

Supplementary Information

Multifunctional Aerogel Fiber Radiative Cooling Fabric for Outdoor Personal Thermal Management

Linan Feng¹, Kangkang Wang¹, Aike Xi¹, Zhenyu Guo¹, Weiyin Su¹, Siming Zhao¹,

Ya Huang¹, Zhuojing Zhao¹, and Rufan Zhang^{1,2 *}

¹Beijing Key Laboratory of Green Chemical Reaction Engineering and Technology,
Department of Chemical Engineering, Tsinghua University, Beijing 100084, China.

²State Key Laboratory of Chemical Engineering and Low-carbon Technology,
Department of Chemical Engineering, Tsinghua University, Beijing 100084, China.

*E-mail: zhangrufan@tsinghua.edu.cn

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^[1]. 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:

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

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:

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

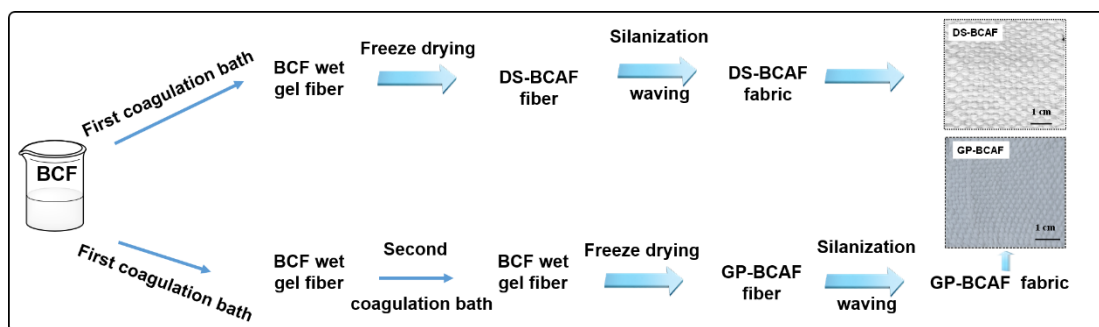


Figure S1. The preparation process of the GP-BCAF and DS-BCAF fabrics. The arrows indicate the sequence of steps from the BCF spinning solution to the final fabrics. The images of the fibers and fabrics are shown in their corresponding colors as labeled.

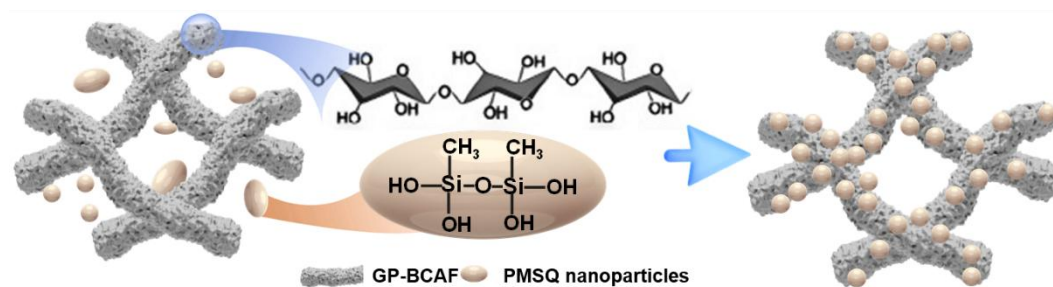


Figure S2. Schematic diagram of the silanization process. Yellow spheres denote PMSQ nanoparticles, and the gray fibers represent the GP-BCAF fibers. After silanization, the PMSQ nanoparticles are grafted onto the fiber.

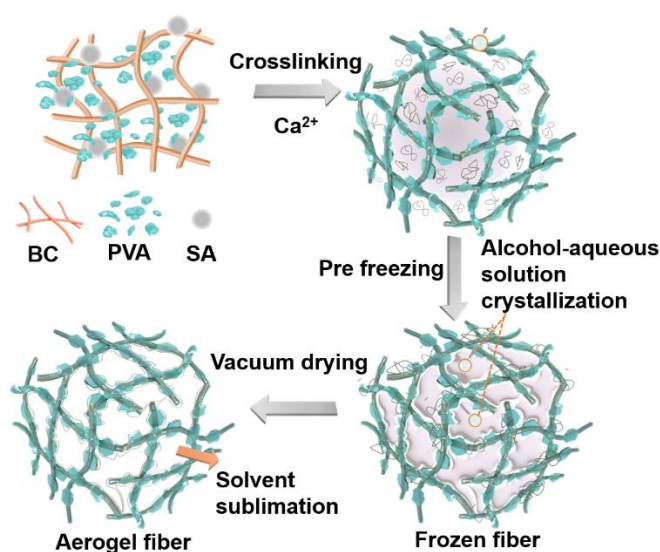


Figure S3. Schematic diagram of the reaction process of the GP-BCAFs and DS-BCAFs, including the BC (orange), PVA (blue), and SA (gray).

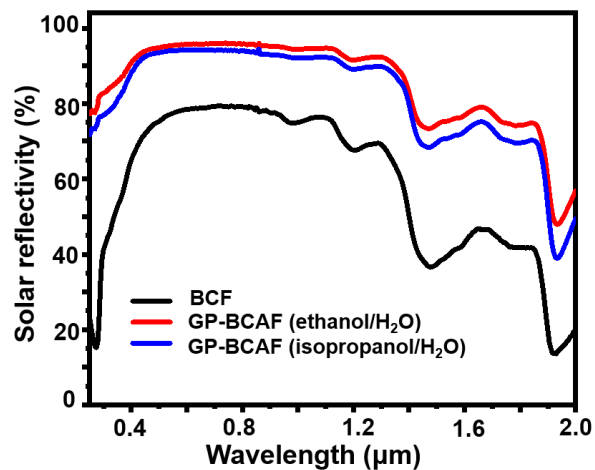


Figure S4. The effect of solidification bath solvent type on solar reflectivity, including the BCF (black line), GP-BCAF (ethanol/H₂O) (red line), and GP-BCAF (isopropanol/H₂O) (blue line).

