# Supporting Information for

## Versatile Nano-micro Collagen Fiber-Based Wearable Electronics for Health Monitoring and Thermal Management

Zhongxue Bai[1,3], Xuechuan Wang[1,2,3,*], Mengchen Huang[1], Manhui Zheng[1,3], Ouyang Yue[1,3], Dongyu Hao[2,3], Yu Wang[2], Xiaoliang Zou[1,3], Boqiang Cui[1,3], Long Xie[1,3], Siyu Zha[2,3], Haiyan Ju[4], Xinhua Liu[1,2,3,*]

[1] College of Bioresources Chemical and Materials Engineering, Shaanxi University of Science & Technology, Xi'an 710021, China.

[2] College of Chemistry and Chemical Engineering, Shaanxi University of Science & Technology, Xi'an, Shaanxi 710021, China.

[3] Institute of Biomass and Functional Materials, Shaanxi University of Science and Technology, Xi'an 710021, China

[4] School of Chemistry and Engineering, Wuhan Textile University, Wuhan 430073, China

[*]Corresponding authors: wangxc@sust.edu.cn (X. Wang); liuxinhua@sust.edu.cn (X. Liu)

# S1. Fabrication of collagen fibers

The strategy for preparing CFs followed traditional leather-processing techniques.[1] The non-collagen components from goat skin were removed via various preparation processes, including washing, degreasing, unhairing, liming, fleshing, splitting, shaving, deliming, bating, pickling, etc. (1) Washing: the fresh skin and a solution containing 100 wt% (based on 4 times the weight of the fresh skin, the same as below) water, 1 wt% sodium hypochlorite, and 0.1 wt% sodium hydroxide were added to the leather drum, which was operated for 12 h at 25℃ to remove dirt from the skin and dissolve partial soluble proteins of the skin. (2) Degreasing: most subcutaneous fat and residual meat were removed using a meat remover. In addition, the skin and a solution comprising 100 wt% water and 4 wt% sodium carbonate were added to the drum, which was operated for 2 h at 38℃ to extract a portion of the skin lipids. (3) Unhairing: the skin and a solution containing 100 wt% water and 1 wt% sodium sulfide were added to the drum, which was operated for 1.5 h at 25℃. After that, 0.09 wt% sodium hydroxide was added, and the drum was operated for 6 h at 25℃ to remove hair from the skin. (4) Liming: the skin and a solution comprising 100 wt% water and 3 wt% calcium hydroxide were added to the drum, which was operated for 18 h at 25℃ to further disperse CFs, remove fibrous stroma, saponify oil, and remove hair and epidermis. (5) Fleshing, splitting, and shaving: the fleshing, splitting, and shaving of the skin were performed using a fleshing machine, splitting machine, and shaving machine, respectively, and the resulting skin had a different thickness. (6) Deliming: the skin and a solution comprising 100 wt% water and 1.0wt% lactic acid were added to the drum, which was operated for 1 h at 30℃ to regulate the swelling state of the skin. (7) Bating: the skin and a solution containing 100 wt% water, 0.15 wt% pancreatin, 0.05 wt% protease, and 0.5 wt% ammonium chloride were added to the drum, which was operated for 1 h at 28℃ to further remove epidermal, hair root, pigment, oil, elastin, myosin, etc., and to disperse CFs. (8) Pickling: the pickling solution was prepared using 100 wt% water and 8 wt% sodium chloride, and its pH was adjusted to 5 using HCl. The skin and the pickling solution were added to the drum, which was operated for 6 h at 25℃, followed by overnight standing for 12 h to ensure sufficient pickling. Therefore, pickling can effectively alter skin's pH and disperse CFs, which is beneficial for the stuffing of functional nanomaterials. (9) Tanning: after adding 1 wt% cationic oil into the pickling solution, the drum was operated for 0.5 h at 25℃. Afterward, 4 wt% chrome tanning liquid was added to the drum, which was operated for 2 h at 25℃. After that, 1 wt% baking soda dissolved in 20 wt% warm water was added to the drum in four batches, 0.5 h apart. The 50 wt% water at 50℃ was added to the drum, which was operated for 2 h at 25 ℃, followed by overnight standing for 12 h to ensure a sufficient multi-point combination of chrome tanning agents and CFs. Subsequently, on the following day, the bath liquor was released, and 300 wt% water was added to the drum, which was operated for 0.5 h at 25℃.

