

## Supplementary Information

### **One material for many uses: facile construction of hydrogel sensors with strong anti-damage, anti-freezing, and anti-drying properties, cancer-killing ability and biocompatibility†**

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**Table S1** Biocompatible PVA hydrogels: A comparison between this work and reported investigations from preparation procedure, environmental aspects (volatility, toxicity or corrosivity of raw starting material), stress, strain, elastic modulus and toughness

| Hydrogel                     | Preparation procedure | Volatile, toxic reagent                                  | Biocompatibility | Stress (MPa) | Strain (%) | Elastic modulus (MPa) | Toughness (MJ m <sup>-3</sup> ) | Ref.      |
|------------------------------|-----------------------|--|------------------|--------------|------------|-----------------------|---------------------------------|-----------|
| PVA/TA/GO                    | Very simple           | No   | Yes              | 3.54         | 605        | 0.59                  | 10.4                            | This work |
| PVA/NaLa/NaDa                | Relatively simple     | No   | Yes              | 0.72, 0.92   | 484, 459   | 0.15, 0.19            | 1.2, 1.71                       | 1         |
| PVA/SG                       | Relatively simple     | No   | Yes              | 1.23         | 387        | 0.315                 | 2.298                           | 2         |
| PVA/d-CNT                    | Complex               | No   | Yes              | 0.00068      | 475        | a                     | a                               | 3         |
| PVA/PANa                     | Simple                | No   | Yes              | 7            | 600        | a                     | a                               | 4         |
| Salecan/PVA                  | Simple                | No   | Yes              | a            | a          | a                     | a                               | 5         |
| TA@HAP NWs/PVA               | Complex               | Ethylene glycol  | Yes              | 0.36         | 480        | a                     | 0.937403                        | 6         |
| CNC-PANI/PVA/borax           | Complex               | Aniline; HCl   | Yes              | 0.17152      | 1085       | a                     | a                               | 6         |
| TA/HLC/PVA/borax             | Complex               | No   | Yes              | a            | a          | a                     | a                               | 8         |
| PVA/chitosan/sodium alginate | Simple                | No   | Yes              | 0.24         | 147        | 0.034                 | 0.12                            | 9         |
| PVA/PEDOT:PSS                | Complex               | $\alpha$ -Ketoglutaric acid; acetic acid; glutaraldehyde | Yes              | < 0.8        | 150        | 0.46                  | a                               | 10        |
| PVA/BH/LiCl/LE               | simple                | LiCl   | Yes              | a            | a          | a                     | a                               | 11        |
| AL-CNF/PAA/PVA-EG            | Complex               | AAM, AMPS, MBA, KPS, TMEDA                               | Yes              | 0.136        | a          | 0.139                 | a                               | 12        |

**Table S1 (Continued)** Biocompatible PVA hydrogels: A comparison between this work and reported investigations from sensitivity, fatigue resistance, anti-freezing performance, anti-drying ability and cancer killing ability

| Hydrogel                     | Sensitivity<br>(gauge factor) | Fatigue resistance | Anti-freezing | Anti-drying | Cancer ability | killing | Ref.      |
|------------------------------|-------------------------------|--------------------|---------------|-------------|----------------|---------|-----------|
| PVA/TA/GO                    | 1.07, 1.2                     | Yes                | Yes           | Yes         | Yes            |         | This work |
| PVA/NaDa/NaLa                | 0.51, 0.88, 0.53, 1.22        | Yes                | no            | no          | no             |         | 1         |
| PVA/SG                       | 0.91, 1.76                    | Yes                | no            | no          | no             |         | 2         |
| PVA/d-CNT                    | 1.04, 1.08, 1.30              | Yes                | no            | no          | no             |         | 3         |
| PVA/PANa                     | a                             | Yes                | no            | no          | no             |         | 4         |
| Salecan/PVA                  | a                             | a                  | no            | no          | no             |         | 5         |
| TA@HAP NWs/PVA               | 2.84                          | Yes                | no            | no          | a              |         | 6         |
| CNC-PANI/PVA/borax           | 2.56-18.79                    | Yes                | no            | no          | no             |         | 7         |
| TA/HLC/PVA/borax             | a                             | a                  | no            | no          | a              |         | 8         |
| PVA/chitosan/sodium alginate | a                             | a                  | no            | no          | no             |         | 9         |
| PVA/PEDOT:PSS                | a                             | a                  | no            | no          | no             |         | 10        |
| PVA/BH/LiCl/LE               | 5.1, 4.8                      | Yes                | below -80 °C  | Yes         | no             |         | 11        |
| AL-CNF/PAA/PVA-EG            | 1.95, 2.09, 4.05, 5.13        | Yes                | -25.88 °C     | No          | No             |         | 12        |