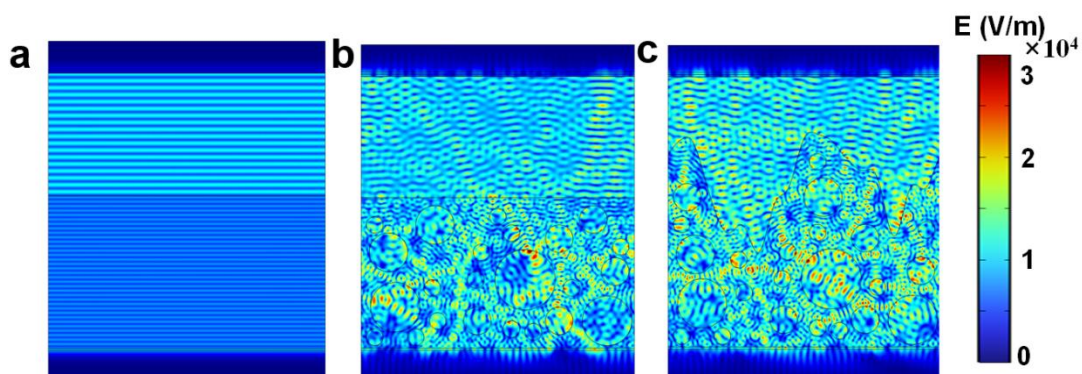


Figure S5. Simulated light scattering field intensity maps. (a) BCF, (b) DS-BCAF, and (c) GP-BCAF fabrics. The incident light wavelength is 500 nm, corresponding to the maximum energy density of solar radiation. E is the electric field intensity of the incident light.

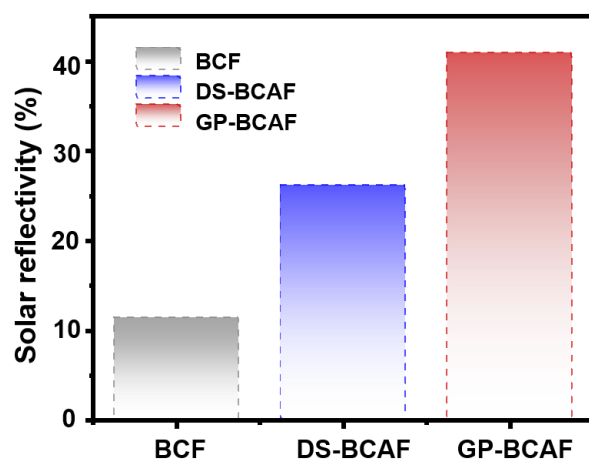


Figure S6. Simulated solar reflectivity of the BCF, DS-BCAF, and GP-BCAF fabrics, including the BCF (gray line), GP-BCAF (red line), and DS-BCAF (blue line).

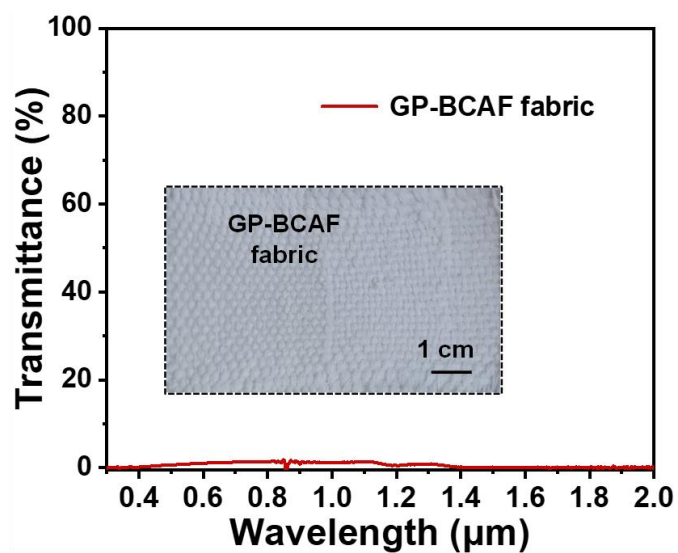


Figure S7. The transmittance of the GP-BCAF fabrics (red line).

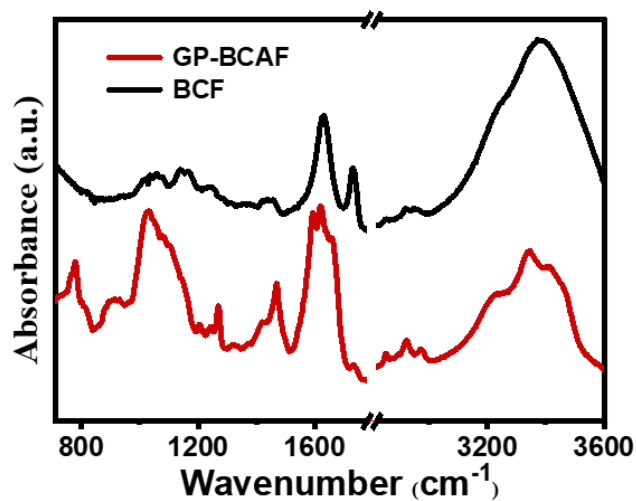


Figure S8. The FTIR-ATR of the BCFs and GP-BCAFs, including the BCF (black line) and GP-BCAF (red line).

