plot the actual value of the skin temperature itself in Fig. S21 rather than the "skin temperature difference ΔT ," for easier reader interpretation. It would also be useful to plot both the skin temperature and the exposed fabric surface temperature for each condition in Fig. S21 - this could be helpful in interpreting the results and supporting the claims. This thermal analysis is important because much of the motivation for using aerogels in the passive radiative cooling relies on the low thermal conductivity, so the reader should be able to understand from the thermal model under what scenario the thermal insulation provided by is useful.

2c) Does the thermal model include the effect of heat transfer away from the skin via sweating/perspiration? It would seem that this is perhaps an important mode of heat transfer through the porous fabric, given the permeability in Fig. 3a, but it is not mentioned in the thermal modeling of the reference provided ((Nat. Sustain., 2023, 6(11), 1446-1454).

Version 3:

Reviewer comments:

Reviewer #7

(Remarks to the Author)

The authors have considered the prior round of comments and updated the SI. I have a remaining question on the new thermal modeling result and discussion.

Major: The modeling in Fig. S21(d) shows that higher textile thermal conductivity would be better to reduce the skin temperature. However I think readers of the main text would come away with the impression that low thermal conductivity is beneficial. I recommend stating clearly in the main text that for the thermal conditions considered in the thermal model of Fig. S21(d), higher thermal conductivity would be better to achieve lower skin temperatures (i.e. the low aerogel thermal conductivity is not necessarily an asset under all conditions).

Minor: Typo in Fig. S21 b,e,h - x axis should be "emissivity" not "emissity".

Open Access This Peer Review File is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made.

In cases where reviewers are anonymous, credit should be given to 'Anonymous Referee' and the source.

The images or other third party material in this Peer Review File are included in the article's Creative Commons license, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons

license and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder.

To view a copy of this license, visit <https://creativecommons.org/licenses/by/4.0/>

A separate response letter

Firstly, thank you for the editors' attention to our article, and we appreciate the insightful comments from the reviewers on our manuscript. We fully understand and accept these comments. Accordingly, we have revised the manuscript in detail based on the reviewers' feedback as follows. We hope the improved paper meets the reviewers' standards.

Remark: The deletions and additions in the annotated copy of the manuscript are **in red** in response to [reviewers #1~5](#).

Reviewer: 1

Comments: In this manuscript, the authors present a significant breakthrough in developing multifunctional aerogel fiber fabrics for passive daytime radiative cooling (PDRC). The work addresses the issue that traditional aerogel fibers are inherently fragile and prone to structural collapse due to stress, reducing their cooling efficiency. They provide an innovative method for the continuous production of radially gradient porous bacterial cellulose (BC) aerogel fibers (GP-BCAFs) fabrics. The multilevel gradient micro- and nano-porous structures achieve an optimal balance between strong mechanical properties and excellent PDRC performance. The GP-BCAF fabrics exhibit a tensile strength of 50 MPa, a solar reflectivity of 94.7%, and a mid-infrared emissivity of 97.3%. Additionally, they also fabricate dense and smooth BC aerogel fibers (DS-BCAF), further validating the enhancement in PDRC and mechanical properties conferred by the gradient porous structure. The flexible GP-BCAF fabrics outperform the DS-BCAF fabrics by over 42.8% in impact resistance. In outdoor tests, the GP-BCAF fabrics exhibit excellent PDRC performance with a temperature of 8.5 °C and 1.8 °C lower than conventional cotton fabrics and DS-BCAF fabrics, respectively. The integrated structure-properties-function design approach provides valuable inspiration for next-generation intelligent thermal management textiles. I am highly impressed by the novelty and impact of this work and consider it suitable for publication after minor revisions.

Reply: Thank you for your high appreciation of this work.

Comment 1: The font size of the numbers appearing in each combination figure should be further standardized to give the best possible presentation.

Reply: Thanks for the comment. We have checked each combination figure and corrected the font size of these figures.

Comment 2: To ensure reproducibility, the outdoor human cooling experiment should include supplementary information regarding the ambient temperature and humidity conditions during testing.

Reply: Thanks for your question and suggestion. We have included detailed environmental conditions for the outdoor human cooling experiment in the revised manuscript. Specifically, during the test, the average ambient temperature was 31 °C, the relative humidity was 65%, and the solar irradiation ranged from 800 to 1000 W/m². We have added more descriptions to the manuscript (lines 27-30, page 8, in the Results and Discussion section).

Comment 3: It is suggested that the author incorporate the color codes from Figure 5f into the textual descriptions of the voltage signals, such as "During repetitive motions (purple), the voltage output displayed regular waveforms in which no output occurred during rest (yellow)."

Reply: Thanks for your question and suggestion. We have added a detailed description of this part of the revised manuscript (lines 9-10, page 12, the section of Results and Discussion).

Comment 4: The grammar of this manuscript needs to be further checked to avoid spelling errors.

Reply: Thank you for your valuable suggestions. We have scrutinized the grammar throughout the

text and corrected any errors.

Reviewer: 2

Comments: Radiative-cooling textiles for personal thermal management have attracted substantial attention, driven by their potential to reduce overheating risks amid accelerating global warming. Their ability to passively dissipate heat without external energy input positions them as promising materials for next-generation wearable cooling solutions. In this work, the authors report the fabrication of BC aerogel fiber fabrics with a wrinkled porous shell and porous core via wet spinning. The textile exhibits commendable mechanical strength (50 MPa) and strong passive daytime radiative cooling performance, with a solar reflectivity of 94.7% and MIR emissivity of 97.3%, suggesting potential use in self-powered sensing applications.

My major concern is: While these results are promising, the manuscript—when evaluated from material design, structural concept, and application perspective—offers limited innovation relative to the existing literature. Similar cellulose aerogel fibers for radiative cooling, including architectures closely resembling those presented here, have already been documented (e.g., comment 1). More specifically, a major claim of the manuscript is that the proposed structure resolves the fragility of traditional aerogel fibers and the associated cooling-performance degradation due to stress-induced collapse. Based on current understanding and available reports, this assertion appears inaccurate. In addition, several key properties highlighted by the authors—such as flexibility, waterproofing, and environmental robustness—are insufficiently supported by experimental evidence.

Given these issues, the manuscript in its current form does not yet meet the technical rigor and level of novelty expected for publication in Nature Communications. Strengthening the scientific justification, clarifying novelty, and providing more comprehensive characterization would be necessary before the work can be considered further.

Reply: We sincerely thank the reviewer for the insightful and constructive comments on our work. In response to the concerns about technical rigor and insufficient novelty, we have thoroughly addressed all comments through extensive revisions and have added key experimental data and theoretical analyses. We measured the temperature-dependent thermal conductivity of the fabric using the steady-state method. We also conducted softness, washability, UV aging, and hydrostatic pressure testing, thoroughly validating the material's practical performance under outdoor conditions. In terms of novelty, we systematically compared the GP-BCAF fabric with existing radiative cooling textiles. We have highlighted the unique aspects of this work, particularly the gradient coagulation bath method and the multifunctional capabilities, including radiative cooling, mechanical enhancement, and motion monitoring within a pure bacterial cellulose system. We believe these revisions have markedly strengthened the technical rigor and novelty of the manuscript. We sincerely appreciate the reviewer's valuable suggestions, which have greatly contributed to our improvement.

Comment 1: Numerous studies have reported that aerogel fibers are not brittle and can be freely bent and woven into textiles. Only a small amount of literature was listed: Nano-micro Letter, 2025, 7, 1605–1614. Advanced Functional Materials, 2025, e10747. Advanced Functional Materials, 2025, 35, 2413361. Advanced Functional Materials, 2025, e2506968. Matter, 2025, 8, 102155. Advanced Science, 2025, 12, e05306. Another, the wrinkled porous shell and a porous core are not a novel structure for aerogel fiber. Simultaneously, cellulose aerogel fiber for radiative cooling application has also been reported, such as Nano Energy, 2025, 136, 110688. ACS Nano, 2025, 19, 34596–34605. The uniqueness of this work compared with these works is essential.

Reply: Thanks for your comment. We will respond to the three points you raised one by one in the following reply, while also clarifying the uniqueness of this work. Aerogel fibers have shown great potential in fields such as flexible electronics, smart textiles, and personal thermal management due to their excellent properties, including ultralow density and high porosity. However, the mechanical strength and tensile strain of conventional aerogel fibers are typically below a few MPa and 2%, respectively. These poor mechanical properties largely limit their practical applications, particularly in textiles and wearable devices (*Adv. Funct. Mater.*, 2025, 35, 2414229; *Sci. China Mater.*, 2024, 67, 1365–1366). Therefore, researchers have developed various strategies to improve the mechanical properties of aerogel fibers. For instance, Liu et al. pointed out that achieving both high strength and toughness in conventional aerogel fibers remains a major challenge. They proposed an ion-liquid-assisted wet-spinning strategy to successfully prepare cellulose aerogel fibers with ultrahigh toughness (*ACS Nano*, 2023, 17, 18411–18420). Yu et al. also noted that the porous structure of aerogel fibers leads to low tensile strength, limiting their practical application, and emphasized the need to overcome the “strong yet non-insulating, insulating yet non-strong” bottleneck through structural design (*Adv. Fiber Mater.*, 2025, 7, 1605–1614).

Regarding your first point, the flexibility and wearability of aerogel fibers. The studies you listed represent cutting-edge advances in various application fields of aerogel fibers. Shen et al. fabricated dense multilevel pore structures both inside and outside the fibers via phase-separation spinning, primarily to achieve efficient thermal insulation (*Adv. Sci.*, 2025, 12, e05306). Zhou et al. achieved precise control over fiber structure and spatial material distribution using a multi-channel microfluidic spinning system, thereby preparing gradient Janus aerogel fibers for high-performance hydrovoltaic power generation (*Adv. Funct. Mater.*, 2025, 35, e10747). Hu et al. prepared structured engineering aramid aerogel fibers with a dense and highly ordered shell by adjusting the coagulation bath, targeting thermal protection (*Adv. Funct. Mater.*, 2025, 35, 2506968). Xue et al. fabricated polyimide aerogel fibers with a “skin-core” structure via wet-freeze spinning, with the primary goal of improving mechanical strength (*Matter*, 2025, 8, 102155). Zhang et al. constructed a dual-network structure by incorporating carbon nanotubes, achieving a fracture strength of 26.0 MPa, aiming to prepare ultra-strong and tough aerogel fiber textiles for thermal management (*Adv. Funct. Mater.*, 2025, 35, 2413361). These studies have contributed significantly to the development of aerogel fibers by demonstrating the designability of their properties. In these works, the improvement of mechanical properties, while important, generally serves as a supporting means for their respective core functions (thermal insulation, power generation, thermal protection, etc.). This is consistent with the starting point of our work: our core objective is to achieve efficient radiative cooling, and the optimization of mechanical properties similarly serves the basic requirements for outdoor wearable applications. However, the uniqueness of our work lies in the fact that we employed a gradient coagulation bath wet-spinning technique, which uses only the simple parameter of adjusting the coagulation bath concentration, to achieve synergistic optimization of mechanical strength (50 MPa) and radiative cooling efficiency (a solar reflectivity of 94.7%) within a pure bacterial cellulose system, and further extended the material to motion monitoring functionality. This concept of “structure-driven multifunctional synergy” complements the specialized explorations of the aforementioned studies in their respective fields and together enriches the application landscape of aerogel fibers.

Regarding your second point, the structural novelty of a wrinkled porous shell and a porous core. Similar structures have been reported by Xue et al. (*Matter*, 2025, 8, 102155) and Hu et al. (*Adv. Funct. Mater.*, 2025, 35, 2506968). However, the innovation of our work lies not in the initial proposal of this

structural morphology, but rather in the differences in implementation methods and performance. Implementation method: The aforementioned studies mostly employed high-performance synthetic polymers (e.g., aramid, polyimide) or complex equipment (e.g., microfluidics). In contrast, our work employs a straightforward gradient coagulation bath to spontaneously generate this structure in pure bacterial cellulose, a renewable biomass, by leveraging differences in phase-separation rates. Multifunctional integration: In the aforementioned studies, the gradient structure was primarily used to enhance a single property (e.g., mechanical strength or thermal insulation). In contrast, our work simultaneously employs this structure to synergistically optimize mechanical enhancement and radiative cooling. The porous shell achieves a high solar reflectivity of 94.7% through multi-scale light scattering, while the nano-entangled network and unique wrinkled pore structure improve its mechanical properties by dissipating stress.

Regarding your third point, existing reports on cellulose-based aerogel fibers for radiative cooling. The works you mentioned in *Nano Energy* (2025, 136, 110688) and *ACS Nano* (2025, 19, 34596–34605) indeed report cellulose-based radiative cooling aerogel fibers. The *Nano Energy* work used a hollow-SiO₂/regenerated-cellulose composite strategy, achieving a mechanical strength of 19.4 MPa and a solar reflectivity of 92.6%, relying on the introduction of inorganic fillers to enhance scattering. Our work achieves efficient radiative cooling (a reflectivity of 94.7%) primarily through the gradient pore structure of the aerogel fibers, without relying on the addition of discrete inorganic particles as scattering fillers. The work (*ACS Nano*) employed regenerated cellulose/silica nanoparticle composites, achieving a solar reflectivity of 93.7%, but did not systematically report mechanical properties; it focused on mimicking the micro-structure of human skin to enhance cooling. On this basis, our work further integrates mechanical properties (50 MPa) and motion monitoring functionality.

Here is an overview of the core innovations in this work. Firstly, a pure structural enhancement strategy: Unlike the aforementioned studies that introduce high-strength materials (e.g., aramid, carbon nanotubes) or use complex spinning equipment, we achieve improved mechanical properties solely through the design of a gradient pore structure. The micro-folded structure in the shell dissipates impact stress via elastic deformation under load, while the dense core provides stable mechanical support through a nano-entangled network. This strategy demonstrates that biomass materials can achieve high performance through microstructural regulation, offering a new approach for the design of green and sustainable materials. Secondly, synergistic optimization of mechanical enhancement and radiative cooling: In the aforementioned studies, the relationship between optical properties (such as radiative cooling performance) and mechanical properties is rarely discussed systematically. In contrast, our work couples mechanical and optical properties from the outset. The pores in the gradient structure enhance solar reflection while simultaneously ensuring mechanical strength through elastic deformation and stress dissipation. This design enables the material to maintain a high solar reflectivity of 94.7% while achieving a high strength of 50 MPa, realizing the mechanical and optical integration. Thirdly, a higher degree of functional integration: Most of the aforementioned studies focus on optimizing a single core function. In contrast, our work further integrates motion-monitoring functionality on this basis, employing the GP-BCAF fabric as a triboelectric nanogenerator sensor to achieve real-time monitoring of various motion modes, such as normal movement and impact. Fourthly, simplicity and scalability of the process: Compared with complex processes such as multi-channel microfluidics or bidirectional phase separation, the gradient coagulation bath wet-spinning technique used in this work enables precise control of the gradient porous structure simply by adjusting the coagulation bath concentration. This simplicity makes it more amenable to large-scale production and

application, offering potential for the commercialization of smart sportswear textiles.