a Not investigated, and/or no data reported.

**Table S2** Non-biocompatible PVA hydrogels: A comparison between this work and reported investigations from preparation procedure, environmental aspects (volatility, toxicity or corrosivity of raw starting material), stress, strain, elastic modulus and toughness

| Hydrogel                                       | Preparation procedure | Volatile, Toxic or corrosive reagent                          | Biocompatibility | Stress (MPa) | Strain (%) | Elastic modulus (MPa)  | Toughness (MJ m <sup>-3</sup> ) | Ref. |
|--|-----------------------|---|------------------|--------------|------------|------------------------|---------------------------------|------|
| PVA/SA   | simple                | No  | a                | 0.56-1.32    | 280-400    | 0.34-0.59              | 0.64-3.14                       | 13   |
| PVA/CNF@PDA/CNT                                | Very simple           | No  | a                | 1.23         | 387        | 0.315                  | 2.298                           | 14   |
| TOCNF/PANI/PVA/borax (CPPH)                    | Complex               | Hydrochloric acid, ANI, APS, sodium ionophore, etc.           | a                | 0.56-1.32    | 280-400    | 0.34-0.59              | 0.64-3.14                       | 15   |
| PVA-PAANa-PAH                                  | Relatively simple     | No  | a                | 0.79         | 335-471    | 0.02023-0.08293        | 1.26                            | 16   |
| PVA/CNC  | Complex               | DMSO  | No               | 0.01564      | 1530       | a                      | a                               | 17   |
| Starch/PVA/ionic liquid/GO                     | Simple                | BmimAc  | No               | 0.86         | 768        | 2.25                   | 2.25                            | 18   |
| PANI@(PVA-PAA)                                 | Complex               | Hydrochloric acid, ANI, APS, HCl, etc.                        | No               | 0.75         | 410.47     | a                      | a                               | 19   |
| nanocellulose/PVA/carbon dot                   | Complex               | Ethylene glycol, NaOH, HCl, ethylenediamine, etc.             | a                | 0.64         | 657.5      | ~ 0.275                | < 2.25                          | 20   |
| PVA+ P(SBMA-co-HEMA)                           | Complex               | Aniline; HCl  | No               | 0.09051      | a          | 0.02373                | a                               | 21   |
| PVA/PAAS/Ca <sup>2+</sup>                      | Complex               | No  | a                | 2.98         | a          | a                      | a                               | 22   |
| PVA/polyaniline                                | Simple                | Aniline, APS, HCl   | a                | < 0.4        | < 350      | < 0.125                | 0.518                           | 23   |
| PVA-PEG-SA-180                                 | Complex               | $\alpha$ -Ketoglutaric acid; acetic acid; glutaraldehyde      | a                | 0.75         | 216        | a                      | a                               | 24   |
| PVA-PANa                                       | Simple                | No  | a                | 1.46         | 416        | 4.27                   | 3.28                            | 25   |
| PVA-PA   | Simple                | No  | a                | 16.1         | 204.93     | a                      | a                               | 26   |
| HA-PVA   | Complex               | No  | a                | 7.0          | 600        | a                      | a                               | 27   |