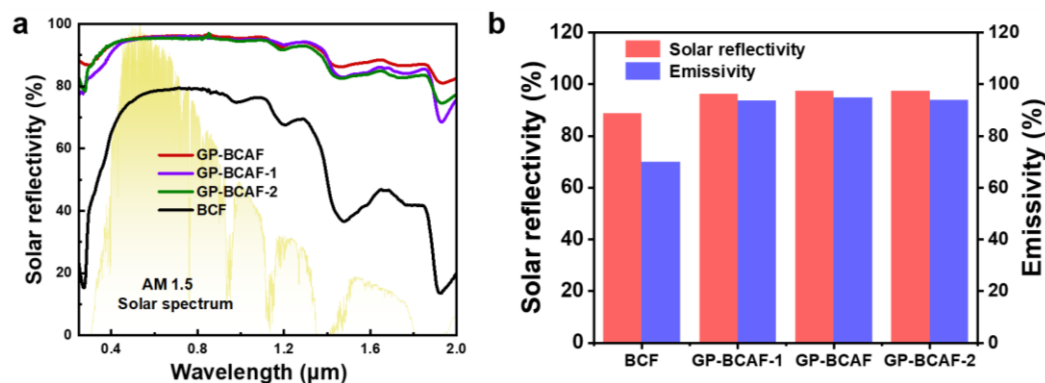


Figure S9. Comparison of reflectivity and emissivity spectra of GP-BCAF, GP-BCAF-1, and GP-BCAF-2 fabrics. (a) Reflectivity, including the BCF (black line), GP-BCAF (red line), GP-BCAF-1 (purple line), and GP-BCAF-2 (green line). (b) Reflectivity and emissivity of different samples; the red bars represent reflectance, and the blue bars represent emissivity.

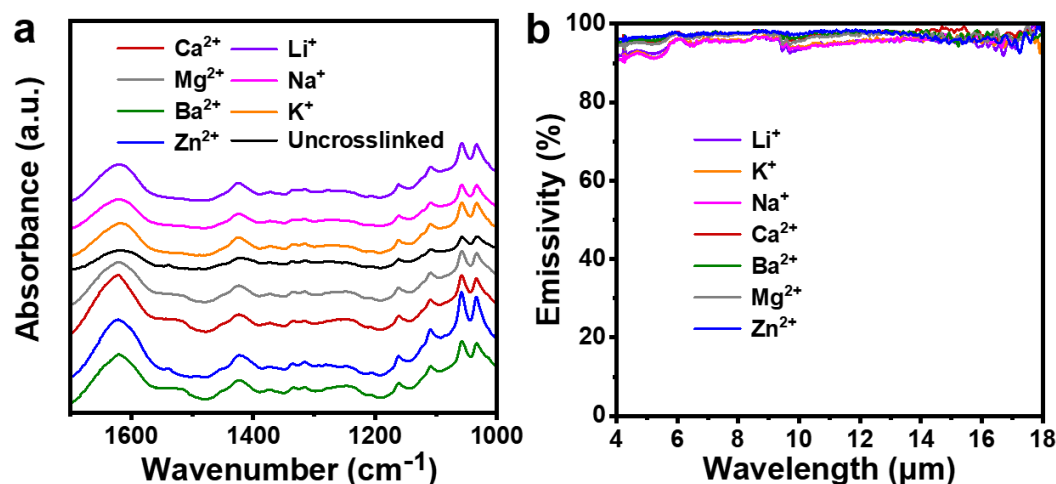


Figure S10. FTIR-ATR spectra and infrared emissivity of GP-BCAFs with different ion crosslinking. The FTIR-ATR (a) and (b) emissivity of the GP-BCAFs across various types of ion crosslinking, including the Ca^{2+} (red line), Mg^{2+} (gray line), Zn^{2+} (blue line), Ba^{2+} (green line), Li^{+} (purple line), Na^{+} (pale purple line), K^{+} (orange line) and uncrosslinked (black).

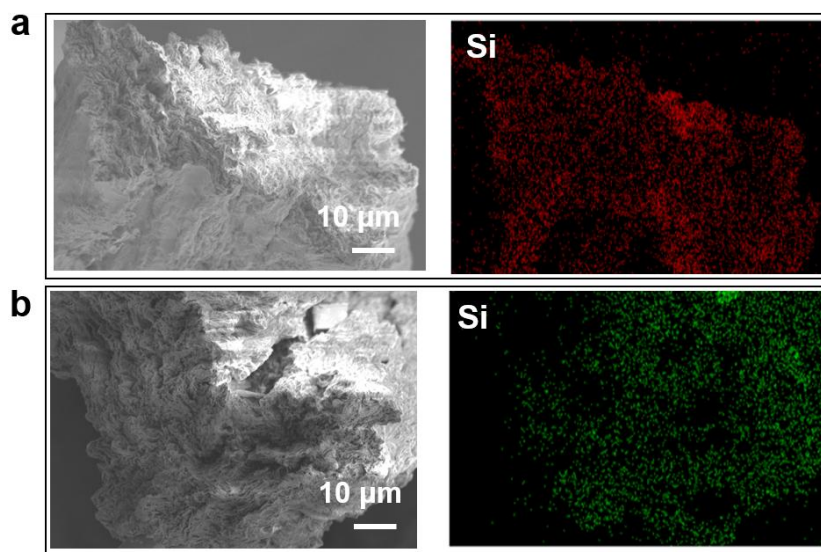


Figure S11. SEM-EDS elemental mapping of GP-BCAF fiber cross-sections. (a) SEM image and corresponding Si elemental mapping of a GP-BCAF fiber cross-section. (b) SEM image and corresponding Si elemental mapping of another GP-BCAF fiber cross-section. Scale bars: 10 μm .

