Supporting Information

Design of Moisturizing and Frost-Resistant Ionic Hydrogels for Multimodal Sensing through Water-Stabilizing Effects

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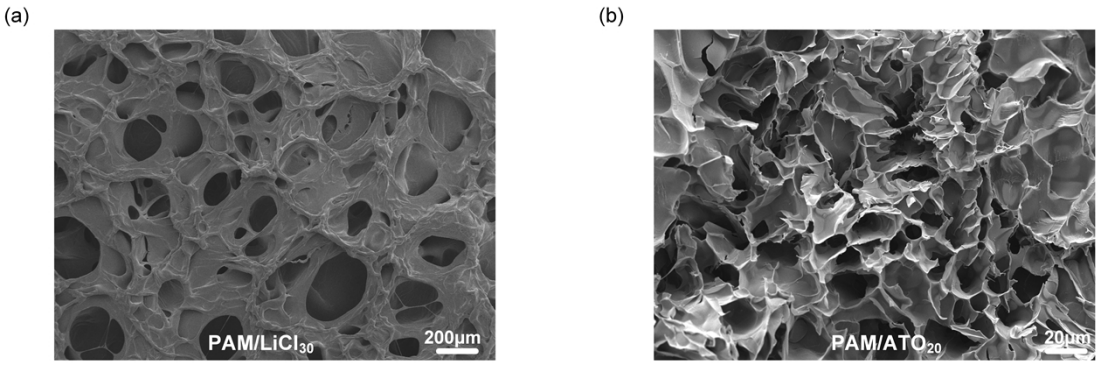

Fig. S1. SEM images of (a) PAM/$LiCl_{30}$ and (b) PAM/ATO_{20} hydrogel.

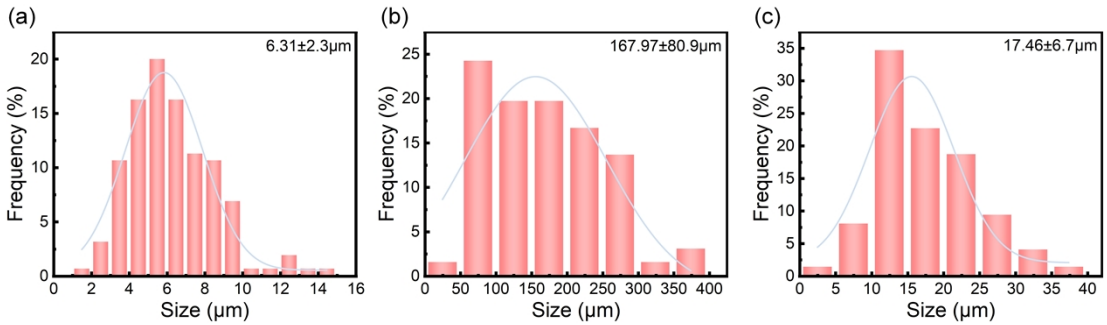

Fig. S2. Pore size diagram and average pore size of (a) MFI hydrogel, (b) PAM/$LiCl_{30}$ and (c) PAM/ATO_{20} hydrogel.

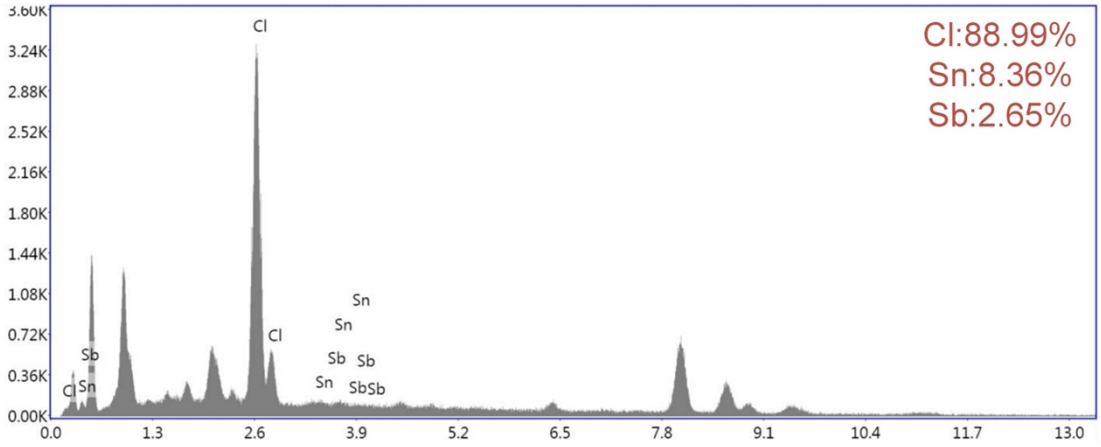

Fig. S3. EDS image of MFI hydrogel. The results reveal the element distribution of hydrogel. Specifically, the Cl element constitutes 88.99% of the composition, followed by the Sn element at 8.36%, and the Sb element at 2.65%.