## S2. Fabrication of hydrophobic $SiO_2$ nanoparticles

The hydrophobic $SiO_2$ nanoparticles were prepared based on previous work.[2] First, 1 wt% (based on the weight of ethanol, the same as below) PFDTES was dropwise added to a mixed solution of 10 wt% deionized water, 4 wt% ammonia hydroxide, 2 wt% $SiO_2$ nano-particles, and 100 wt% ethanol, followed by magnetic stirring for 24 h at 40℃. Afterward, the precipitate was recovered by centrifugation at 10,000 rpm for 10 min and then washed three times using ethanol. After centrifugation, the hydrophobic $SiO_2$ nanoparticles (denoted as F-$SiO_2$) were dried under a vacuum at 60℃ for 12 h.

## Supplementary Figures:

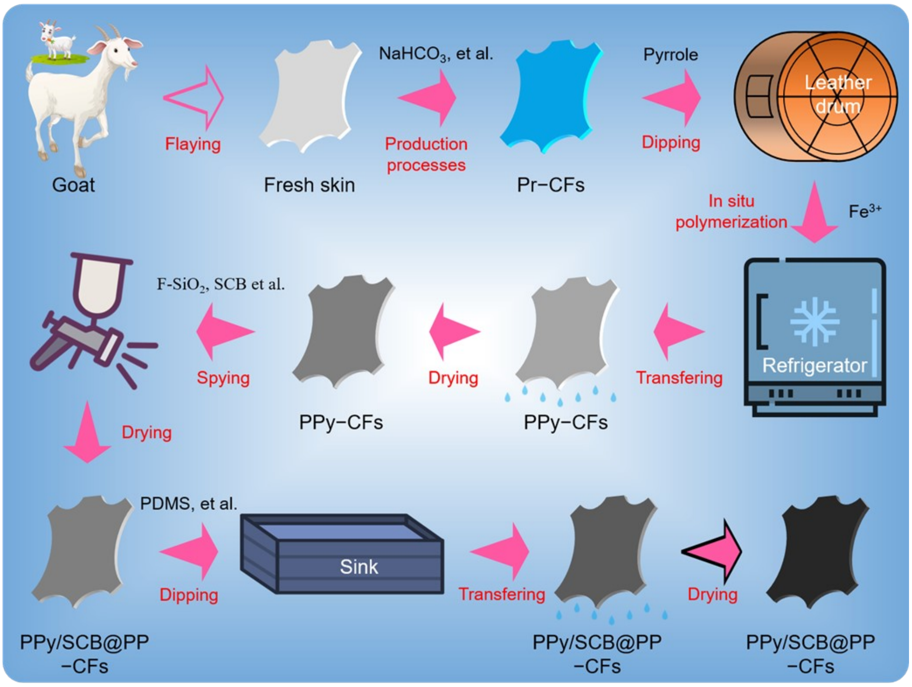


**Fig. S1** Schematic illustration of the preparation of PPy/SCB@PP-CFs.

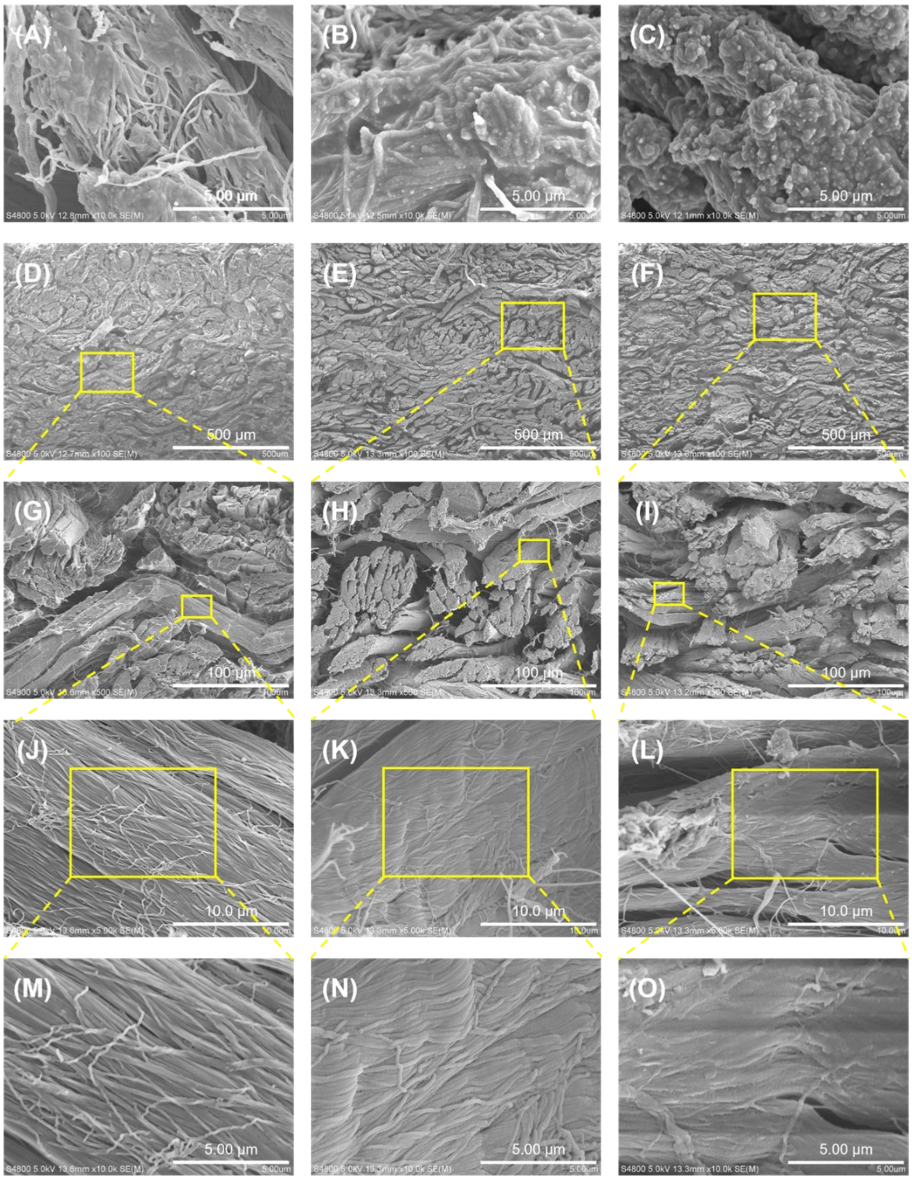


**Fig. S2** SEM images of the surfaces of (A) Pr-CFs, (B) PPy-CFs, and (C) PPy/SCB@PP-CFs, as well as the the cross sections of (D, G, J, M) Pr-CFs, (E, E, K, N) PPy-CFs, and (F, I, L, O) PPy/SCB@PP-CFs.

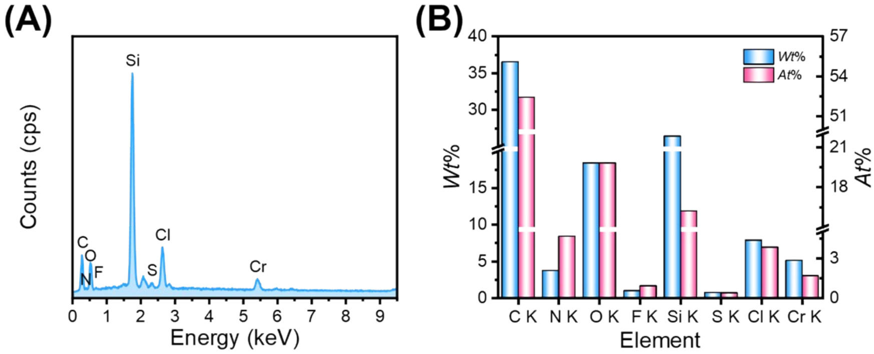


**Fig. S3** The (A) strength and (B) content of different elements on the cross section of PPy/SCB@PP-CFs.

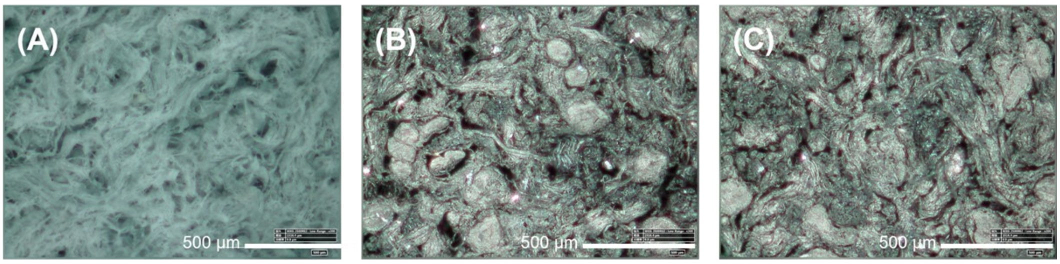


**Fig. S4** Surface morphology of (A) Pr-CFs, (B) PPy-CFs, and (C) PPy/SCB@PP-CFs corresponding to the Ultra-depth microscopic images.