In summary, the novelty of this work does not lie in being the first to achieve wearability or high mechanical strength in aerogel fibers. Rather, it lies in achieving synergistic optimization of mechanical strength, radiative cooling efficiency, and motion-monitoring functionality in a pure bacterial cellulose system using the simple method of gradient coagulation-bath wet-spinning. Our work, together with the studies you mentioned, collectively advances the development of aerogel fibers in their respective fields and opens a new pathway for the application of biomass materials in high-performance smart textiles. We thank you once again for your rigorous feedback, which has helped us present the unique value of our work more clearly.

Comment 2: The aerogel fiber usually has low thermal conductivity, which is used in warmth applications, such as Science, 2023, 382, 1379-1383. But the author applied the BC aerogel fiber for radiative cooling and tested the thermal management efficacy in practical wear scenarios. These two targets using similar materials seem contradictory. A clear analysis and justification regarding why the material can be used for both cooling and warming is required. In addition, measuring the skin temperature under different fabrics would better illustrate the body's thermoregulation.

Reply: Thank you for your question. The work (*Science*, 2023, 382, 1379-1383) you mentioned reports the use of aerogel fibers inspired by polar bear hair for thermal insulation, where the core mechanism relies on the ultra-low thermal conductivity of aerogels to suppress heat conduction and convection, thereby reducing heat loss from the human body to the cold environment. In contrast, our work utilizes aerogel fibers for radiative cooling, in which the core mechanism simultaneously leverages high solar reflectivity (94.7%) to minimize solar heat gain and high infrared emissivity (in the atmospheric window of 8–13 μm) to radiate body heat into outer space. These two applications are not contradictory; rather, they exploit different physical properties of aerogel materials. Thermal insulation depends on low thermal conductivity, while radiative cooling relies on high infrared emissivity and high solar reflectivity. Aerogel materials exhibit rich functional diversity in the field of personal thermal management. A recent review systematically summarized five thermal management functions of wearable aerogels: thermal insulation, active/passive heating, passive cooling, adaptive regulation, and wearable smart devices (*ACS Nano*, 2024, 18, 14, 9798–9822). Aerogels achieve both thermal insulation at low temperatures (*Nat. Commun.*, 2025, 16, 2357; *Adv. Funct. Mater.*, 2024, 2412424; *Energy Environ. Mater.*, 2025, e70046; *Adv. Fiber Mater.*, 2025, 7, 1605–1614) and cool at high temperatures (*Science*, 2024, 385, 6704, 68–74; *Adv. Funct. Mater.*, 2024, 34, 2410285; *Small*, 2025, 21(7), 2409873; *Adv. Funct. Mater.*, 2025, 35, 2414590), and even rapidly switch between heating and cooling (*Adv. Mater.*, 2025, 37, 2415386; *Adv. Funct. Mater.*, 2026, 36, 7, e13665; *ACS Appl. Mater. Interfaces*, 2022, 14, 10, 12617–12629; *Ceramics International*, 2024, 50(22), 48031–48040). Therefore, the use of aerogel fibers for both thermal insulation and radiative cooling is not contradictory. Rather, it fully leverages their multimodal thermal management capabilities.

The efficient radiative cooling performance achieved by GP-BCAFs in this work stems from their unique structural design and material combination, which combines high solar reflectivity with high mid-infrared emissivity. The gradient porous structure enables multi-scale scattering of sunlight in the solar radiation band (0.3–2.5 μm), resulting in a high solar reflectivity of 94.7%. Meanwhile, the C–O–C and Si–O–Si bonds in the bacterial cellulose exhibit strong stretching vibration absorption in the atmospheric window, enhancing the material's thermal radiation capability and thereby increasing its infrared emissivity. Previous studies have demonstrated that bacterial cellulose aerogels possess high emissivity in the atmospheric window, enabling efficient radiative cooling (*Nano Energy*, 2025, 136,

110688; *Compos. Sci. Technol.*, 2026, 273, 111421). The high solar reflectivity of GP-BCAFs reduces the absorption of solar radiation. In contrast, the high infrared emissivity promotes heat dissipation into outer space as infrared radiation, thereby achieving passive radiative cooling. Furthermore, the porous structure of the aerogel fibers further lowers thermal conductivity. Under high-temperature conditions, this helps block environmental heat from conducting to the human body, minimizing solar heating effects and synergistically working with radiative cooling to enhance human thermal comfort (*Adv. Mater.*, 2025, 2505224; *Adv. Funct. Mater.*, 2025, 2425527). To further validate the thermal management performance of GP-BCAF fabric in practical wearing scenarios, we measured the skin surface temperature of the human forearm when covered with different fabrics (Figure 3h). Under strong solar irradiation (800–1000 W/m²), the skin area covered with GP-BCAF fabric exhibited temperatures that were 7.4 °C, 2.8 °C, and 1.4 °C lower than those of uncovered skin, skin covered with cotton fabric, and skin covered with DS-BCAF fabric, respectively (Figure 3i–j). These results directly demonstrate the significant thermoregulatory effect of GP-BCAF fabric on human physiology under real-world wear conditions, confirming its cooling capability in high-temperature outdoor environments.

In summary, aerogel materials exhibit functional diversity in personal thermal management. They can achieve thermal insulation through low thermal conductivity and radiative cooling through high infrared emissivity and high solar reflectivity. These two functions are not contradictory but rather utilize different physical properties of the material. This work leverages the multimodal thermal management capability of aerogel fibers and, through the design of a gradient porous structure, achieves synergistic effects between radiative cooling and thermal insulation. We have incorporated the above analysis and data into the revised manuscript. We thank you again for your insightful comments, which have helped us enhance the scientific rigor, depth, and practicality of our work.

Comment 3: In the current title, “radiative cooling” is presented as one of the fiber’s “multifunctional” properties. As a result, the term “radiative cooling” is unnecessarily repeated.

Reply: Thank you for your valuable suggestions. The title of our manuscript, “Multifunctional Aerogel Fiber Radiative Cooling Fabric for Outdoor Personal Thermal Management,” emphasizes “Radiative Cooling” as the fabric's core function. At the same time, “Multifunctional” summarizes additional features beyond radiative cooling, such as mechanical strength and motion monitoring. We intend to emphasize both the material's primary application direction and its multifunctional integration. In the field of radiative cooling textiles, the use of “Multifunctional” or similar terms to describe multiple functionalities is well established. For example, Ding et al. published “Multimodal Super-Cooling Textiles for All-Scenario Passive Hygrothermal Comfort” (*Adv. Mater.*, 2025, 37, 44, e08518); Huang et al. published “Scalable Multifunctional Radiative Cooling Materials” (*Prog. Mater. Sci.*, 2023, 137, 101144); Zhai et al. published “Multifunctional Polyethylene Fiber Materials with Passive Radiative Cooling and Photocatalytic Antibacterial Properties” (*Adv. Funct. Mater.*, 2025, e29127); Xu et al. published the review “Multifunctional Radiative Cooling Materials: A Transformative Pathway for Zero-Energy Food Preservation and Postharvest Management” (*Trends Food Sci. Technol.*, 2025, 165, 105332); Yang et al. published “Multifunctional Cooling Textiles with Enhanced Radiative and Moisture Management” (*ACS Appl. Mater. Interfaces*, 2025, 17, 21, 31442–31453); and Xue et al. published “Multifunctional Fabrics with Functionalized Core-shell Structures Prepared by Electrostatic Spinning for Passive Daytime Radiation Cooling” (*Applied Surface Science*, 2025, 698, 163047). All these studies adopt a title structure that simultaneously highlights the core functionality and the multifunctional integration. We thank you for your valuable feedback, which has helped us

further refine the manuscript's expression.

Comment 4: According to Figure S12, the core-layer fiber models of DS-BCAF and GP-BCAF are identical, but their simulated tensile behaviors exhibit distinct characteristics. What is the underlying reason for this discrepancy?

Reply: Thank you for your valuable suggestions. The issue you raised in your review comments prompted us to re-examine this simulation content. In the initial simulation design, we sought to highlight the shell layer's contribution to mechanical properties using a simplified model. However, we mistakenly set the DS-BCAFs and GP-BCAFs models with identical initial structures (both core and shell layers were the same), failing to reflect the actual shell differences between the two materials (DS-BCAFs has a smooth, dense shell, while GP-BCAFs has a porous, wrinkled shell). As you insightfully pointed out, this setup is logically contradictory. If the models are identical, they should not yield differentiated simulation results. Since the initial model setup did not faithfully represent the structural characteristics of the two materials, the resulting simulation results could not provide valuable scientific information and might even mislead readers. Therefore, we have completely removed this simulation content from the manuscript. After removing this simulation, the core conclusion of our work that GP-BCAF fabrics exhibit superior tensile properties compared to DS-BCAF fabrics remains strongly supported by the following evidence. Firstly, experimental tensile tests directly show that GP-BCAF achieves a strength of 50 MPa, significantly higher than that of DS-BCAF (Figure 4a). Secondly, a COMSOL Multiphysics finite element model constructed based on real SEM images systematically validates the mechanical reinforcement mechanism of the gradient porous structure (Figure S21). Moreover, SEM images clearly reveal the essential differences in the shell layers of the two materials (Figure 2d–g). The mechanism by which gradient structures enhance mechanical properties is well documented in the literature. For instance, Fu et al. fabricated gradient all-nanostructured aramid aerogel fibers via microfluidic spinning, where the gradient nanostructure effectively dissipates stress during stretching through the loose nanoporous outer layer, preventing severe damage and maintaining good mechanical properties, thereby significantly improving tensile strength and fracture strain (*Nat. Commun.*, 2025, 16, 2357). Yu et al. prepared ultrafine aerogel fibers with a gradient structure via melt spinning, thereby enhancing structural integrity during stretching through sliding and energy dissipation. At the same time, the wrinkled layered microstructure provides high compressibility and tensile performance under compression through buckling and expansion (*Adv. Mater.*, 2024, 2414731). Other related studies (*Nat. Commun.*, 2026, 17, 1913; *Small*, 2026, 22, 13, e10329; *Composite Structures*, 2024, 336, 118021; *Additive Manufacturing Frontiers*, 2024, 3, 3, 200152; *Powder Technology*, 2024, 442, 119856) also provide solid theoretical support for our conclusions. We have removed Figure S12 and the associated discussion from the revised manuscript and made corresponding adjustments to the main text to ensure logical rigor. We sincerely thank you again for your rigorous feedback, which has enhanced the scientific accuracy of our work.

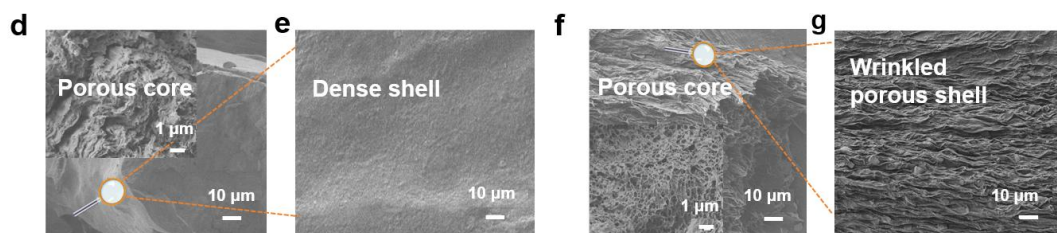


Figure 2. (d, e) SEM images of the DS-BCAFs and their smooth shell surface. (f, g) SEM images of the DS-BCAFs and their rough shell surface.

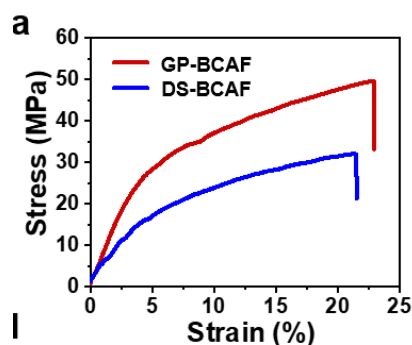


Figure 4. (a) Stress–strain curves of the DS-BCAFs and GP-BCAFs.

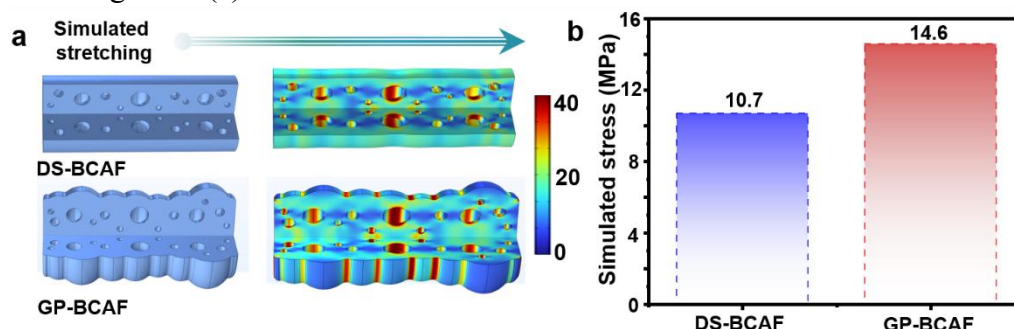


Figure S21. (a) Schematic diagram of internal simulated stretching for the DS-BCAF and GP-BCAF models, along with (b) a comparative stress analysis chart.

Comment 5: Although the authors claim the textile is flexible and suitable for wearability, no relevant characterization is provided—particularly softness measurements, which are essential in textile research. Tensile strength alone does not sufficiently represent flexibility, and no comparative flexibility data are presented.

Reply: Thank you for your valuable suggestions. Multiple factors, including the intrinsic properties of the fiber material, yarn structure, weaving method, and fabric density, influence a fabric's softness. Structural parameters such as fabric weave, yarn twist, linear density, fabric thickness, and warp/weft density are all closely related to the bending stiffness of the fabric. Different weaving methods (e.g., plain weave, twill weave, satin weave) lead to variations in the density and distribution of interlacing points within the fabric, thereby significantly affecting its softness (*J. Nat. Fibers*, 2022, 19, 11, 4148–4155). Therefore, when comparing the softness of different materials, it is essential to strictly control the weaving parameters to eliminate interference from structural differences.

We used the same plain-weaving method, warp/weft density, and yarn thickness to prepare the cotton, wool, and GP-BCAF fabrics. The softness of the three fabrics was characterized using an NW254 softness tester (Quanzhou Meibang Instrument Co., Ltd.). The specimen size was 10 cm × 10 cm, the slit width was 5.0 mm, the test stroke was 8 mm, and the test speed was 1.2 mm/s. The test results are shown in Figure S24. The results indicate that under the same weaving process and testing conditions, the average bending force of the GP-BCAF fabric was 3104.1 mN, significantly lower than that of the cotton (3181.6 mN) and wool (3219.3 mN) fabrics. In fabric softness testing, a lower bending force indicates a softer fabric (*Pigm. Resin Technol.*, 2022, 51, 4, 413–419). Therefore, the softness of the GP-BCAF fabric is superior to that of the cotton and wool fabrics. Since all three fabrics were prepared using the same weaving method and yarn thickness, the differences in softness primarily reflect differences in the materials themselves (e.g., fiber type and their microstructure). Consequently, the GP-BCAF fabric achieves a tensile strength of 50 MPa while maintaining better flexibility than

traditional cotton and wool fabrics, demonstrating excellent wearability and comfort alongside high mechanical performance. We thank the reviewer again for the valuable suggestions, which have helped us further improve the manuscript regarding key indicators in textile evaluation. We have added more descriptions to the manuscript (lines 11, page 11; the Results and Discussion section, lines 27-30, page 16; the Experimental section) and added Figure S24 to the Supporting Information file.