| PVA from salting-out                           | Complex               | No  | a                | 0.5-1.5      | 500-1100   | a                      | a                               | 28   |
| PVA/PAA from cold-drawing                      | Complex               | No  | a                | 23.5         | 2900       | a                      | 210                             | 29   |
| PVA from cold-drawing                          | Complex               | No  | a                | 15           | 2100       | 2.5                    | 20                              | 30   |
| PMZn-GL  | Complex               | Ethylene glycol   | No               | 140          | a          | 100                    | 117                             | 31   |
| PVA/PAMAA                                      | Complex               | MBA, photoinitiator Irgacure 2959, APS, HCl, etc.             | No               | 5            | a          | 0.5                    | a                               | 32   |
| HPC/PVA  | Relatively simple     | DMSO  | a                | 0.875        | 247        | < 1 × 10 <sup>-9</sup> | 0.082                           | 33   |
| PAM/PVA/CNF                                    | Complex               | NaClO <sub>2</sub> , TEMPO, MBA, AAM, AA, APS, etc.           | No               | 0.4363       | 608        | 0.1349                 | 0.0047                          | 34   |
| PAM-PVA  | Complex               | AM, MBAA, APS, etc.   | No               | 1.3          | 975        | 0.9                    | 5.85                            | 35   |
| PVA-gelatin-Fe <sup>3+</sup>                   | Relatively simple     | HCl   | No               | 9.43         | 445.5      | a                      | 15.12                           | 36   |
| PVA/PAA-PEDOT:PSS-TA                           | Complex               | APS, acrylic acid, MBA  | No               | 0.1838       | 488        | 0.087                  | a                               | 37   |
| PVA-TA300                                      | Relatively simple     | No  | a                | 2.5          | 255        | 0.0252                 | 7.22                            | 38   |
| PVA/PEI/SG                                     | Relatively simple     | PEI   | No               | 2.2          | 386        | 0.67                   | 4.1                             | 39   |
| PVA/PEI/NaCl                                   | Relatively simple     | PEI   | No               | 3.49         | 343        | 1.02                   | 5.60                            | 40   |
| PVA/Pro/MXene                                  | Relatively simple     | No  | a                | 0.6          | 433        | a                      | a                               | 41   |
| PVA/CCS/glycerol/FeCl <sub>3</sub> /PPy/cMWCNT | Complex               | Pyrrole, FeCl <sub>3</sub>                                    | a                | a            | a          | a                      | a                               | 42   |
| PAM/PVA/Betaine/AS                             | Complex               | AM, AS  | No               | 0.18         | 1500       | a                      | a                               | 43   |
| PVA/EG/TANI                                    | Complex               | HCl, ammonium hydroxide, APS, diethyl ether, acetone, aniline | No               | 1.36         | 643        | 0.15                   | 4.39                            | 44   |
| PVA-CFBS@PEI@P(AM-Co-AA)                       | Complex               | AM, AA, PEI   | No               | 0.267        | 4100       | a                      | a                               | 45   |