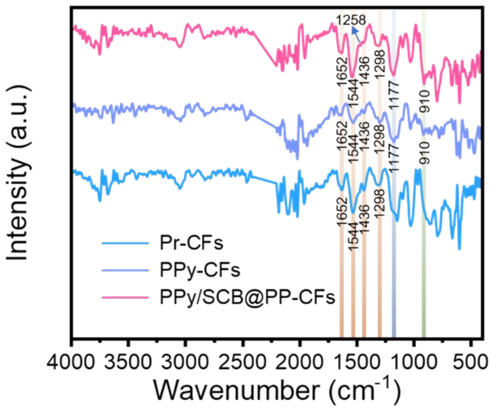


**Fig. S5** FTIR spectra of Pr-CFs, PPy-CFs, and PPy/SCB@PP-CFs.

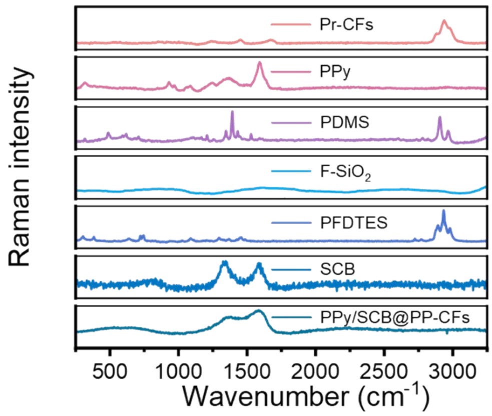


**Fig. S6** Raman spectra of Pr-CFs, PPy, PDMS, F-$SiO_2$, PFDTES, SCB, and PPy/SCB@PP-CFs.

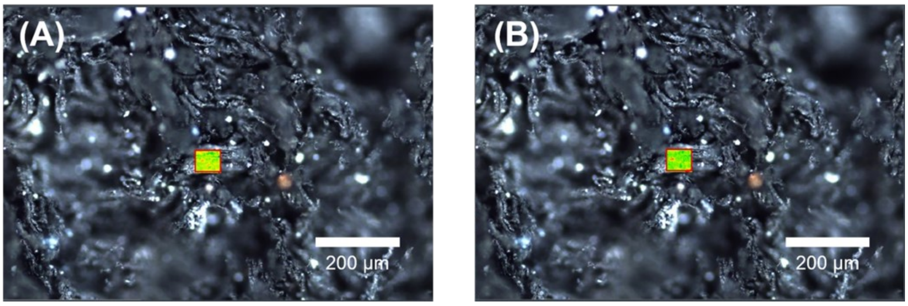


**Fig. S7** The micrographs corresponding to the Raman mapping images of (B) PPy and (C) SCB in PPy/SCB@PP-CFs.

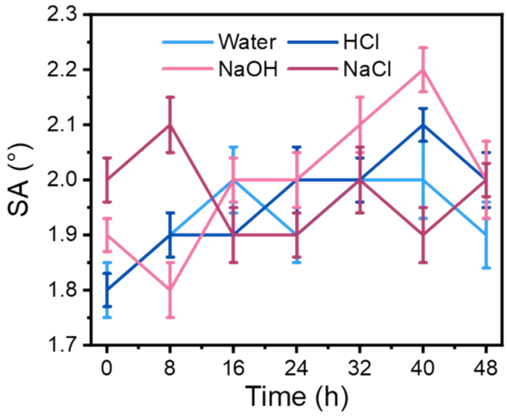


**Fig. S8** The water SAs on PPy/SCB@PP-CFs after immersion in water, 0.1 M HCl, 0.1 M NaOH, and 0.1 M NaCl for 48 h, respectively.