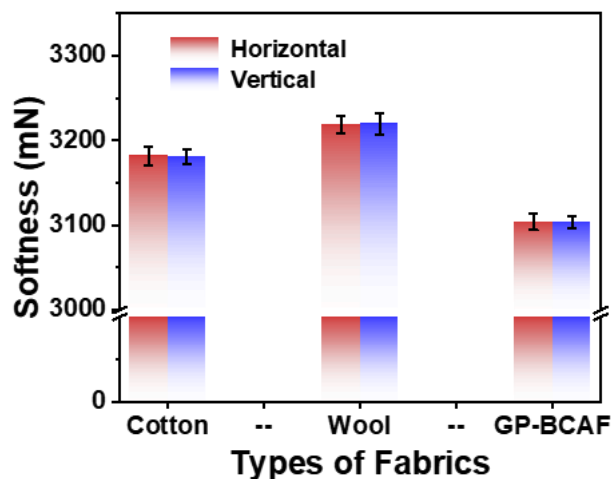


Figure S24. Softness of cotton, wool, and GP-BCAF fabrics.

Comment 6: The manuscript describes the BC aerogel fiber textile as environmentally friendly. However, the material contains polyethylene glycol and siloxane particles, and the preparation steps shown in Figure 1a remain incomplete.

Reply: Thank you for your valuable suggestions. We have re-examined the rigor of our description of our material as “environmentally friendly” through an extensive literature review. We understand the reviewer’s concern that the material’s environmental friendliness requires a clear definition. Our intention is not to claim that the material is 100% natural or has no environmental impact throughout its entire lifecycle, but rather to emphasize its environmentally friendly and sustainable characteristics in terms of material source, which is consistent with the way many studies in the field define “green” or “environmentally friendly”.

Sustainability of the substrate: The main body of our material is bacterial cellulose, a widely available, renewable biopolymer that is inherently sustainable and potentially biodegradable (*Adv. Mater.*, 2023, 35, 2300813; *Small*, 2023, 19, 2301957; *Chem. Eng. J.*, 2024, 493, 152599; *Chem. Eng. J.*, 2025, 520, 165707).

Relative environmental friendliness of the preparation process: Our fabrication process (e.g., wet spinning, freeze-drying) primarily uses water as a solvent, avoiding the large amounts of toxic and harmful organic solvents commonly used in traditional aerogel preparation. This aligns with the principles of “environmentally friendly” preparation methods reported in the literature. For example, Chow et al. developed a custom, wearable passive radiative cooling textile using a scalable, one-step, additive-free wet-spinning process. Although the material was prepared from PVDF and DMAc, the authors claimed that the performance was achieved through a globally applicable wet-spinning process, ensuring immediate industrial scalability and compatibility with standard textile weaving and knitting infrastructure. By eliminating the reliance on nanomaterials, the textile provides a mechanically robust, environmentally friendly, and cost-effective platform (*Adv. Sci.*, 2026, e24380).

Application of functional components: To satisfy the hydrophobicity requirements for outdoor sportswear, we subjected the aerogel fibers to silane treatment. Similarly, many studies introduce SiO₂

or perform silane modification in cellulose-based matrices to optimize performance, while still defining the material's environmental attributes from the perspectives of sustainable sources (i.e., the main raw material is derived from renewable biomass), bio-based content (i.e., biomass carbon dominates the material), or green processes (e.g., water-based preparation, avoidance of toxic solvents) (*Nano Energy*, 2025, 136, 110688; *Chem. Eng. J.*, 2026, 530, 173451; *Adv. Funct. Mater.*, 2025, 2425527). For instance, Li et al. developed a green textile material with high cooling efficiency, wearing comfort, and environmental friendliness using wet-spun regenerated cellulose/silica nanofibers. Although chemicals such as epichlorohydrin and tetraethyl orthosilicate were used in the synthesis process, the authors claimed that the entire process required no post-coating treatment, avoided the use of toxic chemicals, and utilized cellulose derived from sustainable wood pulp, achieving true end-to-end environmental friendliness, thus deeming the process green (*ACS Nano*, 2025, 19, 39, 34596–34605). Wang et al. developed a meta-fabric that integrates passive radiative cooling and latent heat storage, offering both efficient environmental cooling and resistance to thermal shock. The fabric was prepared with polylactic acid (PLA) as the radiative cooling layer and polyvinyl alcohol/cellulose nanocrystal/polyethylene glycol (PVA/CNC/PEG) as the phase-change layer. The authors argued that, in addition to excellent radiative cooling performance in high-temperature environments, the fabric also exhibits good biodegradability in natural environments, offering greater environmental benefits and providing a replicable, environmentally friendly paradigm for the scalable application of green wearable textiles. Liu et al. developed an all-cellulose-based fiber for high-performance radiative cooling. Although the material preparation involved 2,2,6,6-tetramethylpiperidine-N-oxyl (TEMPO) oxidation and sulfuric acid hydrolysis, the authors still claimed that biomass materials, due to their inherent infrared emission, biodegradability, and comfort, represent a new generation of materials, opening new pathways for carbon-neutral cooling and green energy applications (*Adv. Mater.*, 2025, 38, 5, e16401).

Biodegradability of the material: As a natural polymer material, bacterial cellulose can be degraded by microorganisms in the natural environment, ultimately converting into carbon dioxide and water without generating persistent pollutants such as microplastics (*Adv. Funct. Mater.*, 2025, 35, 2413361; *Nat. Commun.*, 2026, <https://doi.org/10.1038/s41467-026-70357-8>; *ACS Nano*, 2022, 16, 10, 15586–15626). Existing studies have confirmed that bacterial cellulose-based materials can achieve complete biological recycling through enzymatic or microbial action after their service life, forming a true closed-loop cycle (*Nat. Sustain.*, 2025, 8(9), 1077–1086; *ACS Nano*, 2025, 19, 3531–3548). This characteristic further reinforces the material's environmental friendliness at the end of its lifecycle.

To avoid potential ambiguity, we have adjusted the relevant wording in the revised manuscript to more precisely describe it as “sustainability” and added the above background explanation. Furthermore, in response to your comment regarding the incomplete preparation steps in Figure 1a, we have added a detailed preparation flowchart (Figure S1) in the Supporting Information that fully illustrates key steps, including gradient coagulation bath formation, freeze-drying, and silane post-treatment. The corresponding process parameters have also been included in the Experimental Section to ensure reproducibility. We thank you again for your rigorous feedback, which has helped us improve the manuscript's scientific accuracy and precision.

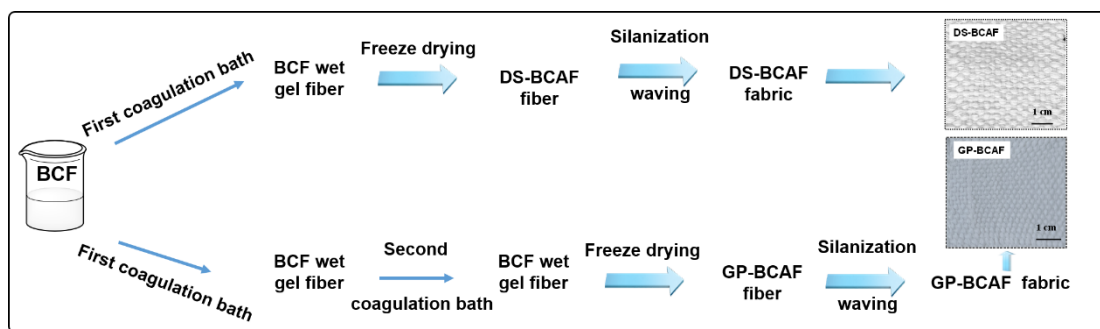


Figure S1. The preparation process of the GP-BCAF and DS-BCAF fabrics.

Comment 7: The BC aerogel fiber exhibits a mechanical strength of 50 MPa, which the authors state is adequate for outdoor use. Please specify the reference standards or benchmarks supporting this assertion.

Reply: Thank you for your valuable suggestions. In recent years, researchers have progressively improved the mechanical properties of aerogel fibers through material optimization and structural design, and have successfully demonstrated their potential for wearable applications. Zhou et al. prepared gradient Janus aerogel fibers for high-performance hydrovoltaic power generation, with a tensile stress ranging from 17.6 to 18.3 MPa and a tensile strain between 15% and 18%, meeting the requirements for fabric formation and proving their suitability for wearable applications (*Adv. Funct. Mater.*, 2025, 35, e10747). Aramid nanofiber aerogel fibers (tensile strength 83.1 MPa, strain 16.2%) have been successfully woven into textiles for thermal insulation (*Nat. Commun.*, 2026, <https://doi.org/10.1038/s41467-026-69790-6>). Cheng et al. prepared aramid aerogel fibers by continuous wet spinning combined with rapid ambient drying, achieving a tensile strength of up to 13.5 MPa, which meets textile requirements (*Small*, 2025, 21, 2409408). Aramid nanofiber aerogel fibers prepared by wet spinning combined with freeze-drying exhibited a tensile strength of 8.1 MPa and an elongation at break of 19.2%; flexible wearable textiles were successfully fabricated by a simple warp-weft weaving method, fully satisfying the conventional weaving requirements of textiles (*Adv. Fiber Mater.*, 2022, 4, 1267–1277). Numerous studies have also demonstrated that aerogel fibers with tensile strengths in the range of 8–30 MPa have been widely validated for textile processing and wearable applications (*Adv. Mater.*, 2025, 37, 2507289; *Chem. Eng. J.*, 2026, 533, 174568; *ACS Nano*, 2021, 15, 15180–15190; *Nano Energy*, 2025, 136, 110688). The tensile strength of our GP-BCAF fabric is 50 MPa, far exceeding the above-validated range (8–30 MPa). Moreover, we have successfully woven GP-BCAF fabric that can be bent arbitrarily and conformally attached to curved surfaces, such as fingers (Figure S8), demonstrating excellent flexibility and wearability. Therefore, the mechanical strength of this fabric is fully sufficient for textile processing and suitable for outdoor sportswear applications.

To comprehensively verify the suitability of GP-BCAF fabric for outdoor environments, we have added a UV-aging test to the revised manuscript to evaluate its performance stability under long-term sunlight exposure. The UV exposure test was performed following the methods reported in the literature (*Nat. Sustain.*, 2023, 6, 1446–1454; *Nat. Commun.*, 2024, 15, 815). GP-BCAF textiles were exposed to high-intensity UV radiation (125 W/m², 60 °C), and spectral characterization was carried out every 20 hours of continuous exposure. After 100 hours of UV aging, the solar reflectivity of GP-BCAF fabric remained above 94% of its original value, and the tensile strength decreased from 50.0 MPa to 45.1 MPa. FTIR spectra showed no significant attenuation or shift of the characteristic cellulose backbone peak (~1640 cm⁻¹), indicating good photostability of the material. GP-BCAF fabric

exhibits excellent aging resistance under simulated outdoor sunlight conditions (Figure S16). Thank you again for your suggestion, which has helped us improve the validation of the practical application performance of our work. We have added more descriptions to the manuscript (lines 10-11, page 7; the Results and Discussion section, lines 9-13, page 17; the Experimental section) and added Figure S16 to the Supporting Information file.

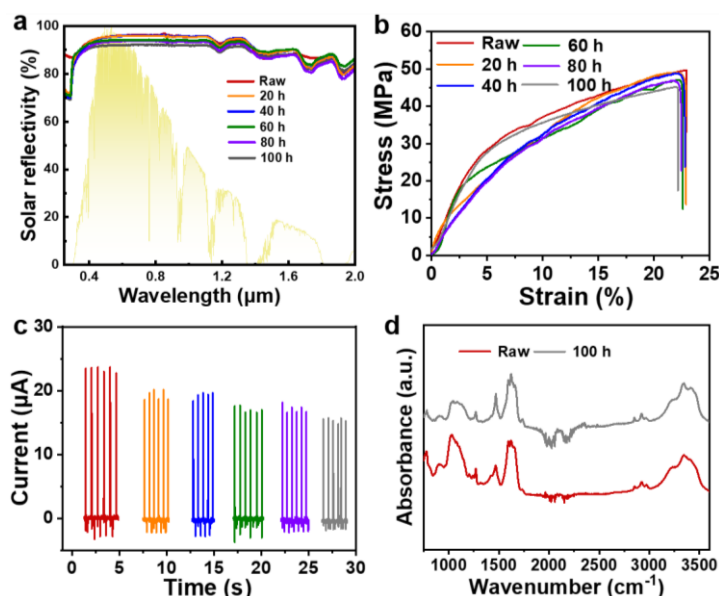


Figure S16. Comparison of solar reflectivity (a), mechanical properties (b), current output signals (c) and FITR (d) for GP-BCAF fabric before and after ultraviolet exposure test.

Comment 8: The authors claim excellent waterproof performance, yet no hydrostatic pressure data are provided to substantiate this point.

Reply: Thank you for your valuable suggestions. Water resistance is a key indicator for evaluating the practical applicability of outdoor sportswear fabrics. In the revised manuscript, we have supplemented the hydrostatic pressure test of the GP-BCAF fabric and systematically compared it with cotton fabric. The test was conducted in accordance with the national standard GB/T 4744-2013 “Textiles – Testing and evaluation of water resistance – Hydrostatic pressure method”. To eliminate the influence of fabric construction on water resistance, both the cotton and GP-BCAF fabrics were prepared using the same warp-weft weaving method and warp/weft densities. A YG825G fully automatic hydrostatic pressure tester was used, and three-square specimens (16 cm×16 cm) were cut from the central area of each sample. The water pressure rise rate was set to 6 kPa/min. The pressure value was recorded when a third water droplet appeared on the specimen surface, and the hydrostatic pressure of each fabric was taken as the average of the three measurements (*Small*, 2026, e13599). The results show that the hydrostatic pressure of the cotton fabric is 6.62 kPa, while that of the GP-BCAF fabric reaches 19.32 kPa, which is approximately 2.9 times that of the cotton fabric (Figure S18). According to GB/T 4744-2013, a hydrostatic pressure in the range of 13 kPa to 20 kPa indicates reliable water-resistant performance. The measured value for the GP-BCAF fabric (19.32 kPa) falls within this range, indicating good resistance to water penetration. This performance is mainly attributed to the silane hydrophobic treatment applied to GP-BCAF. A low-surface-energy surface constructed through hydrophobic modification can significantly enhance the fabric's water-penetration resistance (*Chem. Eng. J.*, 2017, 319, 321–332; *Fibers Polym.*, 2020, 21, 2138–2145). The excellent hydrostatic pressure value verifies the reliable waterproof performance of the GP-BCAF fabric in practical applications.

Thank you again for your suggestion, which has helped us improve the validation of the practical application performance of our material. We have added more descriptions to the manuscript (lines 10, page 7; the Results and Discussion section, lines 12-20, page 17; the Experimental section) and added Figure S18 to the Supporting Information file.