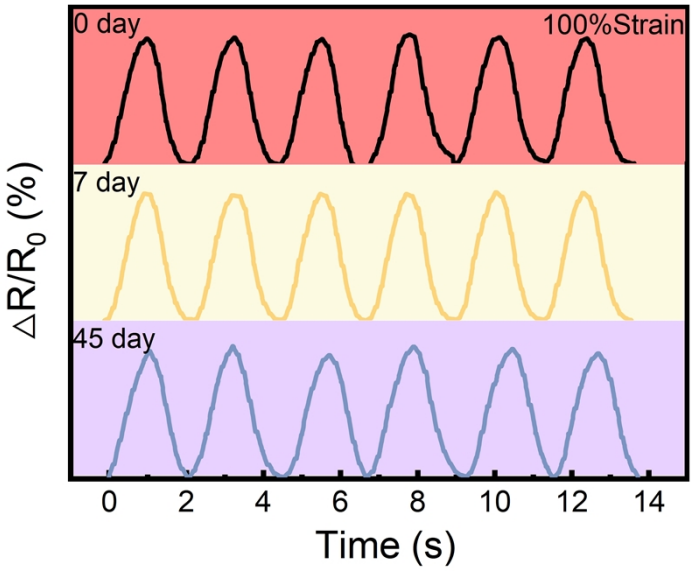

Fig. S4. The relative resistance changes of the MFI hydrogel under a 100% tensile strain over 0 days, 7 days, and 45 days.

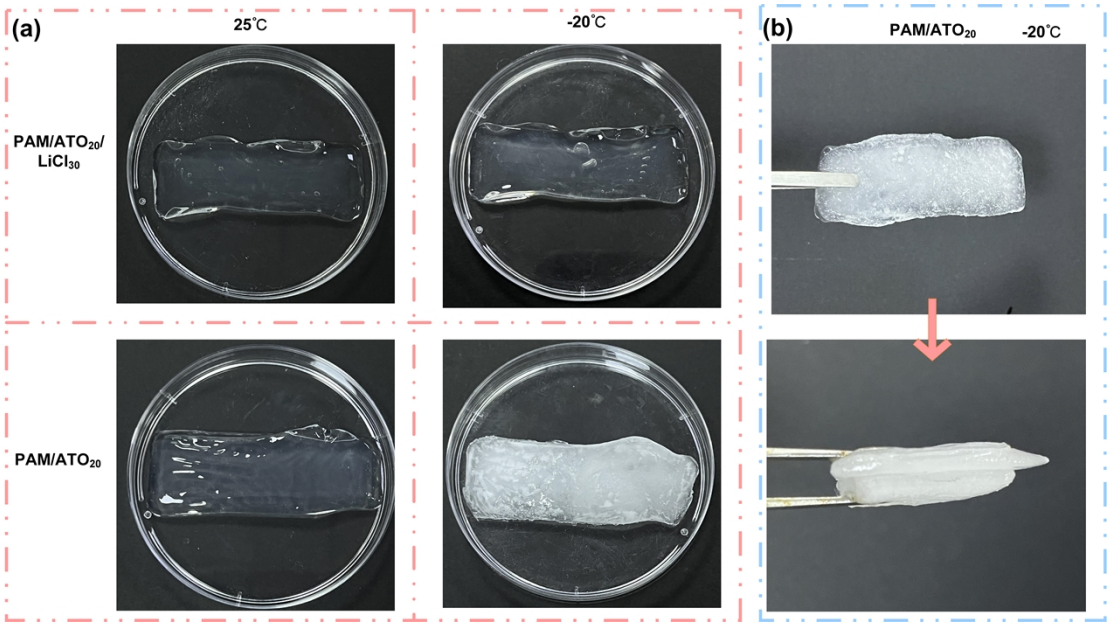

Fig. S5. Impact of LiCl on the frost resistance of MFI hydrogels. (a) Optical images of MFI hydrogel and PAM/ATO_{20} hydrogel after being stored in an environment at 25 ℃ and -20 ℃ for 24 h, respectively. (b) The image of bending PAM/ATO_{20} hydrogel after being placed at -20 ℃ for 24 h.