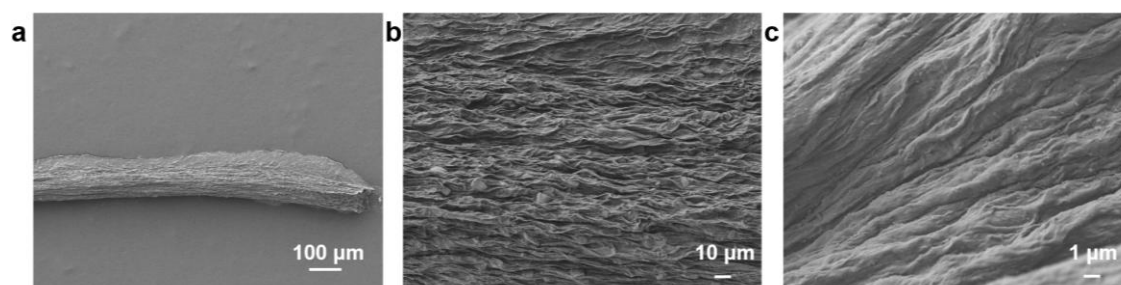


Figure S12. SEM images of the rough shell surface of GP-BCAFs at different magnifications. (a) Low-magnification SEM image showing the overall wrinkled surface morphology. (b) Medium-magnification SEM image revealing the porous wrinkled structure. (c) High-magnification SEM image displaying the detailed micro-wrinkles and nanopores on the shell surface. Scale bars: 100 μm (a), 10 μm (b), 1 μm (c).

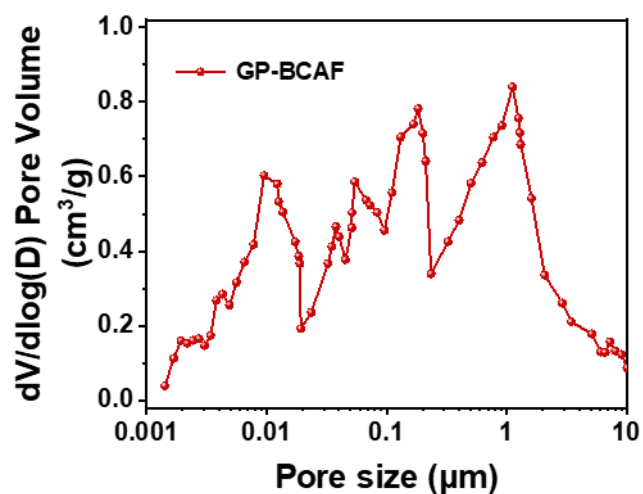


Figure S13. Pore size distribution of the GP-BCAFs.



Figure S14. Optical photograph of the soft GP-BCAFs showing its woven-like structure and high flexibility. The sample is held with gloved fingers, and the scale bar represents 1 cm.

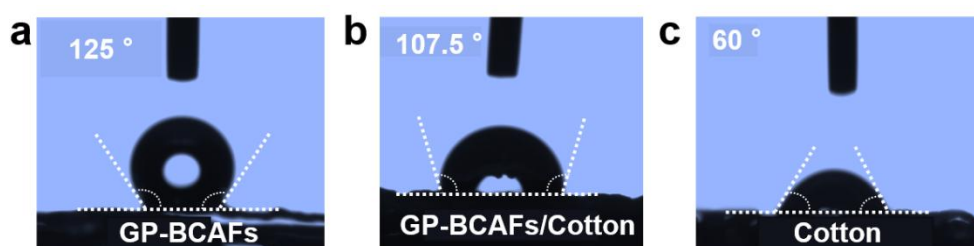


Figure S15. Contact angle measurements of different fabrics. The contact angle of (a) the GP-BCAF fabrics, (b) the GP-BCAF/cotton, and (c) commercial cotton fabrics with water droplets.

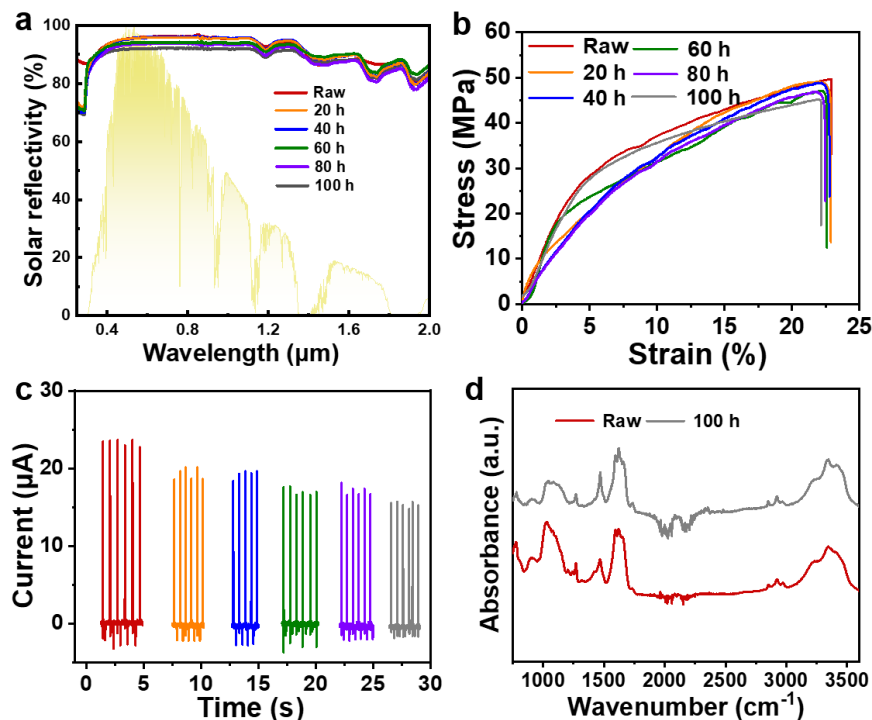


Figure S16. UV resistance and performance retention of GP-BCAF fabric. Comparison of solar reflectivity (a), mechanical properties (b), current output signals (c), including the Raw (red line), 20 h (orange line), 40 h (blue line), 60 h (green line), 80 h (purple line), and 100 h (gray line). (d) FTIR for GP-BCAF fabric before and after the ultraviolet exposure test, including the Raw (red line) and 100 h (gray line).