**Table S2 (Continued)**

|   |                   |  |    |       |       |       |       |    |
|---|-------------------|--|----|-------|-------|-------|-------|----|
| PVA/P(AM-co-AMPS)/Gly/Lap/Na <sub>2</sub> SO <sub>4</sub> | Complex           | AMPS, MBA, AM, (NH <sub>4</sub> ) <sub>2</sub> S <sub>2</sub> O <sub>8</sub> , | No | 0.256 | 1331  | a     | a     | 46 |
| PVA/CA/EG/PEDOT:PSS                                       | Relatively simple | CA   | No | a     | a     | a     | a     | 47 |
| PVA/ZnCl <sub>2</sub> /TMSCl                              | Relatively simple | Paraformaldehyde, ethyl acetate, DMSO  | No | a     | a     | a     | a     | 48 |
| PVA-PBAD@PAM  | Complex           | NPG, 1,6-Dibromohexane, LiCl, AM, acetonitrile, acetone                        | No | a     | a     | a     | a     | 49 |
| PVA/ADSP  | Relatively simple | ADSP   | No | 2.26  | 818.6 | 0.95  | 12.23 | 50 |
| PPy@CNF-PVA   | Complex           | FeCl <sub>3</sub> ·6H <sub>2</sub> O   | No | a     | a     | a     | a     | 51 |
| PVA/P(AM-co-AA)/CaCl <sub>2</sub>                         | Relatively simple | AM, AA, MBAA, DMSO, KPS,   | No | a     | a     | a     | a     | 52 |
| PVA/PVP/P(NIPAAm-co-VBIMBr)                               | Complex           | NIPAAm, irgacure, MBAA   | No | 0.125 | 930   | a     | 0.07  | 53 |
| TOCNs-CNTs/PVA-SA-TA                                      | Complex           | TEMPO, NaBr, NaOH,   | No | 8.06  | 438   | a     | a     | 54 |
| PVA/P(AAm-co-SBMA)/Eu (PDA) <sub>3</sub> /GL              | Complex           | AAM, MBA, KPS, Eu(NO <sub>3</sub> ) <sub>3</sub> ·6H <sub>2</sub> O            | No | a     | a     | a     | a     | 55 |
| PVA:HPEI:PA:CNCs@PA                                       | Complex           | HPEI, ZnCl <sub>2</sub>  | No | 2.6   | a     | a     | a     | 56 |
| PVA/PAAc/XG   | Complex           | ZnCl <sub>2</sub> , AAc, MBAA, APS,  | No | 1.31  | a     | 0.29  | 3.46  | 57 |
| LCBD-PVA  | Complex           | LiCl   | a  | 8.29  | 644   | a     | 23.8s | 58 |
| PVA-SbQ/SA/FeCl <sub>3</sub> /Gly                         | simple            | FeCl <sub>3</sub> ·6H <sub>2</sub> O   | a  | 2.48  | 1452  | 0.118 | 15.08 | 59 |

a Not investigated, and/or no data reported.

**Table S2 (Continued)** Non-biocompatible PVA hydrogels: A comparison between this work and reported investigations from sensitivity, fatigue resistance, anti-freezing performance, anti-drying ability and cancer killing ability