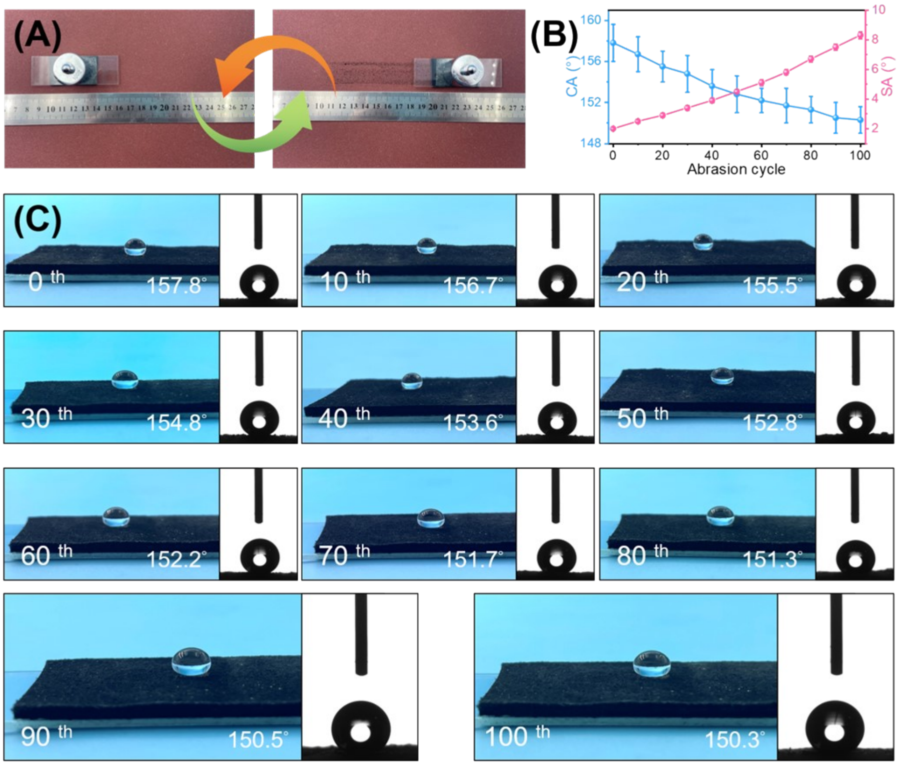


**Fig. S9** (A) Digital pictures of mechanical durability test. (B) CA and SA changes of the water on PPy/SCB@PP-CFs during the mechanical durability test. (C) Digital pictures corresponding to different abrasion cycles.