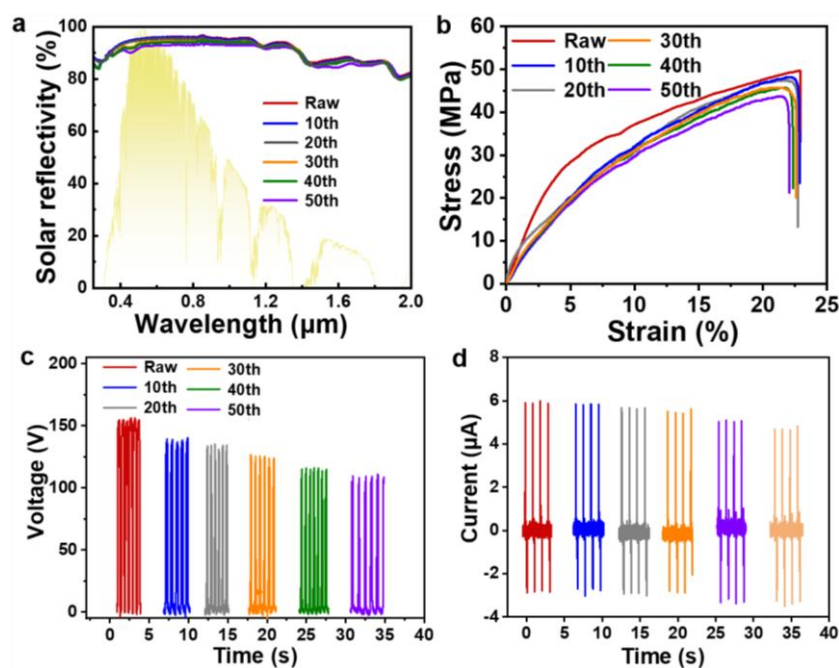


Figure S17. Wash durability and performance retention of GP-BCAF fabric.

Comparison of solar reflectivity(a), mechanical properties(b), voltage (c), and current output(d) signals for GP-BCAF fabric before and after washing, including the Raw (red line), wash 10 times (blue line), wash 20 times (gray line), wash 30 times (orange line), wash 40 times (green line), and wash 50 times (purple line).

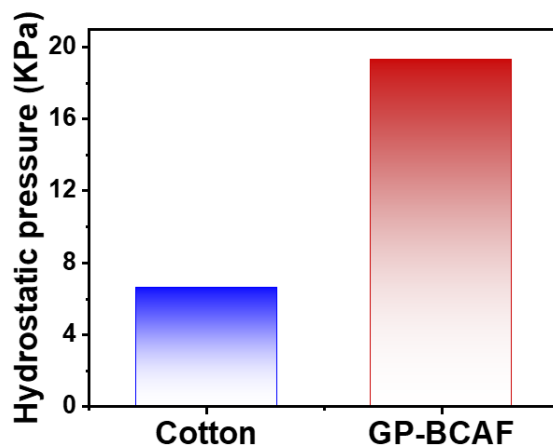


Figure S18. Comparison of the hydrostatic pressure between GP-BCAF and cotton fabrics, including the cotton (blue box) and GP-BCAF (red box).

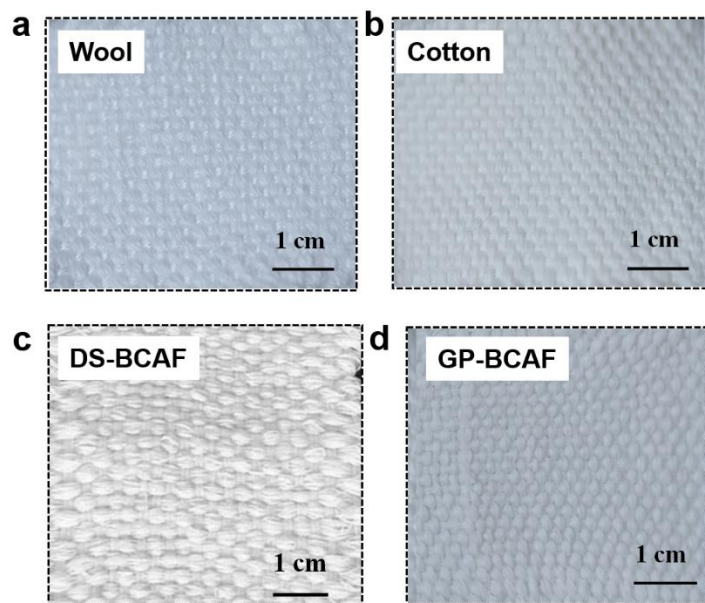


Figure S19. Photographs of four fabrics woven with the same method. (a) wool fabrics, (b) commercial cotton fabrics, (c) the DS-BCAF fabrics, and (d) the GP-BCAF fabrics.

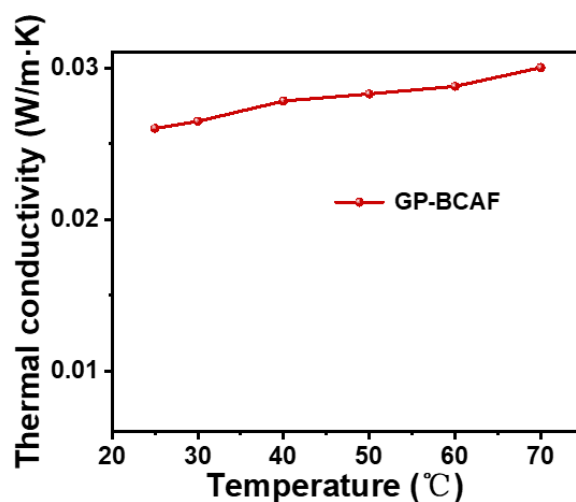


Figure S20. The thermal conductivity of the GP-BCAF.