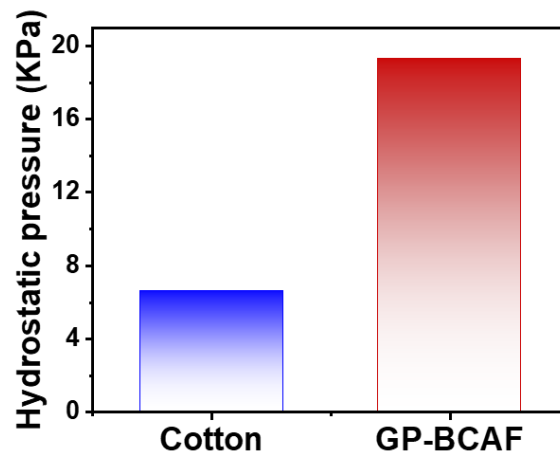


Figure S18. Comparison of the hydrostatic pressure between GP-BCAF and cotton fabrics.

Comment 9: A water-wash resistance test should be included to further demonstrate the practical durability and usability of the textile.

Reply: Thank you for your valuable suggestions. We have tested the fabric's wash durability to further demonstrate its practical durability and usability, and have added the relevant experiments and discussion to the revised manuscript. Washing was performed according to ISO 6330 standards (*Nat. Sustain.*, 2023, 6, 11, 1446–1454; *Nat. Commun.*, 2025, 16, 1, 6735) using a household mini washing machine. Three fabric samples (5 cm × 8 cm) were placed into the machine together with an antibacterial detergent (Ariel, Procter & Gamble). A balancing load was added to achieve a 2 kg washing load, and the standard washing program was carried out, followed by natural hanging drying. After every 10 washing cycles, the fabrics were characterized using spectroscopic analysis, mechanical testing, and measurement of triboelectric nanogenerator output. After 50 washing cycles, the solar reflectivity of the GP-BCAF fabric remained above 96% of its original value, the tensile strength decreased from 50.0 MPa to 43.7 MPa, and the TENG output voltage retained 74.2% of its initial value. The slight decrease in performance is mainly attributed to minor surface pore collapse and micro-damage to the interfacial structure during washing, while the overall performance remained high. Compared with similar materials reported in the literature (e.g., cellulose-based radiative cooling fabrics typically retain about 92–95% of their reflectivity after 50 washes), the wash durability of GP-BCAF fabric is superior. Thank you again for your suggestion, which has helped us improve the verification of the practical application performance of our material. We have added more descriptions to the manuscript (lines 10, page 7; the Results and Discussion section, lines 1-8, page 17; the Experimental section) and added Figure S17 to the Supporting Information file.

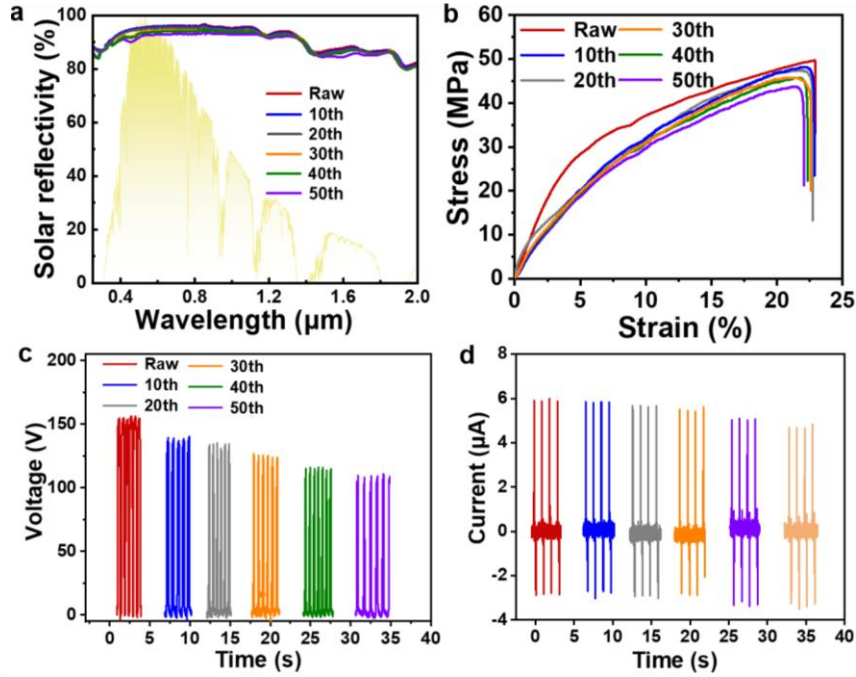


Figure S17. Comparison of solar reflectivity, mechanical properties, and voltage and current output signals for GP-BCAF fabric before and after washing.

Reviewer: 3

Comments: This manuscript by Feng et al. presents a route to a new type of passive radiative cooling material with convincing and comprehensive characterization. The study is well written and concisely presented, and it is interesting for the wide readership of Nature Comm. However, major revisions are necessary before it can be fully recommended for publication.

Reply: Thank you for your high appreciation of this work.

Comment 1: The surface area of the material must be characterized and quantitatively compared with the state-of-the-art materials. The authors should assess as to what extent the surface area contributes to the apparent high performance of their material.

Reply: Thank you for your valuable suggestions. In the revised manuscript, we have supplemented a comparison of the specific surface area of GP-BCAF fabric with that of state-of-the-art radiative cooling materials, along with an in-depth analysis of the contribution of specific surface area to the high performance of the material. As shown in Figure S13, the corresponding pore size distribution curve reveals that GP-BCAF possesses a multi-scale gradient pore structure ranging from micropores (<2 nm) and mesopores (2–50 nm) to macropores (>50 nm), which is in good agreement with the radially gradient porous architecture observed by SEM (Figure 2f–g). The BET specific surface area of GP-BCAF was calculated to be 283.4 m²/g. We systematically compared the specific surface area of GP-BCAF with that of advanced radiative cooling materials reported in recent literature, as summarized in Table 3.

Table 3. Comparison of the specific surface area between GP-BCAF and reported PDRC materials.

Materials	Surface area (m ² /g)	Solar reflectivity (%)	Type	Ref.
CSNA	440.5	96.2	aerogel	[10]
HSiO ₂ /C@C)	163.2	92.6	aerogel fiber	[5]

MST	17.22	97.3	fiber membrane	[11]
PSNF/MNPLA	137.84	97.0	aerogel	[12]
CSP	14.2	93.5	aerogel	[13]
RCSF	36.6	93.7	aerogel fiber	[9]
GP-BCAFs	283.4	94.7	aerogel fiber	this work

As shown in the table, the specific surface area of GP-BCAF is among the highest reported for aerogel fiber-based radiative cooling materials, clearly demonstrating the superiority of its porous structure. We further analyzed the contribution of the high specific surface area to GP-BCAF's excellent performance in the following aspects. (1) Radiative cooling performance: The high specific surface area of the material means abundant porous interfaces, which scatter sunlight at different scales, thereby significantly enhancing solar reflectivity. Yu et al. achieved efficient light scattering through full-scale structural design with a high specific surface area, notably improving solar reflectivity (*Nano-Micro Lett.*, 2025, 17, 192). Li et al. developed regenerated cellulose/silica nanoparticle fibers with a high specific surface area; their abundant porous interfaces scatter sunlight at micro- and nanoscales, thereby enabling efficient daytime radiative cooling (*ACS Nano*, 2025, 19, 44, 38395–38407). These findings are consistent with multiple studies in the field of radiative cooling (*Adv. Mater.*, 2025, 2505224; *Adv. Mater.*, 2025, 37, e08518; *Small*, 2026, e14581; *Nano Energy*, 2025, 136, 110688; *Compos. Sci. Technol.*, 2025, 273, 111421). The multi-scale gradient pore structure of GP-BCAF ensures broadband high reflectivity from ultraviolet to near-infrared wavelengths, providing the structural foundation for achieving 94.7% solar reflectivity. (2) Mechanical performance: The high specific surface area provides more hydrogen-bonding crosslinking sites (bacterial cellulose is rich in –OH groups), enhancing interactions between cellulose molecular chains. Meanwhile, the gradient porous structure of GP-BCAF further improves its mechanical properties. Liu et al. fabricated a silica-coated nanofiber aerogel with a three-dimensional, intertwined nanofiber network, exhibiting good flexibility and shape-processability (*Adv. Funct. Mater.*, 2025, 35, 31, 2425527). Fu et al. prepared gradient all-nanostructured aramid aerogel fibers via microfluidic spinning; their unique nano-entangled network efficiently dissipates stress, achieving high tensile strength (29.5 MPa) and fracture strain (39.2%) (*Nat. Commun.*, 2025, 16, 2357). These reinforcement mechanisms are highly consistent with those reported for cellulose-based materials (*Science*, 2023, 382, 1379–1383; *Adv. Mater.*, 2024, 36, 2411131; *Adv. Funct. Mater.*, 2026, e28466; *Gels*, 2021, 7, 145). (3) Sensing performance: The high specific surface area offers abundant surface-active sites, facilitating charge accumulation and stable output of the triboelectric nanogenerator. Wang et al. developed a multifunctional conductive aerogel composed of thermoplastic polyurethane (TPU) and carbonized wood aerogel (CWA); the conductive network enables uniform charge distribution and efficient transfer, significantly enhancing TENG output (*Adv. Funct. Mater.*, 2026, 36, 18, e21776). Zuo et al. assembled aramid nanofibers (ANFs) into macro-scale aerogel fibers with a hierarchical porous structure; the three-dimensional interconnected conductive network not only improves electrical conductivity but also enhances rapid response to stimuli (*Nano Energy*, 2022, 101, 107559). These conclusions are in agreement with reports in the literature on sensing performance optimization (*Adv. Mater.*, 2024, 2411558; *ACS Sens.*, 2026; *Chem. Eng. J.*, 2025, 519, 165385; *Chem. Eng. J.*, 2024, 497, 154906).

In summary, the high specific surface area of GP-BCAF is a necessary condition for its superior performance. More importantly, the precise design of the gradient porous structure enables synergistic

optimization of specific surface area with mechanical and optical properties, collectively endowing the material with outstanding multifunctional characteristics. We have added the comparison and analysis in the revised Supporting Information. Thank you again for your suggestion, which has made our work more rigorous and complete.

Comment 2: The effect of the calcium counterion with the carboxylate on the IR vibrational frequency is interesting. Is it an effect of cross-linking or molecular weight of the ion which should directly cause a shift in the vibrational spectrum? You can find this out by trialing different monovalent alkaloid metals as counterions (e.g., Li, Na, K, Cs), which do not cross link, and different divalent earth alkaloid metals (e.g., Mg, Ca, Sr, Ba) which do cross link. Can you then tune the radiative cooling response with the selection of the counterion?

Reply: Thank you for your insightful suggestion. We systematically investigated the infrared emission spectra and the shift of the COO^- stretching vibration peak of GP-BCAF fabrics crosslinked with monovalent ions (Li^+ , Na^+ , K^+) and divalent ions (Mg^{2+} , Ca^{2+} , Zn^{2+} , Ba^{2+}). After treatment with all monovalent ions, the asymmetric stretching vibration peak of COO^- showed no obvious shift, remaining essentially unchanged from the uncross-linked control sample (Figure S10). The infrared emissivity of GP-BCAF fabrics crosslinked with Li^+ , Na^+ and K^+ were 90.9%, 90.7% and 90.6%, respectively, staying within the narrow range of 90.6% to 90.9%. Because the masses of the monovalent ions differ significantly, if a mass effect existed, the emissivity should show a monotonic trend with increasing mass. The experimental data do not exhibit such a trend, demonstrating that the ion mass effect has a negligible influence on both the vibrational frequency of the asymmetric stretching peak and the emissivity. After treatment with all divalent ions, the asymmetric stretching vibration peak of COO^- exhibited a clear blue shift to higher wavenumbers. The infrared emissivity of GP-BCAF fabrics crosslinked with Mg^{2+} , Ca^{2+} , Zn^{2+} and Ba^{2+} were 96.5%, 97.1%, 97.4% and 97.0%, respectively, all significantly higher than those of the monovalent ion group. This is attributed to the crosslinking effect between divalent ions and COO^- , which changes the electron cloud distribution of COO^- and raises its vibrational frequency (*J. Mol. Struct.*, 2015, 1087, 46–50; *J. Plant Nutr. Soil Sci.*, 2021, 184, 388–393).

The differences in emissivity among the divalent ions further reveal the distinct modes of interaction with COO^- . Owing to its strong hydration ability, Mg^{2+} primarily forms solvent-shared ion pairs and does not directly interact with COO^- , thereby exerting a relatively small influence on the vibrational environment and emissivity. Ca^{2+} can form bidentate bridging structures with COO^- , and the directly contacted ion pair causes a significant blue shift of the asymmetric stretching vibration. The bidentate bridging structure markedly changes the local environment of COO^- , whereas Mg^{2+} has a much smaller effect due to its stable hydration shell; this difference leads to a more pronounced change in the optical properties of Ca^{2+} in solution (*J. Phys. Chem. B*, 2024, 128, 10688–10698; *J. Phys. Chem. B*, 2021, 125, 11308–11319). After crosslinking with Zn^{2+} , the blue shift is associated with structural features such as monodentate coordination, hydrogen bonding, conjugation effects and geometric deformation of the bridging mode; these factors alter the electron density distribution and bond length differences of the carboxylate group, thereby enhancing the vibrational frequency of COO^- (*Spectrochim. Acta A*, 2007, 66, 262–272). Ba^{2+} directly forms bridging and bidentate coordination structures with COO^- , and these coordination structures cause changes in the infrared spectrum (*J. Phys. Chem. B*, 1999, 103, 435–444). Monovalent ions cannot form strong interactions with COO^- , and their vibrational peak positions and emissivity remain stable, proving that the ion mass effect is negligible. The changes in the infrared spectra induced by divalent ions are mainly determined

by the crosslinking effect between the ions and COO^- . By selecting different divalent counterions, the infrared emissivity of the material can be finely tuned from 96.5% to 97.4%, thereby effectively modulating radiative cooling performance. This finding provides clear experimental evidence and theoretical guidance for optimizing radiative cooling materials through ion engineering. We have added more descriptions to the manuscript (lines 4-7, page 6, the Results and Discussion section) and included Figure S10 in the Supporting Information file.

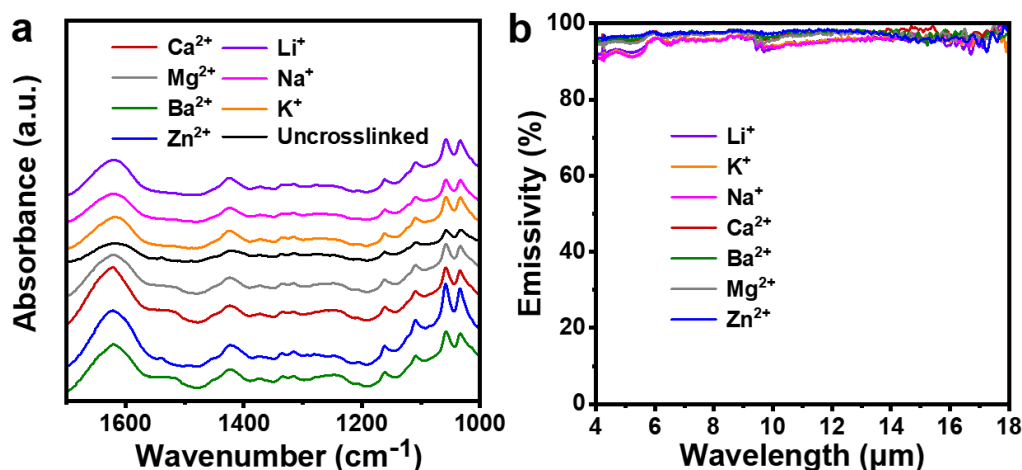


Figure S10. The FTIR-ATR (a) and (b) emissivity of the GP-BCAFs across various types of ion crosslink.