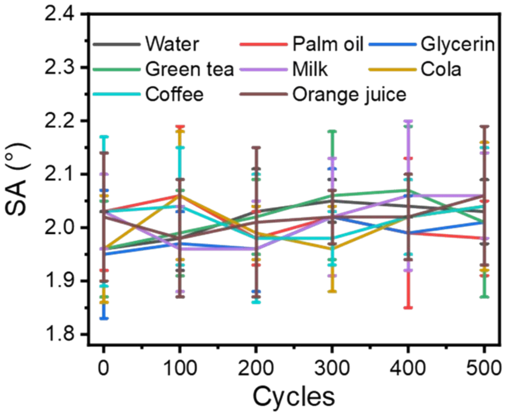


**Fig. S10** SAs of different droplets on the PPy/SCB@PP-CFs during cyclic bending−releasing with the sagitta of 8 mm.

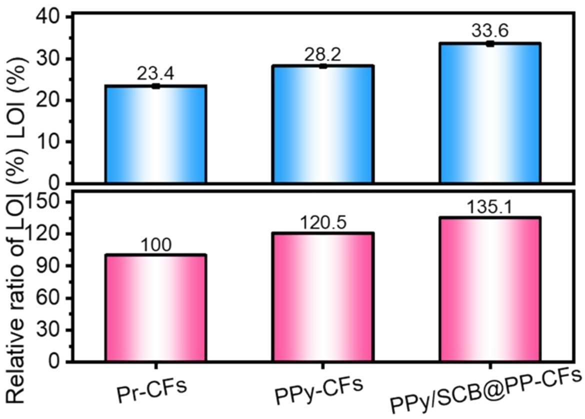


**Fig. S11** LOI values and Relative rations of LOI of Pr-CFs, PPy-CFs, and PPy/SCB@PP-CFs.

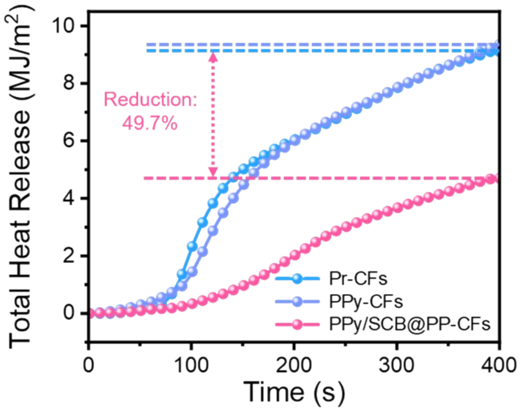


**Fig. S12** Total heat releases of Pr-CFs, PPy-CFs, and PPy/SCB@PP-CFs.

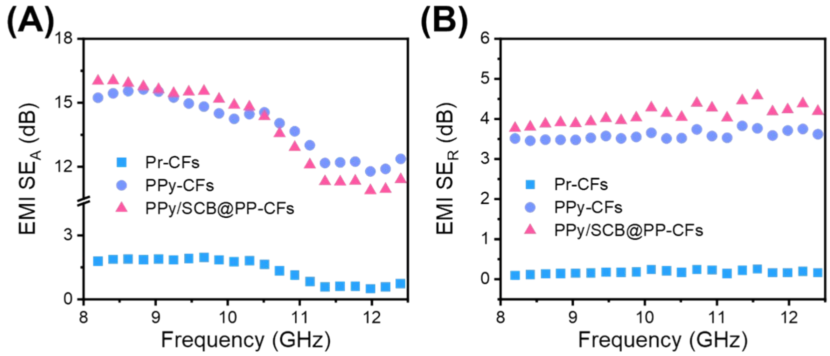


**Fig. S13** EMI $SE_A$ (A) and $SE_R$ (B) of Pr-CFs, PPy-CFs, and PPy/SCB@PP-CFs.

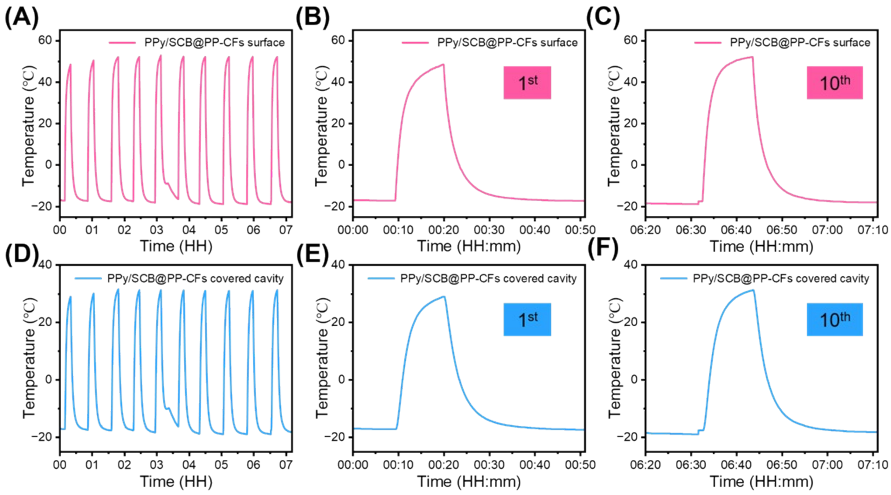


**Fig. S14** The temperature changes of the (A-C) PPy/SCB@PP-CFs surface and (D-F) cavity covered by PPy/SCB@PP-CFs at -20℃ under the