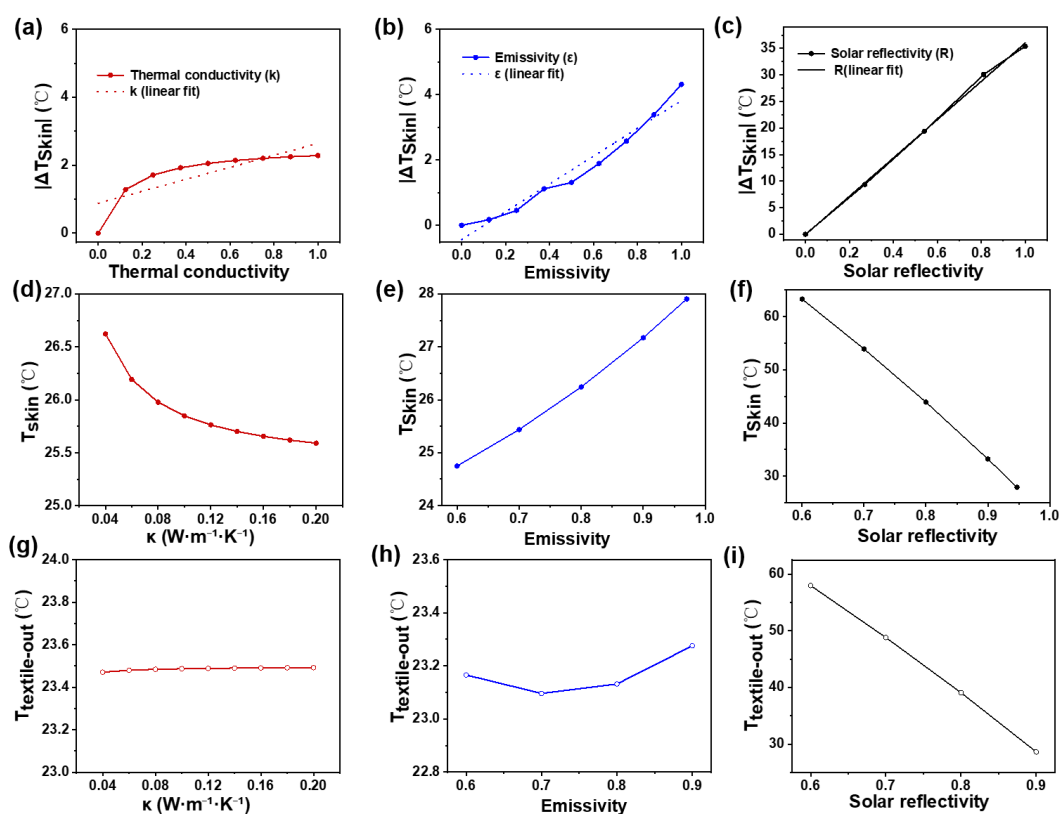


Figure S21. Thermal modeling and parametric sensitivity analysis of skin and textile surface temperatures. (a-c) Analysis of how skin surface temperature responds to variations in thermal conductivity, solar reflectivity, and emissivity; (d-f) Skin surface temperature across various conditions. (g-i) Textile surface temperature across various conditions, including the thermal conductivity (red line), emissivity (blue line), and solar reflectivity (black line).

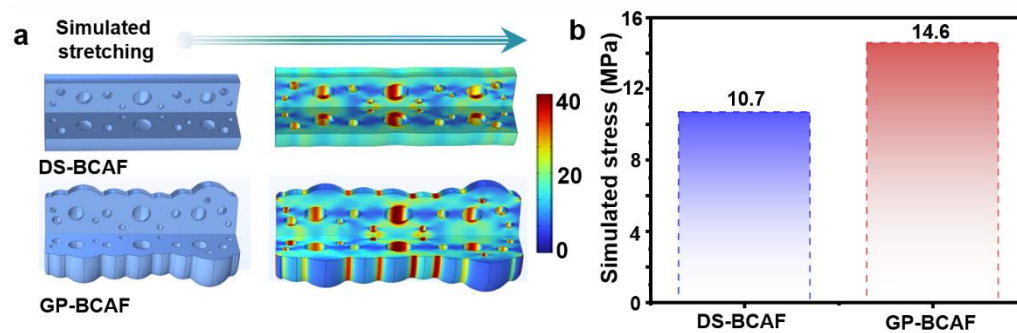


Figure S22. Mechanical simulation and stress analysis of the DS-BCAF and GP-BCAF models. (a) Schematic diagram of internal simulated stretching for the DS-BCAF and GP-BCAF models, along with (b) a comparative stress analysis chart, including the GP-BCAF (red line) and DS-BCAF (blue line).

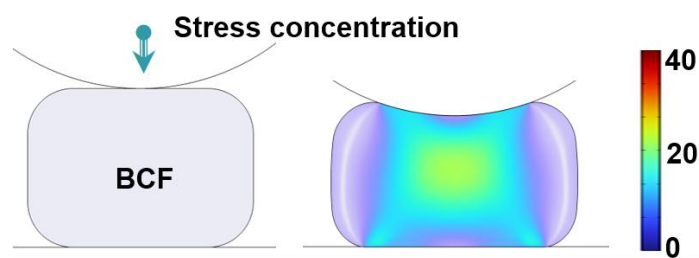


Figure S23. Simulations of the dense BCF under compression.