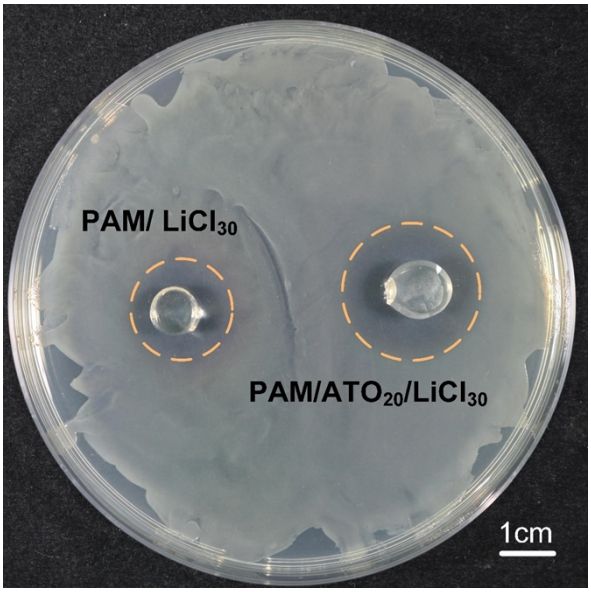

Fig. S6. The inhibition zones of MFI hydrogel against the E. coli.

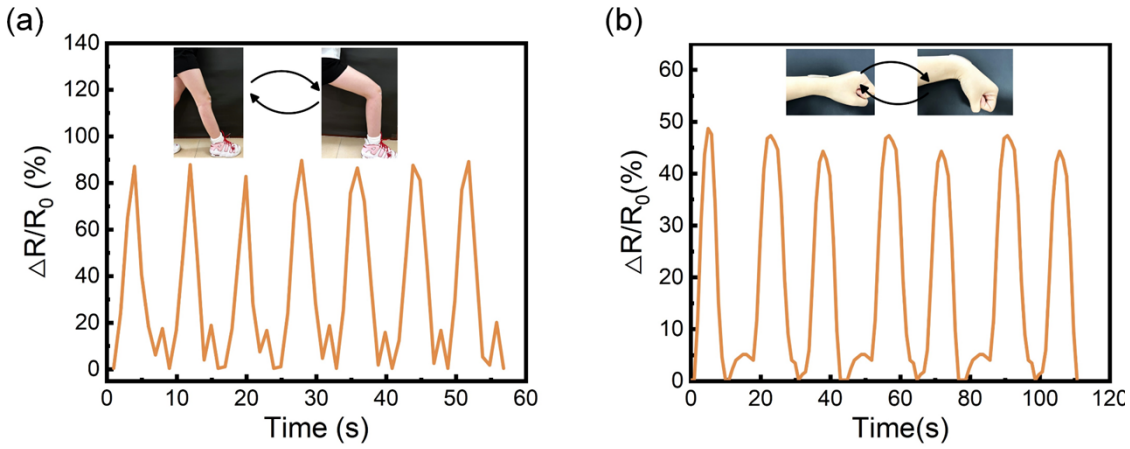

Fig. S7. Time-dependent relative resistance changes of the MFI hydrogel sensor *vs.* time bending and releasing the (a) knee and (b) opisthenar.

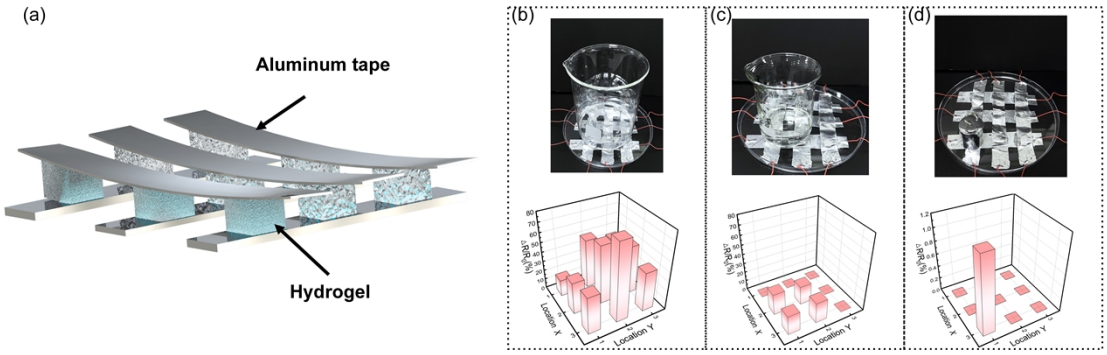

Fig. S8. MFI hydrogels assembled as pressure sensor matrix. (a) Schematic diagram of a 3×3 pressure sensing array. A pressure sensing diagram with a beaker containing (b) 100 g of water, (c) 30 g of water, and (d) 100 g of weights placed on an array.