Comment 3: How do the XPS results indicate that the “silane modification occurred throughout the fiber structure rather than being confined on the surface”? XPS only extracts information from the very surface of the material.

Reply: Thank you for your valuable suggestions. The probing depth of XPS is limited and can only provide chemical information from the very surface of the material; it cannot directly prove that the silane modification penetrates the entire fiber structure. To directly verify the depth of silane modification, we performed SEM-EDS elemental mapping and line-scan analysis on the cross-section of GP-BCAF fibers (Figure S11). The results show that the characteristic signal of the Si element is uniformly distributed from the surface to the central region of the fiber, directly confirming the uniform radial modification of silane. Based on the above evidence, we have revised the relevant statement in the manuscript to: “The X-ray photoelectron spectroscopy (XPS) confirmed the presence of Si–O–Si and Si–C bonds on the surface of GP-BCAFs (Figure 2c). To further verify whether the silane modification penetrates the entire fiber structure, SEM-EDS elemental mapping and line-scan analysis were performed on the fiber cross-section (Figure S11). The results show a uniform distribution of the Si signal from the surface to the central region, directly confirming radial homogeneity of the modification. Therefore, combining XPS surface analysis with SEM-EDS cross-sectional elemental distribution demonstrates that the silane modification occurs throughout the fiber structure rather than being confined to the surface.” Thank you again for your rigorous correction, which has helped improve the scientific accuracy of our work. We have added more descriptions to the manuscript (lines 9-11, page 6, the Results and Discussion section) and included Figure S11 in the Supporting Information file.

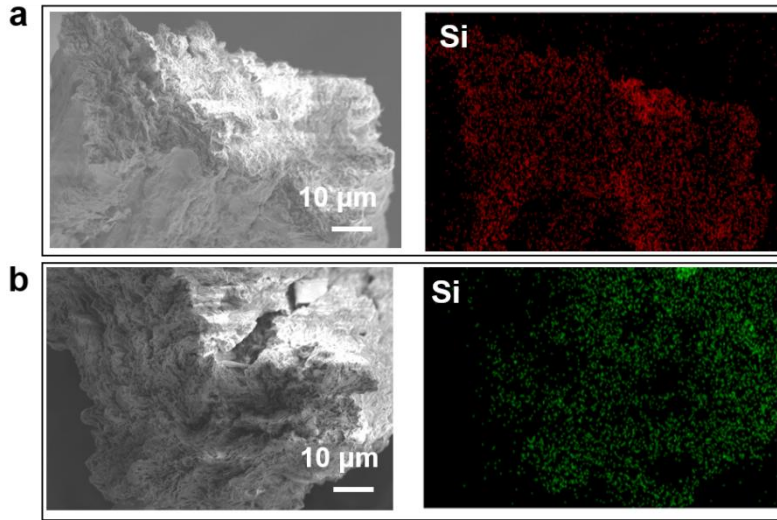


Figure S11. (a-b) The SEM-EDS of the GP-BCAF.

Comment 4: Please compare your mechanical properties quantitatively with other existing PDRC materials, not just the DS-BCAF fabrics.

Reply: Thank you for your valuable suggestions. We have compared the mechanical properties of GP-BCAF fabric with those of advanced radiative cooling materials reported in the recent literature and have added the following analysis and discussion to the revised manuscript. As shown in Table 2.

Table 2. Comparison of the mechanical properties of GP-BCAF and reported PDRC materials.

Materials	Stress (MPa)	Strain (%)	Aerogel fiber fabric	Ref.
SPRF	1.43	28.5	No	[1]
IRT-PA6	7.04	32.6	No	[2]
PE-MSZ	28.1	41.9	No	[3]
RCSF	20.0	9.6	Yes	[4]
HSiO ₂ /C@C)	19.4	17.6	Yes	[5]
PMABF	4.3	18.5	Yes	[6]
SAFs	5.9	400	No	[7]
POM	13.3	300	No	[8]
Meta-fabric	2.4	276	No	[9]
GP-BCAFs	50.0	23	Yes	this work

The tensile strength of GP-BCAF fabric reaches 50 MPa, which is significantly higher than that of most PDRC materials (typically in the range of 5–30 MPa). Among aerogel fiber fabrics, GP-BCAF also exhibits good flexibility with an elongation at break of 23%, making it more suitable for wearable applications. However, its elongation at break is moderate compared with some ultra-flexible radiative cooling fabrics; its much higher tensile strength gives it an advantage in scenarios requiring strong mechanical performance, such as smart wearable devices and high-performance textiles. The excellent mechanical properties of GP-BCAF benefit from its unique gradient porous structure. The micro-folded structure in the shell layer effectively disperses impact stress through elastic deformation under load. In contrast, the dense core layer provides stable mechanical support via a nano-entangled network. This structural integration enables GP-BCAF to attain both high mechanical strength and

effective radiative cooling performance. In summary, through its distinctive gradient structure design, GP-BCAF strikes a favorable balance between mechanical properties and radiative cooling efficiency, demonstrating great potential for multifunctional textile applications. We have added the above comparison and analysis in the Supporting Information. We thank the reviewer again for the suggestion, which has helped highlight the innovation and advantages of our work relative to state-of-the-art materials.

Reviewer: 4

Comments: This work developed a continuous production method to fabricate bacterial cellulose aerogel fiber fabrics with a radially gradient porous structure. This work addressed the long-standing trade-off between mechanical properties and passive daytime radiative cooling performance in traditional aerogel fibers. The integration of self-powered sensing capabilities for real-time monitoring of physiological activities is a powerful boost to the applicability of future smart wearable devices. I will be glad to recommend for publication after addressing a few minor questions.

Reply: Thank you for your high appreciation of this work.

Comment 1: The integration of triboelectric nanogenerator improves functionality. Please comment on the change of voltage signal when the user is sweating and whether encapsulation is needed to stabilize the detecting signals.

Reply: Thank you for your valuable suggestions. In response to the reviewer's concerns about the change in voltage signal when the user sweats and the need for encapsulation, we have added relevant tests and discussions in the revised manuscript. We measured the output signal of the GP-BCAF fabric under human sweating conditions. The results show that the output voltage decreases with increasing humidity, consistent with the well-documented effect of humidity on TENG output (*Adv. Funct. Mater.*, 2026, e29552; *ACS Appl. Electron. Mater.*, 2024, 6, 2, 931–939). Despite signal attenuation, the output signal can still clearly distinguish different motion states (e.g., walking, running, impact), as shown in Figure S28a, demonstrating sufficient signal-to-noise ratio and event-recognition capability in practical scenarios. This humidity-resistant performance is mainly attributed to the excellent hydrophobic properties of the GP-BCAF fabric. Previous studies have shown that superhydrophobic TENGs with micro/nanostructures can maintain stable output under sweat contamination and high-humidity environments, making them suitable for motion monitoring (*Adv. Funct. Mater.*, 2023, 33, 45, 2304809; *Nano Energy*, 2022, 95, 107018; *Adv. Fiber Mater.*, 2025, 7, 1111–1127). Enhancing surface hydrophobicity significantly reduces the influence of humidity on the electrical performance of contact-separation TENGs (*Chem. Eng. J.*, 2025, 524, 169377; *Nano Energy*, 2022, 100, 107506; *Nano Energy*, 2023, 111, 108426). For example, Shang et al. developed a dual-modification strategy by combining liquid metal microdroplets with cellulose nanofibers and embedding them into a waterborne polyurethane matrix, while constructing a rose-petal-like microstructure on the surface to significantly enhance hydrophobicity. Their device retained 79% of its open-circuit voltage at 98% relative humidity (*Adv. Funct. Mater.*, 2026, e28797). Inspired by lotus leaves, Sun et al. prepared a fluorinated polydimethylsiloxane biomimetic triboelectric layer with super hydrophobicity; the resulting biomimetic TENG maintained 80% of its original output performance at 90% relative humidity (*ACS Appl. Electron. Mater.*, 2025, 7, 4, 1520–1530). These studies provide strong support for understanding the signal stability of GP-BCAF under sweaty conditions.

We further validated the sensing performance of the GP-BCAF fabric under real user sweating conditions. As shown in Figure S28b–c, although sweating causes a slight decrease in signal amplitude,

the signal differences among motion states remain clearly distinguishable, demonstrating its reliability for monitoring in real-world outdoor sports scenarios. Based on the above results, we believe that additional encapsulation is unnecessary for the application scenario in this study. First, the intrinsic hydrophobic property of the GP-BCAF fabric provides sufficient moisture resistance, effectively suppressing direct interference from sweat at the triboelectric interface and maintaining the signal's stable motion-recognition capability under sweating conditions. Meanwhile, encapsulation may block the unique multi-scale gradient porous structure of GP-BCAF, thereby compromising its high solar reflectivity (94.7%) and excellent radiative cooling performance. Moreover, avoiding additional encapsulation preserves the simplicity of the material preparation process, which is beneficial for large-scale production and multifunctional integration. We also fully recognize that for applications requiring higher precision or absolute quantitative output (e.g., medical-grade health monitoring), encapsulation is indeed necessary to improve signal stability. This could be a direction for future research, for example, achieving optimized encapsulation through methods such as ultrathin hydrophobic coatings or atomic layer deposition that do not affect the porous structure. Thank you again for your suggestion, which has helped us clarify the balance between functionality and practicality in our work. We have added more descriptions to the manuscript (lines 7, page 12, the Results and Discussion section) and added Figure S28 in the Supporting Information file.

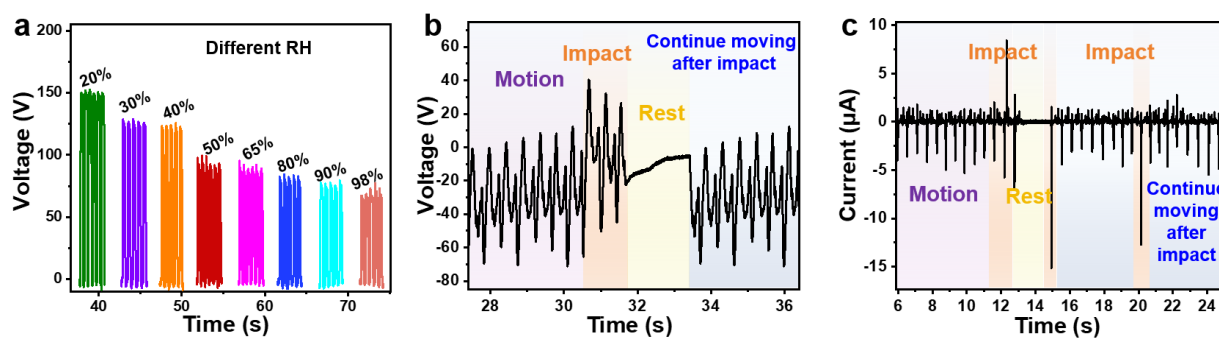


Figure S28. (a) Voltage output of GP-BCAF at different humidity. (b) Voltage and (c) current output signals corresponding to various movement states.

Comment 2: Was the different morphology of GP-BCAF and DS-BCAFs due to the different free-drying procedure, or the coagulation bath? It wasn't very clear in Figure 1 and Experimental section.

Reply: Thank you for your valuable suggestions. Both GP-BCAF and DS-BCAF were prepared by wet spinning combined with freeze-drying, and all post-treatment processes were kept identical. Therefore, the morphological difference between the two materials is not due to the drying method but rather to the precise control of the coagulation bath concentration during wet spinning. For DS-BCAF, a single concentration (8 wt%) of calcium chloride solution was used as the coagulation bath. The fiber underwent rapid phase separation in the coagulation bath, forming a uniform and dense skin layer. For GP-BCAF, the cellulose solution was sequentially extruded into calcium chloride coagulation baths of different concentrations (4 wt% and 8 wt%) to achieve gradient control of the phase separation rate. In the high-concentration coagulation bath (8 wt%), rapid phase separation induced the formation of a porous shell with a wrinkled surface, whereas in the low-concentration coagulation bath (4 wt%), slow phase separation promoted the formation of an ordered dense core. This strategy successfully produced aerogel fiber fabrics with a radially gradient porous structure. Previous studies have demonstrated that adjusting the coagulation bath concentration is an effective approach to obtain gradient porous structures in fibers. For example, Fu et al. fabricated gradient all-nanostructured aramid aerogel fibers

by controlling the coagulation concentration using microfluidic spinning technology (*Nat. Commun.*, 2025, 16, 2357). Xiao et al. tuned the acidity of the coagulation bath and the draw ratio to produce fibers with a unique dual-scale porous architecture consisting of a dense nanoporous core and a macroporous honeycomb-like shell wrapped by an interconnected nanofiber network (*Nat. Commun.*, 2026, <https://doi.org/10.1038/s41467-026-69790-6>). This strategy of regulating phase-separation kinetics via the composition of the coagulation bath is the key innovation of our work in achieving the gradient porous structure. We have added relevant details in the Experimental section (4.1) and Figure S1 of the revised manuscript, and all additions and modifications have been highlighted in red.

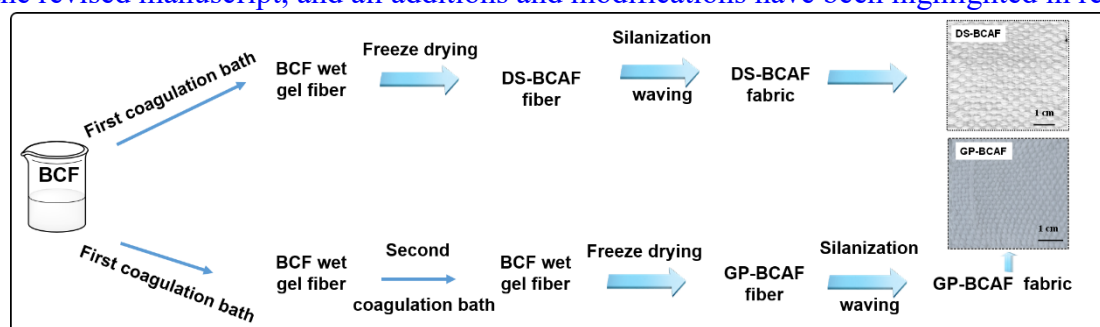


Figure S1. The preparation process of the GP-BCAF and DS-BCAF fabrics.

Comment 3: The label for Figure 1f seems unclear. It is recommended to enlarge the text in the images to improve clarity and readability.

Reply: Thank you for your valuable suggestions. We have enlarged the text in the image to enhance clarity and readability.

Comment 4: I suggest combine Fig 2a and 2b if they are from the same spectra.