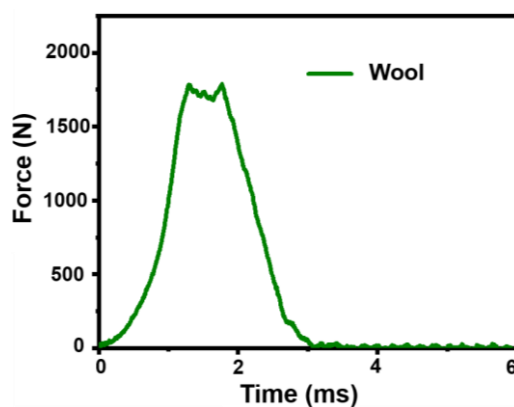


Figure S24. Impact force-time curve of the wool fabrics.

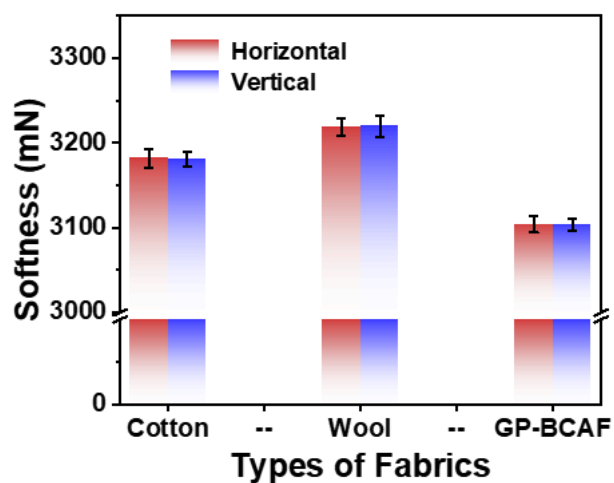


Figure S25. Softness of cotton, wool, and GP-BCAF fabrics. Error bars represent the mean $\pm$ s.d. ($n = 3$ independent measurements), including the horizontal (red line) and vertical (blue line).

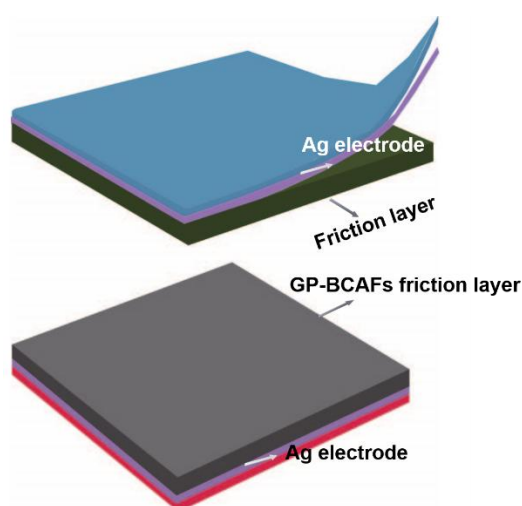


Figure S26. Schematic diagram of the GP-BCAFs-based triboelectric nanogenerator.

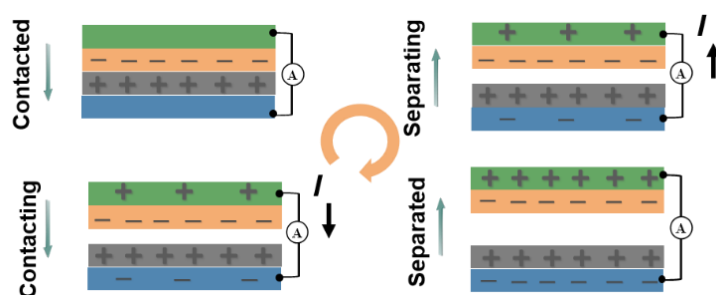


Figure S27. Working mechanism of the GP-BCAFs-based triboelectric nanogenerator,

including orange and gray representing the friction layer; green and blue represent the electrodes.

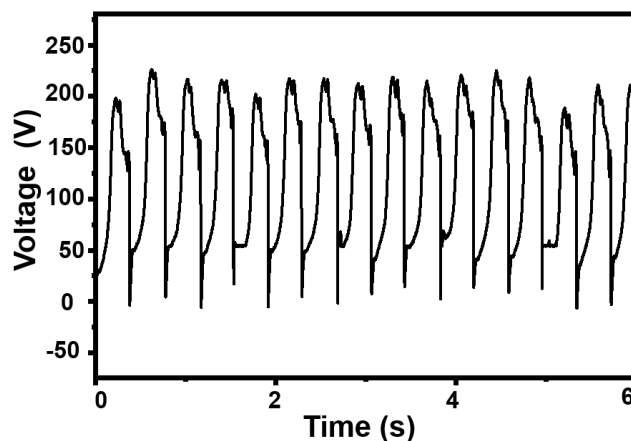


Figure S28. The voltage output signal is generated by clapping hands (a GP-BCAF fabric was placed in the palm).

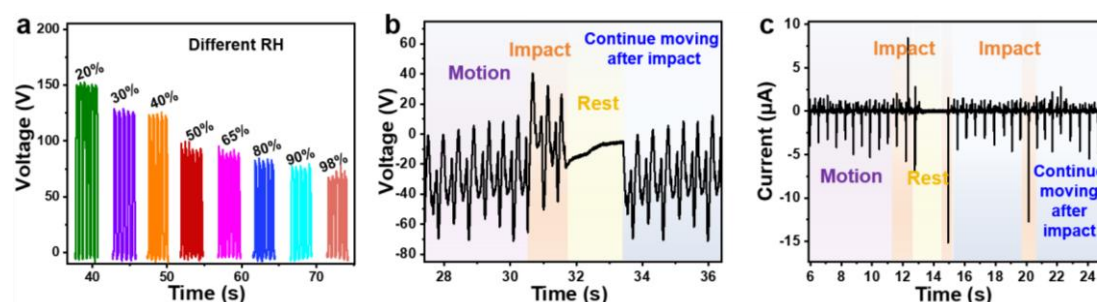


Figure S29. Sensing performance of the GP-BCAF fabric under different humidity and motion states. (a) Voltage output of GP-BCAF at different humidity. (b) Voltage and (c) current output signals corresponding to various movement states (purple (motion), yellow (rest), orange (impact), and blue (continue moving after impact)).