Fig. S9. Potential application of MFI hydrogel as a dielectric assembled in a capacitive pen writing “Apple” in English and in Chinese on the mobile phone screen.

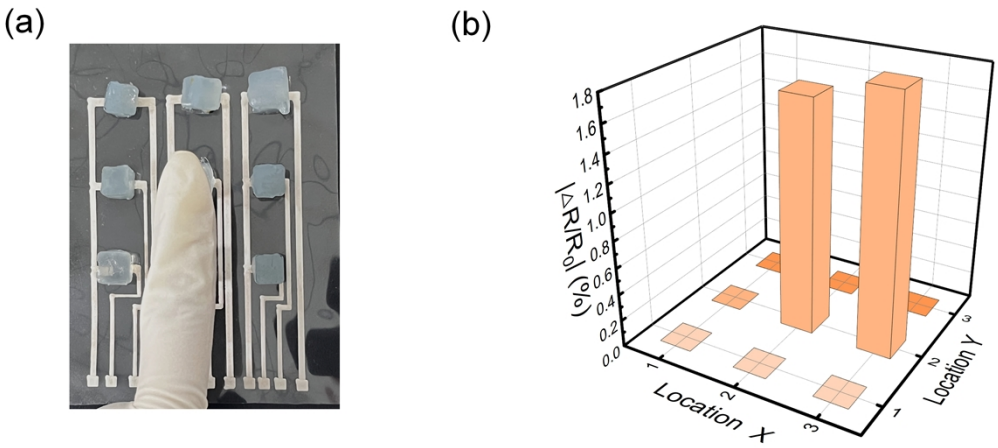

Fig. S10. (a) Optical images of remote actuation diagram. (b) Distribution of the corresponding response signal when a finger is brought near the array.

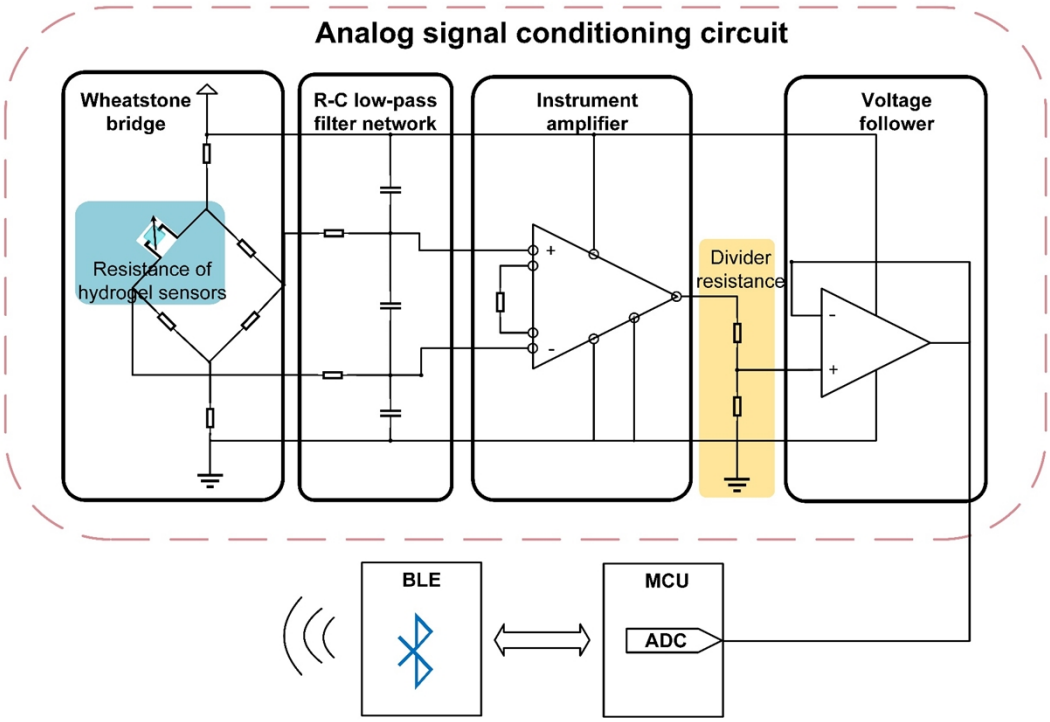

Fig. S11. Schematic diagram of contactless sensing system connected to the humidity sensor array.