Xenon lamp with a power of 1000 W·m$^{-2}$. The (A, D) 10 heating-cooling cycles, as well as the (B, E) 1$^{st}$ and (C, F) 10$^{th}$ heating-cooling cycle.

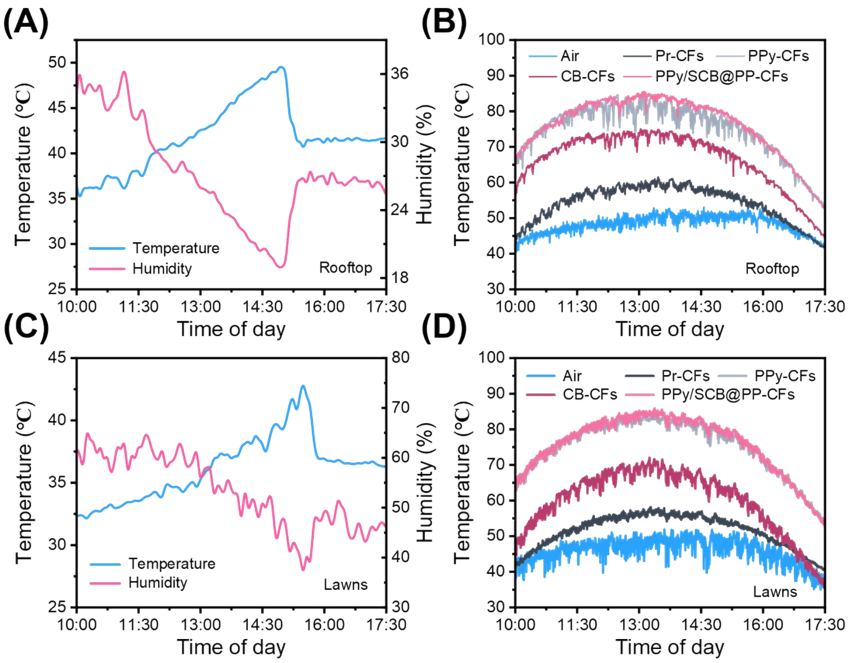


**Fig. S15** The temperature and humidity of (A) roofs and (C) grass. The surface temperature changes of Pr-CFs, PPy-CFs, PPy/SCB@PP-CFs, and CB-CFs, as well as the temperature changes of the air in PE films, on (B) roofs and (D) grass.

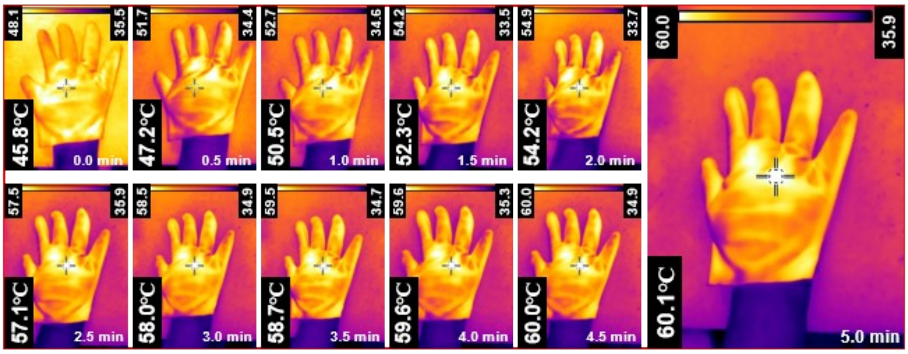

**Fig. S16** The thermal IR images of the glove made by PPy/SC@PP-CFs under direct sunlight.


**Fig. S17** Digital pictures of the (A and C) white and (B and D) black T-shirt modified by PPy/SCB@PP-CFs: (A and B) front, (C and D) back.