| Hydrogel  | Sensitivity (gauge factor) | Fatigue resistance | Anti-freezing | Anti-drying | Cancer ability | killing | Ref. |
|---|----------------------------|--------------------|---------------|-------------|----------------|---------|------|
| PVA/SA  | 0.91, 1.76                 | Yes                | No            | No          | No             |         | 13   |
| PVA/CNF@PDA/CNT   | 2.29                       | Yes                | No            | No          | No             |         | 14   |
| TOCNF/PANI/PVA/borax                                      | a                          | a                  | No            | No          | No             |         | 15   |
| PVA-PAANa-PAH   | 1.20, 1.64                 | a                  | No            | No          | No             |         | 16   |
| PVA/CNC   | a                          | a                  | No            | No          | No             |         | 17   |
| Starch/PVA/ionic liquid/GO                                | 6.04                       | Yes                | -20 °C        | No          | No             |         | 18   |
| PANI@(PVA-PAA)  | a                          | Yes                | No            | No          | No             |         | 19   |
| nanocellulose/PVA/carbon dot                              | a                          | a                  | No            | No          | No             |         | 20   |
| PVA+ P(SBMA-co-HEMA)                                      | 1.434, 2.448, 3.356        | a                  | No            | No          | No             |         | 21   |
| PVA/PAAS/Ca <sup>2+</sup>                                 | 1.58                       | Yes                | No            | No          | No             |         | 22   |
| PVA/polyaniline   | a                          | Yes                | No            | No          | No             |         | 23   |
| PVA-PEG-SA-180  | a                          | a                  | No            | No          | No             |         | 24   |
| PVA-PANa  | 0.45                       | Yes                | No            | No          | No             |         | 25   |
| PVA-PA  | a                          | a                  | No            | No          | No             |         | 26   |
| HA-PVA  | a                          | a                  | No            | No          | No             |         | 27   |
| PVA from salting-out                                      | a                          | a                  | No            | No          | No             |         | 28   |
| PVA/PAA from cold-drawing                                 | a                          | a                  | No            | No          | No             |         | 29   |
| PVA from cold-drawing                                     | a                          | a                  | No            | No          | No             |         | 30   |
| PMZn-GL   | 3.42, 4.77, 5.82           | a                  | yes           | No          | No             |         | 31   |
| PVA/PAMAA   | a                          | Yes                | No            | No          | No             |         | 32   |
| HPC/PVA   | a                          | a                  | No            | No          | No             |         | 33   |
| PAM/PVA/CNF   | 1.47, 2.72, 4.39           | a                  | No            | No          | No             |         | 34   |
| PAM-PVA   | a                          | a                  | No            | No          | No             |         | 35   |
| PVA-gelatin-Fe <sup>3+</sup>                              | 0.55                       | Yes                | a             | No          | No             |         | 36   |
| PVA/PAA-PEDOT:PSS-TA                                      | 1.29, 2.34                 | Yes                | No            | No          | No             |         | 37   |
| PVA-TA300   | a                          | Yes                | No            | No          | a              |         | 38   |
| PVA/PEI/SG  | 1.28, 1.41                 | Yes                | No            | No          | No             |         | 39   |
| PVA/PEI/NaGluc  | 1.13, 1.22                 | Yes                | No            | No          | No             |         | 40   |
| PVA/Pro/MXene   | 2                          | a                  | -34.1 °C      | Yes         | No             |         | 41   |
| PVA/CCS/glycerol/FeCl <sub>3</sub> /PPy/cMWCNT            | 1.75, 2.35                 | Yes                | Below -80 °C  | No          | No             |         | 42   |
| PAM/PVA/Betaine/AS  | 1.49, 3.4, 14.52           | Yes                | -68 °C        | No          | No             |         | 43   |
| PVA/EG/TANI   | 2.7, 4.79, 6.98            | Yes                | Below -60 °C  | No          | No             |         | 44   |
| PVA-CFBS@PEI@P(AM-Co-AA)                                  | 2.8, 5.6, 8.7              | Yes                | -60 °C        | No          | No             |         | 45   |
| PVA/P(AM-co-AMPS)/Gly/Lap/Na <sub>2</sub> SO <sub>4</sub> | 2.57, 5.77, 10.01          | a                  | No            | No          | No             |         | 46   |
| PVA/CA/EG/PEDOT:PSS                                       | 0.9, 2.87, 4.46            | Yes                | -31.34 °C     | No          | No             |         | 47   |
| PVA/ZnCl <sub>2</sub> /TMSCl                              | 1.596                      | No                 | Below -80 °C  | No          | No             |         | 48   |
| PVA-PBAD@PAM  | 2.08, 5.91, 13.89          | Yes                | -20 °C        | Yes         | No             |         | 49   |
| PVA/ADSP  | 0.96, 1.4, 1.82            | Yes                | -48 °C        | Yes         | No             |         | 50   |
| PPy@CNF-PVA   | 2.18, 2.84                 | Yes                | -18 °C        | No          | No             |         | 51   |
| PVA/P(AM-co-AA)/CaCl <sub>2</sub>                         | 1.12                       | Yes                | -25.1 °C      | No          | No             |         | 52   |
| PVA/PVP/P(NIPAAm-co-VBIMBr)                               | 1.26, 2.01 2.6             | Yes                | -24.83 °C     | Yes         | No             |         | 53   |
| TOCNs-CNTs/PVA-SA-TA                                      | 1.47, 2.49                 | Yes                | Below -20 °C  | No          | No             |         | 54   |
| PVA/P(AAm-co-SBMA)/Eu (PDA) <sub>3</sub> /GL              | a                          | Yes                | -20 °C        | Yes         | No             |         | 55   |
| PVA:HPEI:PA:CNCs@PA                                       | 2.5                        | Yes                | -28.3 °C      | No          | No             |         | 56   |
| PVA/PAAc/XG   | No                         | a                  | Below -60 °C  | No          | No             |         | 57   |