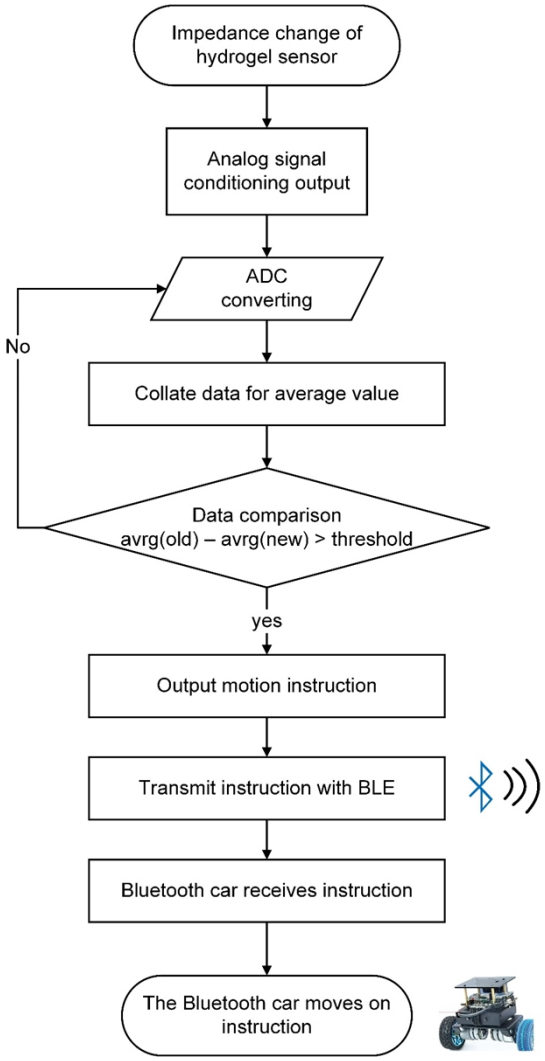

Fig. S12. Algorithm flowchart of human-computer interaction system.

Working mechanism of the signal process modules in remote actuation diagram: The system is powered by a lithium battery and functions by converting the resistance signal generated by the sensor into an analog voltage signal, which is further digitized. It predominantly consists of signal conditioning circuits for the hydrogel humidity array, a microcontroller unit (MCU), and a Bluetooth module. The signal conditioning circuit includes essential components such as a Wheatstone bridge, an R-C low-pass filtering network, an instrumentation amplifier, a resistive divider circuit, and a voltage follower. These components collectively adjust the resistance signals from each sensor within the array to stable voltage signals for output. The conditioned voltage signal is then processed by an analog-to-digital converter (ADC) through the

MCU, converting it into a digital signal. Finally, this digital signal is wirelessly transmitted to the terminal via the Bluetooth module. This setup enables the hydrogel humidity sensor array to control the Bluetooth-connected balancing car through non-contact sliding gestures.

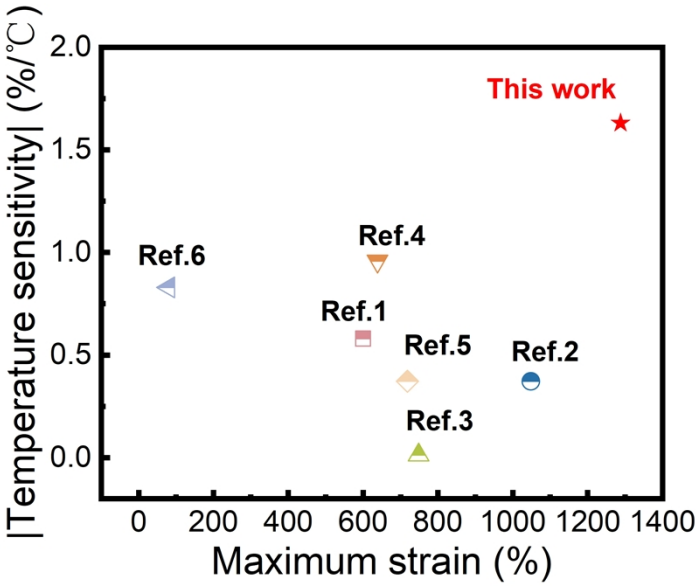

Fig. S13. This work is compared with other hydrogels in terms of maximum strain and temperature sensitivity.