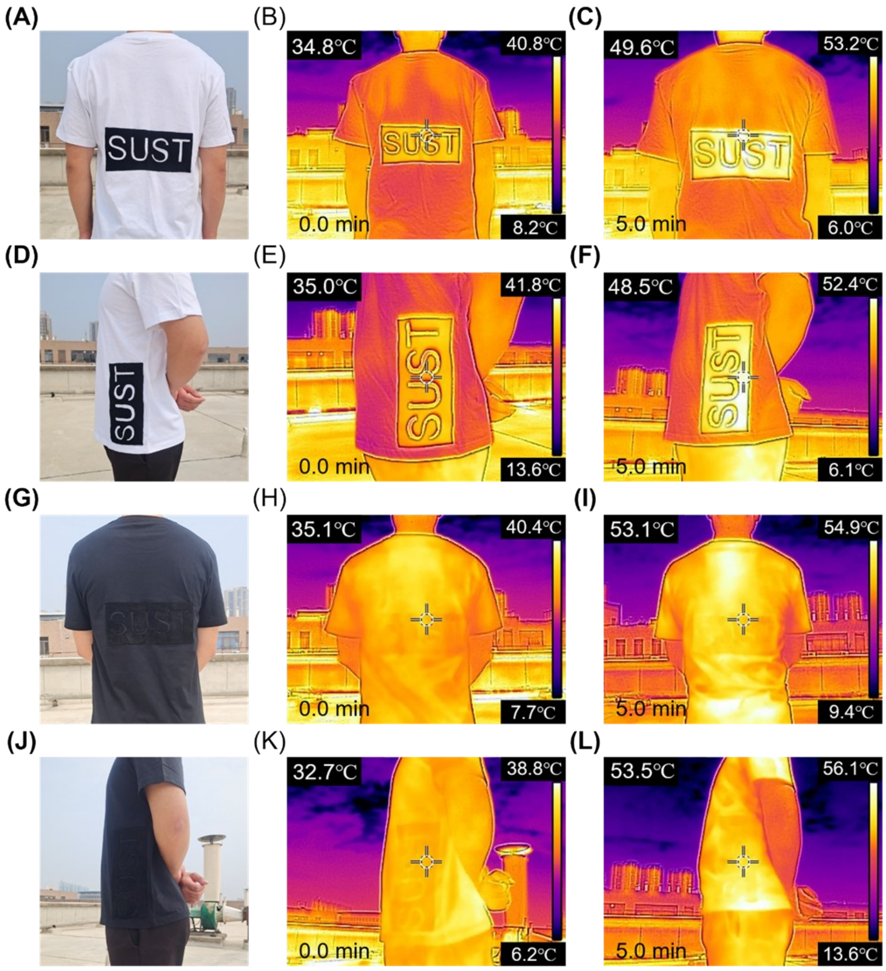


**Fig. S18** Digital pictures and thermal IR images of the white and black T-shirt modified by PPy/SCB@PP-CFs.

# Supplementary Tables:

**Table S1** The effect of F-$SiO_2$ usage on the superhydrophobicity and anti-abrasion property of PPy/SCB@PP-CFs.

| Dosage | CA (°) | SA (°) | Anti-abrasion property |
|---|---|---|---|
| 0.2 wt% | 147.2 ± 1.4 | 8.43 ± 0.22 | Good |
| 0.3 wt% | 150.5 ± 1.5 | 4.12 ± 0.20 | Good |
| 0.4 wt% | 156.6 ± 2.1 | 1.84 ± 0.17 | Good |
| 0.5 wt% | 162.1 ± 1.6 | 1.79 ± 0.13 | General |
| 0.6 wt% | 164.6 ± 2.0 | 1.73 ± 0.09 | Not good |

**Table S2** The effect of PFDTES usage on the super-amphiphobic property, anti-abrasion property, as well as air and moisture permeabilities of PPy/SCB@PP-CFs.