Reply: Thank you for your valuable suggestions. These two figures are derived from the same FTIR spectrum, and the full spectrum is provided in the Supplementary Information (Figure S8). We have kept the two figures separate in the main text to present two distinct pieces of scientific information, allowing readers to grasp the key conclusions more clearly. Figure 2a focuses on the atmospheric window (8–13 μm). Passive radiative cooling technology utilizes this atmospheric transparent window to emit heat from terrestrial objects as mid-infrared radiation to the cold outer space, thereby achieving cooling. The figure clearly shows enhanced stretching vibrations of C–O–C and Si–O–Si bonds in GP-BCAFs within this band; these functional groups directly contribute to the material's absorption and emission capabilities in the mid-infrared region. Presenting this specific spectral range independently allows readers to more intuitively correlate the chemical structure with the radiative cooling performance. Figure 2b focuses on the peak shift of the carboxylate (COO^-) group. Compared with unmodified BCF, the asymmetric stretching vibration peak of COO^- in GP-BCAF shows an obvious shift, which directly demonstrates the successful crosslinking reaction between Ca^{2+} and sodium alginate. Numerous studies have confirmed that the COO^- vibration peak shifts upon crosslinking of sodium alginate with Ca^{2+} (*Adv. Mater.*, 2024, 2411558; *Adv. Funct. Mater.*, 2025, 35, 36, 2501094; *Adv. Funct. Mater.*, 2025, 35, 2412412; *Chem. Eng. J.*, 2024, 480, 148192). Isolating this figure allows a clearer view of the peak shift before and after crosslinking. In summary, although the two figures originate from the same spectrum, they serve different scientific purposes, and presenting them separately facilitates rapid comprehension of the key information. We have clearly indicated the relationship between the two figures in the revised manuscript and added corresponding explanations in the figure captions. Thank you again for your suggestion.

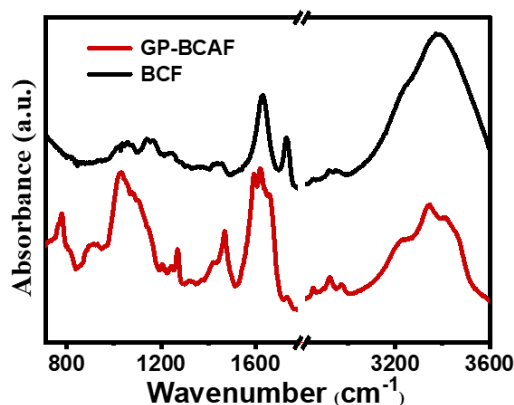


Figure S8. The FTIR-ATR of the BCFs and GP-BCAFs.

Comment 5: To provide convincing, visual proof of the continuous production process described for the fibers, I suggest that the authors consider adding a supplementary video demonstrating this fabrication step.

Reply: Thank you for your valuable suggestions. We have added a video of the continuous preparation process to the supplementary materials (Video S1).

Reviewer: 5

Comments: The manuscript presents an interesting and well-structured study on the synthesis of porous fabrics based on cellulose aerogel fibers, showing a multilevel gradient from micro- to nano scale. The authors also report a novel methodology for controlling the structure of the bacterial cellulose fibers through gradient coagulation into a hydro-spinning bath, allowing for the production of these fibers at a large-scale. In order to validate the optimal structure, dense and smooth aerogel fibers were also produced for comparison, thus leading to a systematic and thorough study.

The produced material showed high solar reflectivity (94.7%) and tensile strength (50 MPa), as well as high emissivity, thus providing an excellent combination for efficient passive cooling and enabling its use at lower temperatures than conventional commercial cotton fabrics. Moreover, this fabric was tested in wearable garments to monitor human electrophysiological signals during physical activities, maintaining stable signals and high sensitivity. The electrical signals collected can also be transmitted to a smartphone, thereby facilitating user-friendly operation, promoting accessibility for personal use, and opening new opportunities for advancements in wearable sports and health-monitoring technologies.

Therefore, this study provides an innovative solution to improve the performance of other fabrics currently employed for thermal management, being applicable to smart textile designs.

Despite being a high-quality study, very complete by the employment of many characterization techniques, there are several issues that should be addressed prior publication:

Reply: Thank you for your high appreciation of this work.

Comment 1: The authors could analyze the dependence of transmittance on wavelength in order to confirm the Mie scattering mechanism and the possibility of having Rayleigh scattering.

Reply: Thank you for your valuable suggestions. According to scattering theory, the scattering intensity of Rayleigh scattering is inversely proportional to the fourth power of the wavelength, so the transmittance increases monotonically with increasing wavelength. When the scatterer size approaches or exceeds the wavelength, Mie scattering dominates, and the wavelength dependence of the scattering intensity weakens significantly, causing the transmittance spectrum to become flat or to exhibit

oscillatory features. This approach has been used in the literature to distinguish scattering mechanisms at different scales (*Am. J. Phys.*, 2002, 70, 620–625; *Surf. Coat. Technol.*, 2018, 336, 39–53). Accordingly, we measured the transmittance spectrum of GP-BCAF fabric in the 0.3–2.5 μm wavelength range using a UV-Vis-NIR spectrophotometer equipped with an integrating sphere (Figure S12). The results show typical multi-segment characteristics. In the 0.3–1 μm range, the transmittance increases monotonically with wavelength, consistent with Rayleigh scattering. This indicates the presence of abundant nanoscale pores (<100 nm) that are much smaller than the wavelength and strongly scatter short-wave solar radiation. In the 1–2.0 μm range, the transmittance exhibits oscillations and then levels off, showing little dependence on wavelength, which is characteristic of large-particle Mie scattering. This demonstrates the presence of numerous microscale pores (>1 μm) that are much larger than the wavelength, whose scattering efficiency is wavelength-independent. The above transmittance spectral features are consistent with the scattering behavior of multi-scale porous materials reported in the literature (*J. Eur. Ceram. Soc.*, 2021, 41, 2169–2192; *Advances in Engineering Research*, 2017, 134, 108–113), confirming the synergistic effect of Rayleigh scattering (dominated by nanopores) and Mie scattering (dominated by micropores) in the GP-BCAF fabric. This multi-scale scattering mechanism is the structural basis for achieving a high solar reflectivity of 94.7%. We have added more descriptions to the manuscript (lines 20, page 4, the Results and Discussion section) and added Figure S7 in the Supporting Information file.

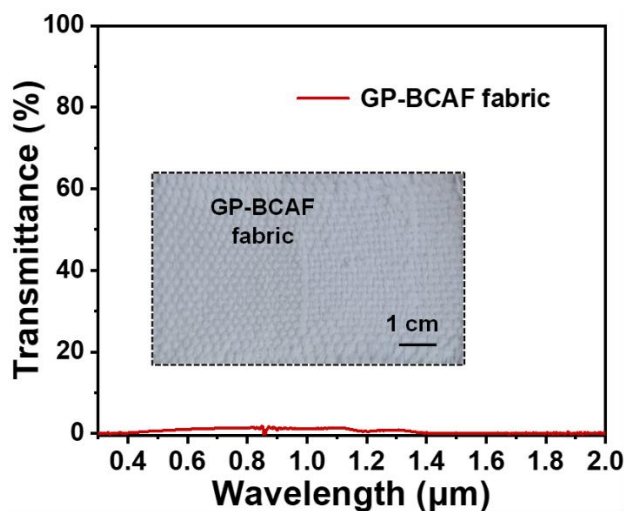


Figure S7. The transmittance of the GP-BCAF fabrics.

Comment 2: The pore size provided by nitrogen sorption is likely far from the real value since this technique only measures pores smaller than 100nm, underestimating bigger pores that can contribute with a high percentage. Thus, a more realistic average pore size should be provided by calculating first the real pore volume through the relationship between densities, and then assuming cylindrical pores (see 10.2136/sssabookser5.4.c11).

Reply: Thank you for your valuable suggestions. We agree that nitrogen sorption can only characterize micropores and mesopores (<100 nm) and underestimates the contribution of macropores to the total pore volume. To obtain more realistic pore-structure parameters, we supplemented the characterization with mercury intrusion porosimetry (MIP), which directly measures the macropore distribution (>50 nm) in GP-BCAF. A full-range pore size distribution from micropores to macropores was thus obtained (Figure S13). The results show a multimodal distribution with distinct peaks at 9 nm, 54 nm, 183 nm and 1.1 μm , among which the peak at 1.1 μm is the highest. This multimodal distribution

directly demonstrates that GP-BCAF possesses a gradient porous structure spanning nanometer- to micrometer-scale, providing direct structural evidence for the multi-scale scattering mechanism. The nano-/mesopores contribute to Rayleigh scattering to enhance short-wavelength reflection, while the sub-micro-/micropores dominate Mie scattering to broaden the reflection band. This multi-scale synergistic scattering is the structural basis for achieving a high solar reflectivity of 94.7%. Meanwhile, following the reviewer's recommended density method, we calculated the average pore size using the cylindrical pore model, with $D = 4V/S$. Using the total pore volume measured by MIP and the BET specific surface area, the calculated hydraulic average pore size is approximately 945 nm. The average pore size directly obtained from MIP is 1.071 μm . Both values are much larger than the pore size derived from nitrogen sorption, confirming the significant contribution of macropores to the total pore volume. Thank you again for your rigorous and constructive feedback. We have added more descriptions to the manuscript (lines 26, page 6, the Results and Discussion section) and included Figure S13 in the Supporting Information file.

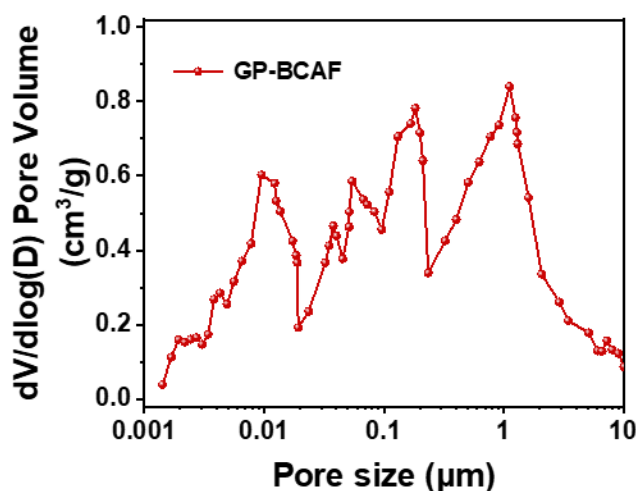


Figure S13. Pore size distribution of the GP-BCAFs.

Comment 3: Evaluating the thermal insulation capability of the composite aerogel felt at different temperatures is necessary since the thermal conductivity values and their dependence with temperature will provide relevant information for its performance in human bodies in different months of the year and different environments.

Thermal conductivity should therefore be quantitatively determined using standardized measurement techniques. In particular, steady-state methods are strongly recommended rather than transient techniques, as highly insulating materials typically require steady-state conditions to ensure reliable and reproducible measurements (10.1007/s10971-023-06282-9 and 10.3390/polym14132556).

Reply: Thank you for your valuable suggestions. We fully agree that standardized steady-state testing methods should be used to ensure the reliability of thermal conductivity data. The thermal conductivity of the GP-BCAF fabric was systematically measured over the range of 25 °C to 70 °C using the steady-state heat flow meter method (GB/T 10295-2008; ASTM C518-04). The heat flow meter method is a steady-state technique suitable for obtaining reliable thermal conductivity data, especially for low-thermal-conductivity materials (*Polymers*, 2022, 14, 2556; *J. Sol-Gel Sci. Technol.*, 2024, 109, 569–579). The measurements were performed with a DRPL-V high-precision thermal conductivity tester using 6 cm × 6 cm × 1.2 cm samples. The temperature points were set at 25 °C, 30 °C, 40 °C, 50 °C, 60 °C and 70 °C, covering the typical ambient temperature range to which the human body may be exposed (from comfortable room temperature to extreme heat). The results are shown in Figure S20.

The results demonstrate that the GP-BCAF fabric maintains a low thermal conductivity of 0.026–0.030 W·m⁻¹·K⁻¹ over the entire 25 °C to 70 °C range. This low thermal conductivity evidences the superiority of its gradient porous structure in suppressing heat conduction (*Nat. Commun.*, 2025, 16(1), 2357; *Nat. Commun.*, 2026, <https://doi.org/10.1038/s41467-026-69790-6>; *Chem. Eng. J.*, 2026, 534, 174080). In hot summer outdoor environments, the ultra-low thermal conductivity of this fabric can effectively block external heat from conducting to the human body, synergizing with its radiative cooling function to further improve human thermal comfort (*Science*, 2024, 384, 670, 1203-1212). The synergistic design of radiative cooling and thermal insulation can significantly enhance the thermal management efficiency of textiles under high-temperature conditions (*Nano Energy*, 2025, 136, 110688; *Colloid Interface Sci.*, 2025, 680, 345-354; *Compos. Commun.*, 2026, 63, 102751). The temperature-dependent thermal conductivity data provide a key basis for evaluating the practical thermal management performance of the GP-BCAF fabric in outdoor environments. We thank the reviewer again for the insightful suggestion, which has enabled us to gain a more comprehensive understanding of the temperature dependence of our material's thermal performance and has significantly improved the rigor and practicality of our work. We have added more descriptions to the manuscript (lines 27-30, page 8, the Results and Discussion section) and included Figure S20 in the Supporting Information file.

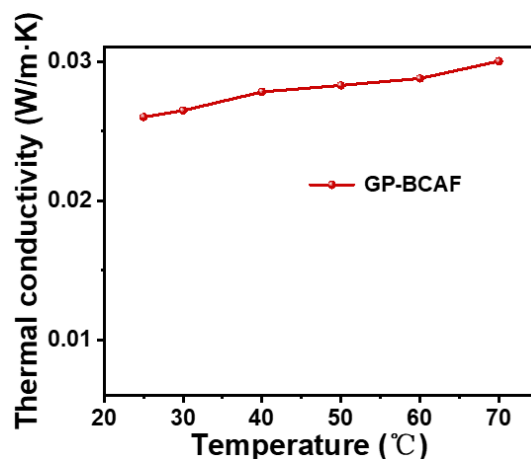


Figure S20. The thermal conductivity of the GP-BCAF.