Reference:

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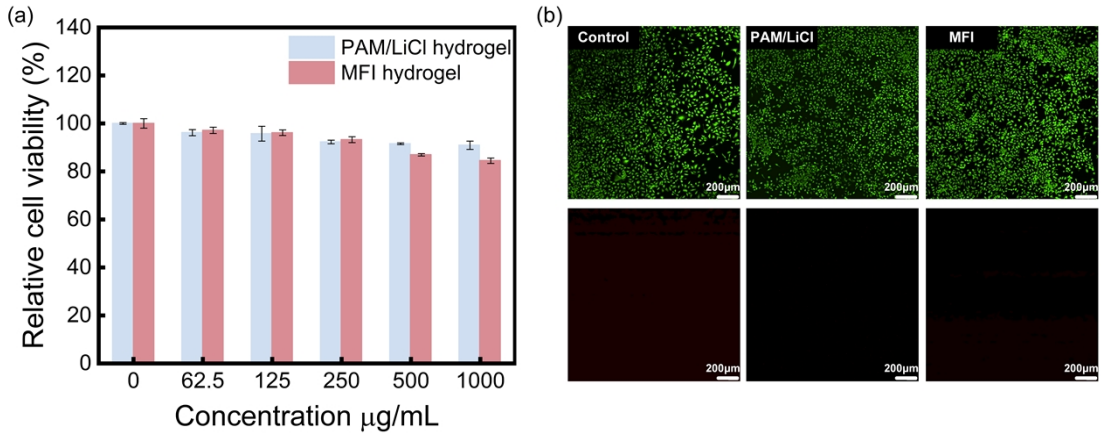

Fig. S14. (a) Histogram of cell viability of PAM/LiCl and MFI hydrogels. (b) Calcein AM/PI double staining kit to assess HaCaT cells treated with blank control, PAM/LiCl and MFI hydrogels.

Specific experimental operations:

- Cell culture

The hydrogel samples were submerged in DMEM medium at a constant temperature of 37 °C for 24 h. The samples were filtered through a 0.22 μm sterile filter membrane and the extract was collected and set aside.

Add 10 % fetal bovine serum and 1 % penicillin/streptomycin double antibiotic solution (DMEM^{++}) to DMEM as culture medium for HaCaT cells. The cells were cultured in a constant temperature incubator (5 % CO_2) at 37 ℃, and when the spreading density was 70 ~ 90 %, the cells were extracted by digestion and centrifugation with 0.05 % trypsin. Subsequently, the extracted cells were subjected to passaging culture at a ratio of 1:2 to 1:3. Cells with a passaging number of 3 to 10 generations were used for all relevant experiments in this section.

- Cytotoxicity assay

HaCaT cells were inoculated in 96-well plates at a density of 104 cells per well and incubated in DMEM^{++} medium for 24 hours. The medium was removed and 100 μl of different concentrations of hydrogel soaking solution was added, and after 12 hours of incubation, the dispersion was removed and the cells were washed with PBS buffer solution (pH = 7.4). Subsequently, 100 μL of CCK-8 solution (10 v/v% in

DMEM) was added to each well and incubated for 1-3 hours. Absorbance (OD value) at 450 nm was measured for each well using an enzyme marker.

Control group: DMEM medium was used instead of sample dispersion and other experimental conditions were kept the same as the sample group. The absorbance was finally measured at 450 nm using an enzyme meter and recorded as OD (control group).

Blank group: no inoculation of cells, other experimental conditions are consistent with the sample group. The absorbance was finally measured at 450 nm using an enzyme marker and recorded as OD (blank group).

Cell survival rate (%) = {OD (control group) - OD (blank group) / OD (experimental group) - OD (empty group) } ×100%

- Cell staining

HaCaT cells were inoculated at a density of 105 cells per well in 35 mm confocal dishes and incubated in $DMEM^{++}$ medium for 24 hours. The medium was removed, 1 ml of hydrogel soaking solution of different concentrations was added, and after 12 h of incubation, the dispersion was removed and the cells were washed with PBS buffer solution (pH = 7.4). A working solution (calcein 0.1 v/v%, pyridinium iodide 1 v/v%, dissolved in PBS) was added to the cell culture dish and incubated at 37 °C for 15 min, and the cells were observed for staining using a laser confocal microscope.