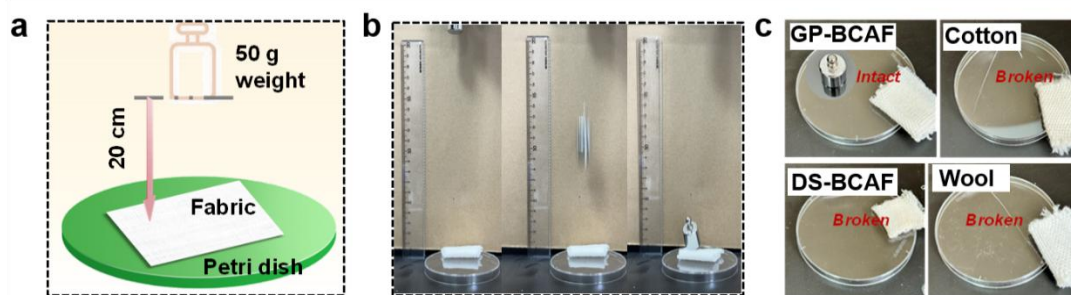


Figure S30. Impact resistance test of the fabrics. (a) A schematic of the 50 g weight-

drop test. (b) Sequential frames capturing the falling weight. (c) A photograph of the weight impacting the fabric-covered Petri dish.

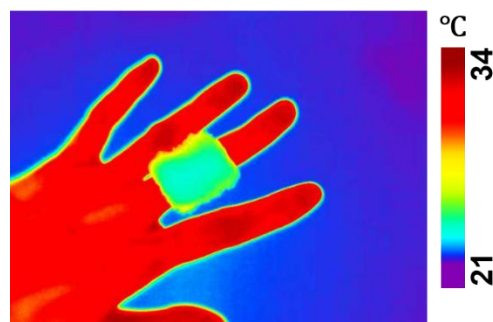


Figure S31. Infrared image of the GP-BCAFs covering a finger in outdoor sunlight.

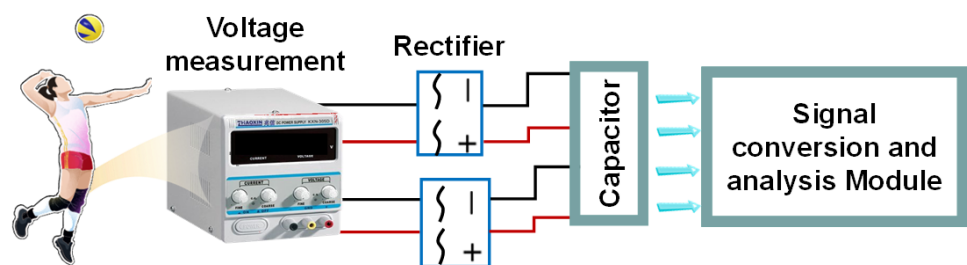


Figure S32. A circuit control schematic of the GP-BCAFs-based sensing system.

Supplementary Table S1. Performance comparison of the GP-BCAFs with other representative aerogel fiber fabrics in the literature.

Material	Solar reflectivity (%)	BET surface area (m ² /g)	Mechanical strength at 15% strain (MPa)	Impact resistance	Sensing	Sustaninability
PBS/PVDF-HFP	92.3	/	1.5	Yes	Yes	No
PMABF	86.7	/	3.4	Yes	No	Yes
HSiO ₂ /C	92	163.2	22.5	No	No	Yes
PFCDM	93.6	/	3	No	No	No
HPPAF	/	222.9	32.3	No	No	No
CMS _x	93	/	0.72	No	No	No

MNFA	/	47.5	0.12	Yes	No	No
PVDF-HFP	94	/	2.4	No	No	No
BC/GO	/	121	11.8	No	Yes	No
CSNA	96.2	632.7	0.15	Yes	No	Yes
GP-BCAFs	94.7	280.2	42	Yes	Yes	Yes

Supplementary 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	[2]
IRT-PA6	7.04	32.6	No	[3]
PE-MSZ	28.1	41.9	No	[4]
RCSF	20.0	9.6	Yes	[5]
HSiO ₂ /C@C)	19.4	17.6	Yes	[6]
PMABF	4.3	18.5	Yes	[7]
SAFs	5.9	400	No	[8]
POM	13.3	300	No	[1]
Meta-fabric	2.4	276	No	[9]
GP-BCAFs	50.0	23	Yes	this work

Supplementary Table 3. Comparison of the specific surface area between GP-BCAF and the 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	[6]
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

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

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

Supplementary Reference:

- [1] 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.
- [2] Y. Zhang, S. Liao, L. Fei, D. Wu, Q. Wang, P. Lv, K. Moth-Poulsen, Q. Wei, Adv. Fiber Mater., 2026, DOI 10.1007/s42765-025-00671-1.
- [3] 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.
- [4] Y. Zhai, J. Li, X. Su, J. Zhao, S. Wei, Z. Pan, C. Jia, M. Wang, M. Zhu, Adv. Funct. Materials., 2025, e29127.
- [5] 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.
- [6] S. Jiang, S. Jiang, J. Yan, C. Lin, W. Wang, S. Jiang, R. Guo, Nano Energy, 2025, 136, 110688.
- [7] X. Li, Z. Guo, Y. Ji, P. Du, J. Wang, B. Xu, F. Ge, Y. Zhao, Z. Cai, Adv. Fiber Mater., 2025, 7, 607.
- [8] Y. Wang, X. Chen, X. Zhang, J. Zang, L. Lu, W. Yuan, Small, 2026, e14581.
- [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. Fiber 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.