Reference:

- [1] Y. Zhang, S. Liao, L. Fei, D. Wu, Q. Wang, P. Lv, K. Moth-Poulsen, Q. Wei, *Adv. Fiber Mater.*, 2026.
- [2] Z. Chen, Q. Zhang, L. Ding, G. Lv, T. Liu, Z. Yang, Y. Jiang, L. Li, W. Li, F. Ding, W. Xu, J. Zhu, B. Zhu, *Nat. Commun.*, 2025, 16, 2009.
- [3] Y. Zhai, J. Li, X. Su, J. Zhao, S. Wei, Z. Pan, C. Jia, M. Wang, M. Zhu, *Adv. Funct. Mater.*, 2025, e29127.
- [4] Q. Li, J. Li, C. Zeng, J. Song, Y. Jiang, H. Yu, Y. Fang, S. Hu, Y. Zhang, W. Kong, M. Zhu, *ACS Nano*, 2025, 19, 34596.
- [5] S. Jiang, S. Jiang, J. Yan, C. Lin, W. Wang, S. Jiang, R. Guo, *Nano Energy*, 2025, 136, 110688.
- [6] X. Li, Z. Guo, Y. Ji, P. Du, J. Wang, B. Xu, F. Ge, Y. Zhao, Z. Cai, *Adv. Fiber Mater.*, 2025, 7, 607.
- [7] Y. Wang, X. Chen, X. Zhang, J. Zang, L. Lu, W. Yuan, *Small*, 2026, e14581.
- [8] X. Wu, J. Li, Q. Jiang, W. Zhang, B. Wang, R. Li, S. Zhao, F. Wang, Y. Huang, P. Lyu, Y. Zhao, J. Zhu, R. Zhang, *Nat. Sustain.*, 2023, 6, 1446.
- [9] R. Liu, S. Zhao, X. Wu, Z. Zhao, K. Wang, Z. Guo, A. Xi, F. Lan, R. Li, R. Liu, M. Ma, Y. Zang, F. Wang, Q. Jiang, Y. Li, P. Lyu, R. Zhang, *ACS Nano*, 2025, 19, 826.
- [10] J. Sun, Y. Zhang, Y. Wang, Y. Peng, J. Long, H. Liu, W. Fan, Y. Miao, N. Willenbacher, C. Zhang, T. Liu, *Adv. Funct. Mater.*, 2025, 2425527.
- [11] C. Ding, P. Gao, X. Wang, X. Yin, J. Yu, B. Ding, *Adv. Mater.*, 2025, 37, e08518.
- [12] J. Xu, K. Chen, A. Maturilli, A. Laroche, L. Meng, J. Knollenberg, S. Seeger, *ACS Nano*, 2025, 19, 38395.
- [13] C. Ren, Z. Wei, J. Wang, C. Cai, B. Cai, Z. Wang, H. Lei, *Nano Energy*, 2025, 141, 111076.

A separate response letter

Firstly, thank you for the editors' attention to our article, and we appreciate the insightful comments from the reviewers on our manuscript. We fully understand and accept these comments. Accordingly, we have revised the manuscript in detail based on the reviewers' feedback as follows. We hope the improved paper meets the reviewers' standards.

Remark: The deletions and additions in the annotated copy of the manuscript are in red in response to reviewers #2, #3 and #5.

Reviewer: 2

Comments: The authors have conducted extensive additional experiments and provided a thorough review of the relevant literature. Their efforts have largely resolved the technical issues I raised, which is highly appreciated. However, there are still issues that remain unsolved, especially the overall theme and innovation of the current work (i.e., the first two major issues).

Comment 1: The manuscript would benefit from a clearer articulation of the scientific gap and a more tightly aligned statement of novelty. At present, there appears to be an inconsistency between the authors' response—where the brittleness of traditional aerogel fibers is described as largely resolved—and the revised abstract and introduction, which continue to position the work as addressing intrinsic fragility. Clarifying this point would help sharpen the central contribution and ensure that the claimed innovation—a simple strategy for enhancing mechanical robustness—is grounded in a well-defined problem statement.

In supporting the discussion of brittleness, references [19–24] are cited; however, a closer reading of these works suggests several points that may merit reconsideration for accuracy and clarity. First, aerogel fibers and fibrous aerogels represent structurally distinct classes of materials and should not be used interchangeably, as appears to occur in Refs. [19, 21, 22]. Second, aramid aerogel fibers reported in Refs. [20, 24] demonstrate notable flexibility rather than brittleness, which contrasts with the current characterization. Third, while conventional ceramic aerogels are indeed brittle, ceramic nanofibrous aerogels (Ref. [23]) have been shown to exhibit remarkable super-elasticity, an important nuance that could be incorporated to provide a more balanced perspective. Addressing these points would substantially strengthen the manuscript by improving conceptual precision, reinforcing the validity of the cited literature, and clarifying the true scope and novelty of the work.

Reply: Thank you for the insightful comments. We have revised the expression from “brittleness of aerogel fibers” to “mechanical strength of aerogel fibers” throughout the manuscript. In the abstract, we have revised the wording to: “However, the porous structure of aerogel fibers significantly weakens their mechanical strength, thereby reducing their cooling efficiency.” In the introduction, we adopted the following logical structure: first, we noted that aerogel fibers possess exceptional, tunable optical properties and represent a highly promising radiative cooling strategy. At the same time, their porous structure severely compromises their mechanical strength, limiting their wearability and practical application. Therefore, the scientific problem addressed in this work is “developing aerogel fibers that combine excellent mechanical performance with superior cooling capability through a simple structural design.” Specifically, we have revised the text to: “Benefiting from their exceptional tunable optical properties, aerogel fibers represent a novel radiative cooling strategy.^[19–22] However, their porous structure substantially degrades their mechanical strength, limiting their wearability and real-world utility.^[23,24]” Furthermore, regarding the terminological distinction you highlighted, we have fully resolved the issue in the revised manuscript by replacing the relevant references, ensuring

that the concepts of “aerogel fiber” and “fibrous aerogel” are no longer conflated. The newly cited references [19–24] are closely aligned with their respective supporting points, thereby ensuring the accuracy and rigor of the discussion. After these adjustments, the conceptual precision, appropriateness to the literature, and clarity of the novelty have been significantly improved. Thank you again for your valuable corrections.

Comment 2: The authors present comparisons of skin temperature reduction using the aerogel fiber fabric relative to bare skin, cotton, and GP-BCAF. While these comparisons are informative at a phenomenological level, the underlying heat transfer mechanisms within the coupled human–fabric–environment system remain insufficiently resolved. In particular, the manuscript would benefit from establishing a clear functional framework that links radiative cooling (arising from spectral selectivity) with thermal insulation (governing conductive and convective heat transport), and from quantifying the relative contributions of each pathway in determining the net heat flux from the skin to the ambient environment. At present, the specific role of the aerogel fiber’s thermal insulation in the overall heat transfer process is not clearly delineated. This raises an important conceptual question regarding material selection: what is the mechanistic rationale for employing a thermally insulating aerogel fiber in a radiative cooling textile? In principle, a highly effective insulating layer suppresses heat transfer between the skin and the fabric’s surface, potentially decoupling the radiative exchange at the outer interface from the thermal state of the skin. Reconciling this apparent tension—between minimizing heat conduction and enabling effective heat dissipation—would significantly strengthen the theoretical foundation of the work.

Reply: Thanks for your question and suggestion. To quantitatively elucidate the relative contributions of each heat-transfer pathway in the coupled skin–fabric–environment system, we have conducted a single-parameter sensitivity analysis using the method described in the literature (*Nat. Sustain.*, 2023, 6(11), 1446-1454). We independently varied the solar reflectivity (R), infrared emissivity (ϵ), and thermal conductivity (k), and calculated the resulting change in skin temperature (ΔT). The results are shown in Figure S21. The solar reflectivity has the most pronounced effect: increasing R from 0.6 to 0.9 yields a ΔT of 29.8 °C. Increasing ϵ from 0.1 to 0.9 gives a ΔT of 4.3 °C, while increasing k from 0.02 to 0.18 W·m⁻¹·K⁻¹ results in a ΔT of only 2.3 °C. These data clearly demonstrate that under strong solar irradiation, radiative heat exchange, governed by the optical properties (R and ϵ), is the dominant mechanism determining the net heat flux from the skin to the ambient environment, whereas conductive heat transfer through the aerogel fibers plays a synergistic role.

Based on this, we have established a clear functional framework: the fabric's high solar reflectivity (94.7%) and high infrared emissivity (97%) endow it with strong radiative cooling capability, which is the dominant cooling mechanism. Meanwhile, the low thermal conductivity of the aerogel fiber effectively blocks parasitic heat conduction from the external environment to the skin, preventing the low surface temperature established by radiative cooling from being offset by environmental heating. The synergy of these two mechanisms enables efficient outdoor thermal management.

In a high-temperature outdoor scenario with strong solar irradiation (800-1000 W/m²), the environmental heat flux is directed towards the skin. The main heat sources include solar radiation (0.3-2.5 μ m) and long-wave radiation from hot ground and buildings, which strongly heat the outer surface of the fabric (*Science*, 2024, 384, 1203-1212). The low thermal conductivity of the aerogel fiber can effectively minimize the transfer of environmental heat to the human body (*ACS Nano*, 2025, 19, 44, 38395-38407). Meanwhile, the fabric’s high solar reflectivity reflects most of the incoming solar radiation, effectively lowering the outer surface temperature, while its high infrared emissivity

in the 8-13 μm atmospheric window efficiently dissipates heat to outer space. Therefore, the core mechanistic rationale for employing a thermally insulating aerogel fiber in a radiative cooling textile is to minimize the penetration of external heat through the insulation layer, thereby reducing the net heat load on the human body. In this work, the thermally insulating aerogel fiber works synergistically with the radiative cooling mechanism, significantly improving human thermal comfort. Several recent high-impact studies have also explicitly highlighted that the synergistic design of radiative cooling and thermal insulation can significantly enhance thermal management efficiency under high-temperature conditions (*Small*, 2026, 22(20), e14581; *Adv. Mater.*, 2025, 37(35), 2505224; *Nano Energy*, 2025, 136, 110688; *Small*, 2025, 21(7), 2409873). We thank the reviewer again for the valuable suggestions, which have helped us further improve the manuscript regarding key indicators in textile evaluation. We have added more descriptions to the manuscript (lines 3-8, page 9; the Results and Discussion section) and added Figure S21 to the Supporting Information file.

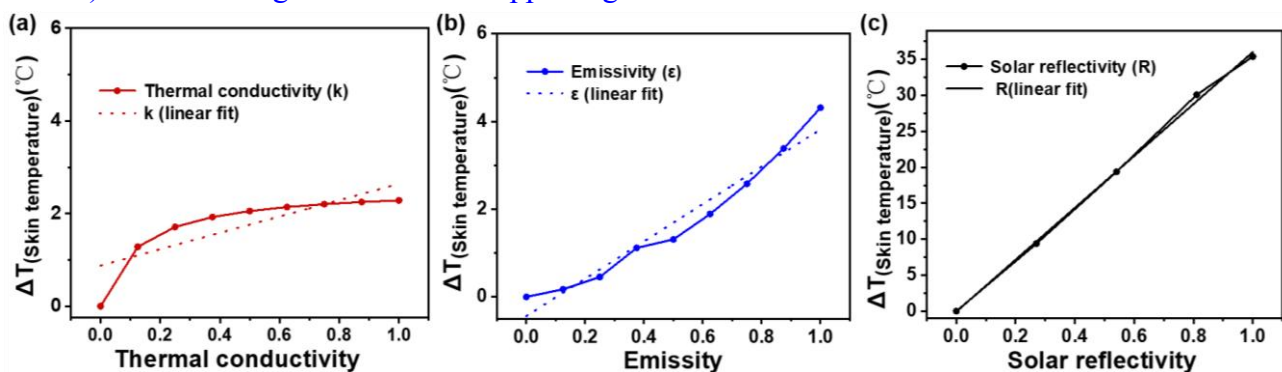


Figure S21. Simulated skin temperature change as a function of (a) thermal conductivity, (b) infrared emissivity, and (c) solar reflectivity of the GP-BCAF textile.

Comment 3: More detailed experimental information, for example, the raw material manufacturers and preparation details, is required for readers to better understand the reported technique. Additionally, please specify whether the material shown in Figure S3 is polyethylene glycol (PEG) or polyvinyl alcohol (PVA).

Reply: Thank you for your careful review. We have supplemented the Experimental section of the revised manuscript with more detailed information on the preparation of the main raw materials, including manufacturers, purity specifications, and pretreatment methods (e.g., bacterial cellulose, sodium alginate, polyvinyl alcohol, calcium chloride). We have also confirmed that the polymer shown in Figure S3 is polyvinyl alcohol (PVA) and have clearly indicated this in the Experimental section. Thank you again for your valuable suggestion, which has clarified our experimental methods. A detailed description has been added to the revised manuscript (lines 6-12, page 14, Experimental section).

Comment 4: In the textile industry, materials exhibiting hydrostatic pressure below 20 kPa are not considered to possess excellent waterproof properties. According to GB/T 4744-2013 (Textiles – Testing and evaluation for water resistance – Hydrostatic pressure method), a hydrostatic pressure value of 35–50 kPa is classified as “excellent water resistance” (Level 4), while 20–35 kPa is only classified as “good water resistance” (Level 3).

Reply: Thank you for your rigorous correction regarding the classification of fabric hydrostatic pressure. According to the national standard GB/T 4744-2013 (Textiles-Testing and evaluation for water resistance – Hydrostatic pressure method), hydrostatic pressure values are classified as follows: 35–50 kPa as “excellent water resistance” (Level 4), 20–35 kPa as “good water resistance” (Level 3),

and 13–20 kPa as “water resistance” (Level 2). The hydrostatic pressure of our GP-BCAF fabric is 19.32 kPa, which falls within Level 2, i.e., “water resistance”. Thank you again for your rigorous correction, which has helped us improve the scientific accuracy and normative expression of our manuscript. The corresponding modifications have been made in the revised manuscript (lines 9–11, page 7, Results and Discussion section).

Reviewer: 3

Comments: The authors have credibly addressed all points raised by the reviewers. Just one comment: monovalent ions do not cross-link carboxylates. You use this term for the monovalent ions in the response letter, but it requires no revisions as the terms are correct in the actual revised manuscript.

Reply: Thank you very much for your careful correction and understanding. Monovalent ions (such as Na^+ and K^+) cannot cross-link carboxylate groups ($-\text{COO}^-$). We have reconfirmed that, in the revised manuscript, the term “cross-linking” is used only to describe divalent ions (such as Ca^{2+} , Mg^{2+} , Ba^{2+}). Thank you again for your attention to terminological accuracy, which helps us further improve the rigour of our academic expression.

Reviewer:5

Comments: The authors have addressed all my comments. Nevertheless, I would like to suggest a more balanced representation in the literature review. Currently, the citations are almost exclusively restricted to Chinese researchers, and diversifying the references with international studies would better reflect the global state-of-the-art and strengthen the paper’s theoretical framework.

Reply: Thank you for your valuable suggestions. We fully agree that a comprehensive literature review can more accurately reflect the global state of the art in the field and enhance the paper's theoretical depth. In the revised manuscript, we have supplemented the discussion with several representative international research achievements, as you recommended, including:

- [2] M. Lee, G. Kim, Y. Jung, K. R. Pyun, J. Lee, B.-W. Kim, S. H. Ko, *Light Sci. Appl.* 2023, 12(1), 134.
- [3] B. Bhatia, A. Leroy, Y. Shen, L. Zhao, M. Gianello, D. Li, T. Gu, J. Hu, M. Soljačić, E. N. Wang, *Nat. Commun.* 2018, 9(1), 5001.
- [6] D. Hong, Y. J. Lee, O. S. Jeon, I.-S. Lee, S. H. Lee, J. Y. Won, Y. P. Jeon, Y. La, S. Kim, G.-S. Park, Y. J. Yoo, S. Y. Park, *Nat. Commun.* 2024, 15(1), 4457.
- [7] J. P. Bijarniya, J. Sarkar, P. Maiti, *Renew. Sustain. Energy Rev.* 2020, 133, 110263.
- [12] Y. Y. Choi, K. Zhou, H. K. Woo, D. Patel, M. Salauddin, L. Cai, *ACS Materials Lett.* 2024, 6, 10, 4624-4631.
- [13] K. M. F. Hasan, S. Bai, S. Chen, K. Lin, T. Ahmed, J. Chen, A. Pan, Y. Zhu, C. S. Ki Lin, C. Y. Tso, *Cell Rep. Phys. Sci.* 2024, 5(9), 102108.
- [14] S. Ahn, J. Lee, S. Kwak, E. Im, Y. Cho, H. H. Kim, H. Lee, S. Lee, *Small Sci.* 2026, 6(4), e70273.
- [19] J. Xu, K. Chen, A. Maturilli, A. Laroche, L. Meng, J. Knollenberg, S. Seeger, *ACS Nano.* 2025, 19, 44, 38395-38407.