**Table S2 (Continued)**

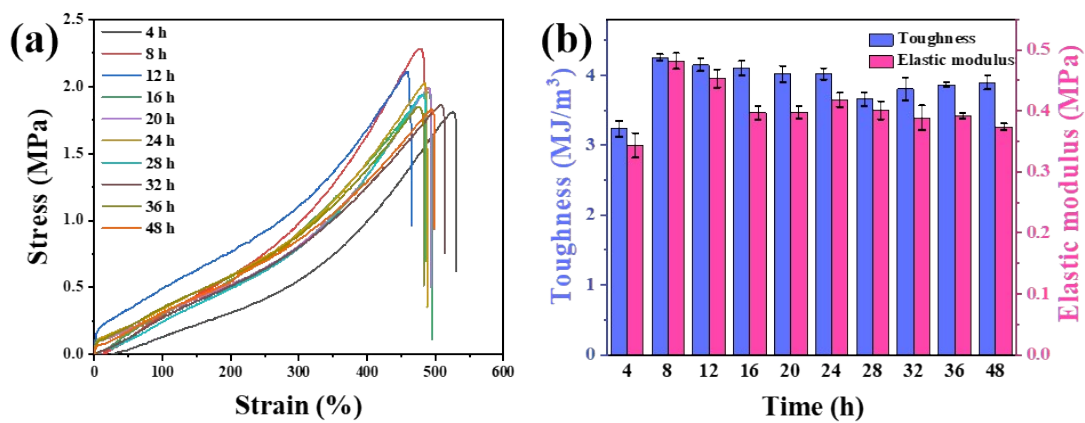
|                                   |               |       |     |             |      |    |    |    |
|-----------------------------------|---------------|-------|-----|-------------|------|----|----|----|
| LCBD-PVA                          | 3.16,<br>1.86 | 5.62, | Yes | Below<br>°C | -150 | No | No | 58 |
| PVA-SbQ/SA/FeCl <sub>3</sub> /Gly | 0.61, 2.49    |       | Yes | -42.3 °C    |      | No | No | 59 |

a Not investigated, and/or no data reported.

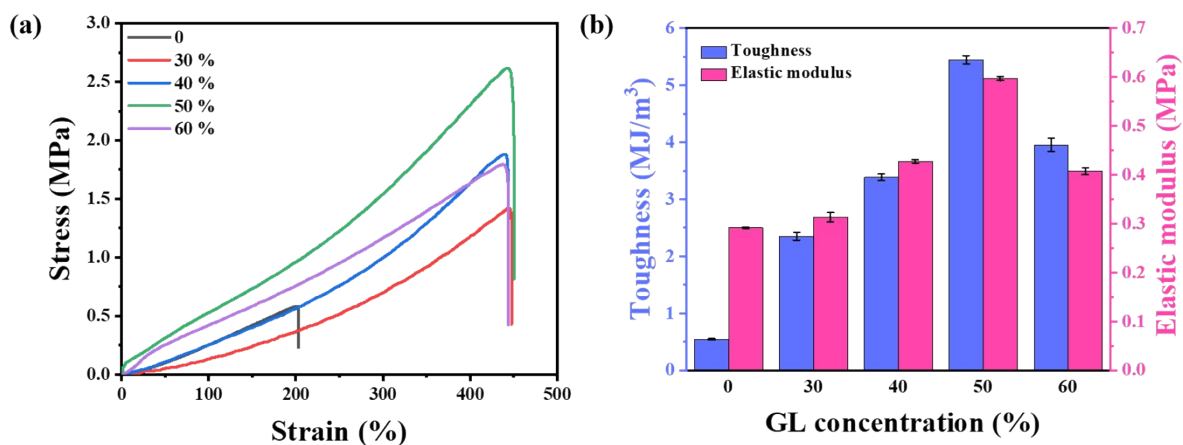
**Table S3** Parameters of preparation of PVA-x/TA-y/GO-z/GL-m hydrogel