| Dosage | CA (°) | SA (°) | Air permeability (mL/(cm$^2$·h)) | Moisture permeability (mg/(10 cm$^2$·24 h)) | Anti-abrasion property |
|---|---|---|---|---|---|
| 0.2 wt% | 148.6 ± 1.5 | 8.55 ± 0.23 | 40.5 ± 2.2 | 353.5 ± 5.7 | Not good |
| | 146.5± 1.4 | 9.39 ± 0.20 | | | |
| 0.3 wt% | 150.2 ± 1.7 | 3.94 ± 0.21 | 38.2 ± 2.3 | 338.2 ± 6.1 | General |
| | 148.6 ± 1.5 | 4.52± 0.18 | | | |
| 0.4 wt% | 156.6 ± 2.1 | 1.84 ± 0.17 | 35.8 ± 2.7 | 324.7 ± 5.3 | Good |
| | 154.3 ± 1.5 | 2.63 ± 0.11 | | | |
| 0.5 wt% | 161.1 ± 1.9 | 1.80 ± 0.10 | 32.7 ± 2.9 | 302.2 ± 4.8 | Good |
| | 157.3 ± 1.6 | 2.31± 0.08 | | | |
| 0.6 wt% | 163.3 ± 2.1 | 1.76 ± 0.08 | 30.3 ± 2.8 | 287.4 ± 4.6 | Good |
| | 159.6 ± 1.8 | 2.12 ± 0.10 | | | |

The blue and orange backgrounds represent CAs and SAs of water and palm oil on PPy/SCB@PP-CFs, respectively.

**Table S3** The effect of PDMS usage on the superhydrophobicity and anti-abrasion property of PPy/SCB@PP-CFs.

| Dosage | CA (°) | SA (°) | Anti-abrasion property |
|---|---|---|---|
| 0.2 wt% | 147.6 ± 1.5 | 8.32 ± 0.22 | Not good |
| 0.3 wt% | 151.4 ± 1.3 | 3.77 ± 0.20 | General |
| 0.4 wt% | 156.6 ± 2.1 | 1.84 ± 0.17 | Good |
| 0.5 wt% | 161.3 ± 1.7 | 1.80 ± 0.11 | Good |
| 0.6 wt% | 164.6 ± 2.1 | 1.77 ± 0.12 | Good |

**Table S4** The effect of Py usage on the conductivity and anti-abrasion property of PPy/SCB@PP-CFs.

| Dosage | Conductivity (S/m) | EMI shielding effectiveness (dB) | Anti-abrasion property |
|---|---|---|---|
| 0.67 wt% | 1.21 ± 0.21 | 7.8 | Good |
| 1.34 wt% | 4.16 ± 0.28 | 12.7 | Good |
| 2.01 wt% | 6.53 ± 0.40 | 18.3 | Good |
| 2.68 wt% | 8.52 ± 0.53 | 22.1 | General |
| 3.35 wt% | 11.34 ± 0.61 | 24.7 | Not good |

**Table S5** The effect of SCB usage on the conductivity and anti-abrasion property of PPy/SCB@PP-CFs.

| Dosage | Conductivity (S/m) | EMI shielding effectiveness (dB) | Anti-abrasion property |
|---|---|---|---|
| 0.2 wt% | 1.21 ± 0.21 | 17.9 | Good |
| 0.3 wt% | 4.16 ± 0.28 | 18.1 | Good |
| 0.4 wt% | 6.53 ± 0.40 | 18.3 | Good |
| 0.5 wt% | 8.52 ± 0.53 | 18.5 | General |
| 0.6 wt% | 11.34 ± 0.61 | 18.6 | Not good |

# Supplementary Movies:

**Supplementary Movie S1:**

The water CAs on Pr-CFs, PPy-CFs, and PPy/SCB@PP-CFs.

**Supplementary Movie S2:**

The self-cleaning test of PPy-CFs and PPy/SC@PP-CFs.

**Supplementary Movie S3:**

The vertical combustion test (UL 94) of Pr-CFs, PPy-CFs, and PPy/SCB@PP-CFs.

**Supplementary Movie S4:**

PPy/SCB@PP-CFs was used as a conductor to connect the LED and power.

**Supplementary Movie S5:**

The modified glove was employed to unlock the phone and make a phone call.

**Supplementary Movie S6:**

Relative current changes in response to the different fingers of the PPy/SCB@PP-CFs modified glove under repeated bending.

**Supplementary Movie S7:**

The self-cleaning test of the glove made by PPy/SC@PP-CFs.

# References


1 H. Zhang, X. Chen, X. Wang, X. Qiang, X. Li and M. Li, *Journal of Cleaner Production*, 2017, **142**, 1741-1748.

2 C. H. Xue, H. G. Li, X. J. Guo, Y. R. Ding, B. Y. Liu, Q. F. An and Y. Zhou, *Chem. Eng. J.*, 2021, **424**, 130553.