We have updated the reference list accordingly and added a discussion and comparison of these works in the main text. Thank you again for your rigorous guidance and valuable suggestions, which have significantly strengthened the academic integrity of our manuscript.

A separate response letter

Firstly, thank you for the editors' attention to our article, and we appreciate the insightful comments from the reviewers on our manuscript. We fully understand and accept these comments. Accordingly, we have revised the manuscript in detail based on the reviewers' feedback as follows. We hope the improved paper meets the reviewers' standards.

Remark: The deletions and additions in the annotated copy of the manuscript are in red in response to Reviewer #7.

Reviewer: 7

Comments: The revised manuscript has addressed many of the comments from Reviewer 2, though there are several follow-up point on the thermal analysis mentioned in comment 2:

Comment 1: First, not enough information is provided on the thermal modeling in Figure S21 for the reader to evaluate or interpret the results. The citation to the details of the thermal model, and the information about all of the inputs to the model, can be provided in the SI - no information is currently provided.

Reply: Thank you for the insightful comments. We appreciate the reviewer's pointing out the insufficient information regarding the thermal model, and we fully accept this criticism. In the previous revision, we only briefly cited the modeling method from the literature without fully presenting the model equations, boundary conditions, and input parameters. This caused inconvenience for the reviewer's evaluation and understanding and affected the reproducibility of the results. We sincerely apologize for this oversight. In response to the reviewer's suggestion, we have included a detailed description of the thermal model in the Supporting Information, covering the one-dimensional steady-state energy balance equation and all relevant input parameters (Supplementary Text 1, Table 4). The relevant information is now provided in detail in the Supporting Information, as follows:

Supplementary Text 1. Skin surface temperature simulation in outdoor environments

To quantitatively elucidate the relative contributions of each heat-transfer pathway in the coupled skin–fabric–environment system, we have conducted a single-parameter sensitivity analysis following the method described in the literature (*Nat. Sustain.*, 2023, 6(11), 1446-1454). The model includes four heat-transfer interfaces: the skin surface, the inner surface of the textile, the outer surface of the textile, and the atmospheric environment. It comprehensively accounts for absorption of solar radiation, infrared radiative heat exchange, heat conduction through the air gap, and natural convection at the outer surface.

Based on the Stefan-Boltzmann law and energy conservation, the energy balance equations for these four interfaces are:

For the air gap between skin and textile:

$$q = \varepsilon_{skin}\sigma(T_{skin}^4 - \varepsilon_{textile-in}T_{textile-in}^4 - \tau\varepsilon_{atm}T_{amb}^4) + \kappa_{air}\frac{T_{skin} - T_{textile-in}}{d_{air}} - \gamma P_{sun}$$
$$\gamma = \frac{\tau_{sun}(1 - \rho_{skin,sun})}{1 - \rho_{skin,sun}\rho_{sun}}$$

For the outer surface of the textile:

$$q = \varepsilon_{skin}\sigma(\tau T_{skin}^4 + \alpha T_{textile-in}^4 + \varepsilon/\varepsilon_1 T_{textile-out}^4 + \beta\varepsilon_{atm}T_{amb}^4) + h_{non}(T_{textile-out} - T_{amb}) - \eta P_{sun}$$

$$\eta = [(1 - \rho_{sun})] - \frac{\tau_{sun}^2 \rho_{skin,sun}}{1 - \rho_{skin,sun} \rho_{sun}}$$

For the inner surface of the textile:

$$T_{textile-out} = \frac{d_{textile}}{2\kappa_{textile}} \left\{ \varepsilon\sigma(T_{textile-in}^4 + \varepsilon\sigma T_{textile-out}^4 - \tau\sigma T_{skin}^4 - \beta\sigma T_{amb}^4) \right. \\ \left. - \left[(1 - \rho_{sun}) - \frac{\tau_{sun}^2 \rho_{skin,sun} + \tau_{sun}(1 - \rho_{skin,sun})}{1 - \rho_{skin,sun} \rho_{sun}} \right] q_{sun} \right\} \\ - \frac{\kappa_{air} d_{textile}}{\kappa_{textile} d_{air}} (T_{skin} - T_{textile-in}) + T_{textile-in}$$

Table 4. Input parameters for the skin-fabric-environment heat transfer model.

Symbol/Unit	Definition	Value
$T_{amb}/^{\circ}\text{C}$	Ambient air temperature	303.15 K
$\kappa/(\text{Wm}^{-1} \text{K}^{-1})$	Thermal conductivity	Air $\kappa_{air} = 0.03$; Textile $\kappa_{textile} = 0.02$
d/m	Thickness	Air gap: $d_{air} = 1 \times 10^{-3}$; Textile: $d_{textile} = 5 \times 10^{-4}$
$h_{non}/(\text{Wm}^{-2} \text{K}^{-1})$	Natural convection heat transfer coefficient	3
$q/(\text{Wm}^{-2})$	Metabolic heat flux	70
ε_{skin}	MIR emissivity of skin	0.98
$\sigma/(\text{Wm}^{-2} \text{K}^{-4})$	Stefan-Boltzmann constant	5.67×10^{-8}
$T_{skin}/^{\circ}\text{C}$	Skin/textile inner surface/textile outer surface temperature	Unknown
$T_{textile-in}/^{\circ}\text{C}$		
$T_{textile-out}/^{\circ}\text{C}$		
$\rho_{skin-sun}$	Skin solar reflection	0.38
ε_{atm}	Atmospheric absorptivity	0.62
ρ_{sun}	Solar reflectivity	0.9
τ_{sun}	Solar transmissivity	0.1
$\varepsilon_{textile}$	MIR emissivity of textile	0.97
$q_{sun}/(\text{Wm}^{-2})$	Solar irradiation	1000

At a given ambient temperature (T_{amb}), the solar reflectivity, infrared emissivity, and thermal conductivity are varied independently to determine the skin temperature (T_{skin}) and quantify each parameter's influence on it. The model input parameters are summarized in Table 4. Thank you again for your valuable corrections. We have added additional descriptions (Supplementary Text 1) and Table

4 to the Supporting Information file.

Comment 2: Second, is higher or lower thermal conductivity better for reducing skin temperature? The current results are presented ambiguously, so I could not tell whether the insulation is desirable or undesirable for achieving low skin temperature at the given conditions. (I imagine if the surface of the fabric achieves sub-ambient cooling, then high thermal conductivity is better for reduced skin temperature to better pull the metabolic heat generation out of the body; if the surface of the fabric is warmer than ambient due to the solar absorption, then low thermal conductivity is desirable to block the heat flow from the surface into the skin). It may be useful to plot the actual value of the skin temperature itself in Fig. S21 rather than the "skin temperature difference ΔT ," for easier reader interpretation. It would also be useful to plot both the skin temperature and the exposed fabric surface temperature for each condition in Fig. S21- this could be helpful in interpreting the results and supporting the claims. This thermal analysis is important because much of the motivation for using aerogels in the passive radiative cooling relies on the low thermal conductivity, so the reader should be able to understand from the thermal model under what scenario the thermal insulation provided by is useful.

Reply: Thanks for your question and suggestion. When there are no significant external heat sources and the fabric surface temperature is below ambient, a high thermal conductivity more effectively lowers skin temperature. In these situations, heat transfers from the skin to the cooler surroundings. A fabric with higher thermal conductivity facilitates the transfer of heat to its outer surface (*Science*, 2016, 353, 1019-1023).

In outdoor situations with intense external heat sources, such as direct sunlight and radiation from the ground and nearby buildings, a lower thermal conductivity helps reduce skin temperature. When the fabric surface is warmed by solar radiation and long-wave radiation from the ground to a temperature exceeding ambient, heat transfers to the skin. A material with low thermal conductivity prevents heat transfer to the skin via conduction and convection, thus avoiding skin heating (*Adv. Mater.*, 2025, 2505224). The fabric simultaneously exhibits high emissivity in the mid-infrared spectrum and strong reflectivity of solar light. It cools the body by preventing external heat from entering while allowing it to lose heat through radiation. This explains the main reason for using aerogels in passive radiative cooling. The nanoporous structure of aerogels reduces thermal conductivity to nearly that of air, thereby preventing external heat transfer via convection and conduction (*Small*, 2025, 21(7): 2409873; *Adv. Funct. Mater.*, 2025, 2425527). Simultaneously, its adjustable structural optical properties allow for a combination of high solar reflectivity and high infrared emissivity.

We developed a heat-transfer model for human skin under fabric to evaluate the relative contributions of various heat-transfer pathways. We simplified the heat transfer model to a one-dimensional, steady-state approach that accounts for solar radiation absorption, infrared heat exchange, conduction through the air gap, and natural convection at the outer surface. This model was employed to examine how the fabric's optical properties and thermal conductivity affect skin surface cooling at a given ambient temperature. Following the reviewer's recommendation, we updated the vertical axis of Figure S21 to show the actual skin temperature values. Additional data on the fabric's outer-surface temperature under various conditions are provided in the Supporting Information. We appreciate the reviewer's detailed feedback once again.

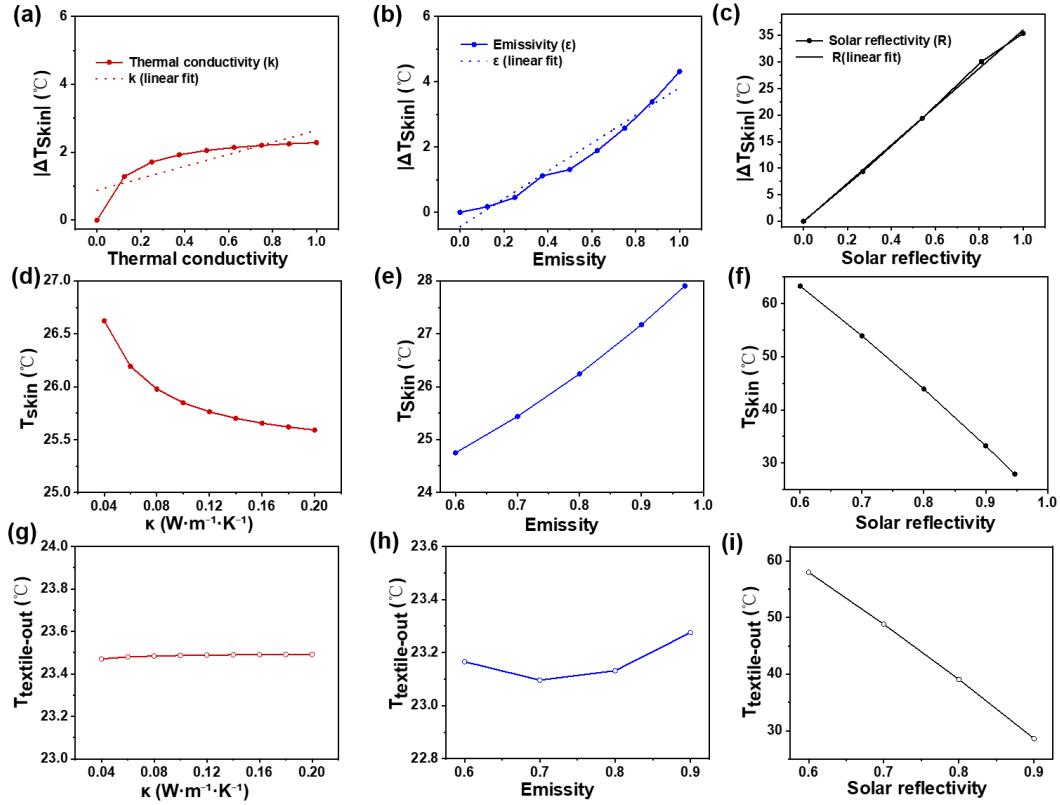


Figure S21. (a-c) Analysis of how skin surface temperature responds to variations in thermal conductivity, solar reflectivity, and emissivity; (d-f) Skin surface temperature across various conditions. (g-i) Textile surface temperature across various conditions.

Comment 3: Does the thermal model include the effect of heat transfer away from the skin via sweating/perspiration? It would seem that this is perhaps an important mode of heat transfer through the porous fabric, given the permeability in Fig. 3a, but it is not mentioned in the thermal modeling of the reference provided (Nat. Sustain., 2023, 6(11), 1446-1454).

Reply: Thank you for your thorough review and helpful comments. Our steady-state heat transfer model does not consider sweating evaporation as a separate parameter. The primary goal of this model is to assess the sensitivity of skin temperature to solar reflectivity, infrared emissivity, and thermal conductivity. The model requires a set of standard input parameters, such as a steady metabolic heat generation rate of 70 W/m^2 , as well as fixed ambient temperature and solar irradiance. The model emphasizes evaluating how optical properties (such as solar reflectivity and mid-infrared emissivity) and thermal conductivity influence the cooling effect on the skin surface.

Adding evaporative cooling would require incorporating numerous additional variables. Factors such as skin wetness, ambient humidity, and fabric moisture resistance are included. Various studies employ distinct test conditions, which may complicate comparing their performance data (*Science*, 2016, 353, 1019-1023; *Nat. Sustain.*, 2023, 6, 1446; *Adv. Mater.*, 2018, 30, 1802152). To emphasize how sensitive these three parameters are to cooling performance, we excluded evaporation and other variables that could interfere from the model. This is because the model emphasizes the relative sensitivity rankings of material parameters instead of providing absolute predictions of skin temperature. We specifically evaluated air permeability and water vapor transmission performance, both of which relate to evaporation. The GP-BCAF fabric demonstrated performance similar to that of traditional cotton fabric. It meets the human body's evaporative cooling requirements. The model

demonstrates the fundamental mechanism, and the experiments confirm its real-world effectiveness. These two approaches complement each other and fulfill different functions.

Integrating evaporative cooling into the heat transfer model could improve the accuracy of skin temperature predictions in various real-world situations. This is an area we intend to explore further. All equations, input parameters, and boundary conditions for the thermal model are thoroughly detailed in the Supporting Information. We thank the reviewer for their detailed and valuable feedback.

A separate response letter

The modeling in Fig. S21(d) shows that higher textile thermal conductivity would be better to reduce the skin temperature. However, I think readers of the main text would come away with the impression that low thermal conductivity is beneficial. I recommend stating clearly in the main text that for the thermal conditions considered in the thermal model of Fig. S21(d), higher thermal conductivity would be better to achieve lower skin temperatures (i.e. the low aerogel thermal conductivity is not necessarily an asset under all conditions).

Thank you for your valuable comment. We have added a clear statement to the discussion section of the Manuscript, “In the simplified thermal model (Figure S21d), higher thermal conductivity helps lower skin temperature. Conversely, under actual outdoor conditions with intense external heat, low thermal conductivity is advantageous because it prevents external heat from reaching the skin.”

Typo in Fig. S21 b,e,h - x axis should be "emissivity" not "emissity".

Thank you for your valuable comment. We have corrected the typo in Figure S21. The figures have been updated in the revised Supporting Information.