| Hydrogel sample             | x = PVA concentration (wt.%) | y = TA concentration (wt.%) | z = GO concentration (mg/ml) | m = GL concentration (wt.%) |
|-----------------------------|------------------------------|-----------------------------|------------------------------|-----------------------------|
| PVA-10/GO-0.5/GL-50         | 10                           | 0                           | 0.5                          | 50                          |
| PVA-10/TA-0.05/GO-0.5/GL-50 | 10                           | 0.05                        | 0.5                          | 50                          |
| PVA-10/TA-1.1/GO-0.5/GL-50  | 10                           | 1.1                         | 0.5                          | 50                          |
| PVA-10/TA-1.8/GO-0.5/GL-50  | 10                           | 1.8                         | 0.5                          | 50                          |
| PVA-10/TA-2.5/GO-0.5/GL-50  | 10                           | 2.5                         | 0.5                          | 50                          |
| PVA-10/TA-3.3/GO-0.5/GL-50  | 10                           | 3.3                         | 0.5                          | 50                          |
| PVA-10/TA-4.3/GO-0.5/GL-50  | 10                           | 4.3                         | 0.5                          | 50                          |
| PVA-10/TA-1.8/GL-50         | 10                           | 1.8                         | 0                            | 50                          |
| PVA-10/TA-1.8/GO-0.1/GL-50  | 10                           | 1.8                         | 0.1                          | 50                          |
| PVA-10/TA-1.8/GO-1/GL-50    | 10                           | 1.8                         | 1                            | 50                          |
| PVA-10/TA-1.8/GO-1.5/GL-50  | 10                           | 1.8                         | 1.5                          | 50                          |
| PVA-10/TA-1.8/GO-2/GL-50    | 10                           | 1.8                         | 2                            | 50                          |
| PVA-10/TA-1.8/GO-1          | 10                           | 1.8                         | 1                            | 0                           |
| PVA-10/TA-1.8/GO-1/GL-20    | 10                           | 1.8                         | 1                            | 20                          |
| PVA-10/TA-1.8/GO-1/GL-30    | 10                           | 1.8                         | 1                            | 30                          |
| PVA-10/TA-1.8/GO-1/GL-40    | 10                           | 1.8                         | 1                            | 40                          |
| PVA-10/TA-1.8/GO-1/GL-60    | 10                           | 1.8                         | 1                            | 60                          |

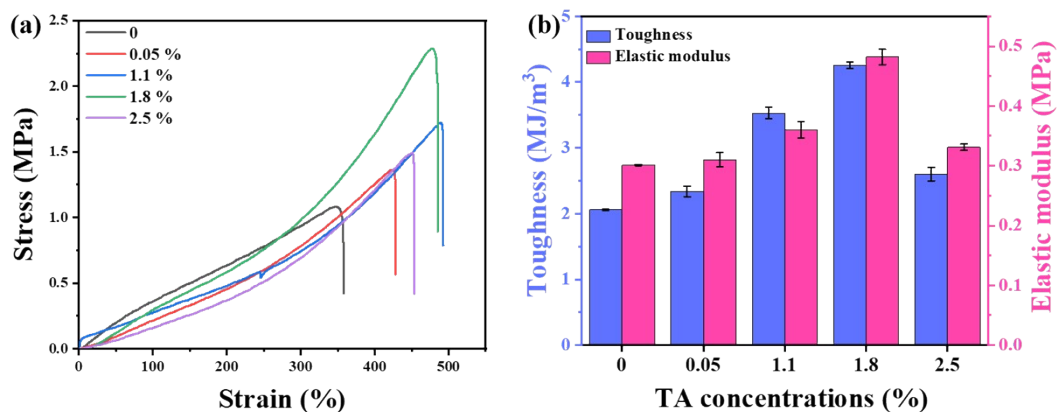




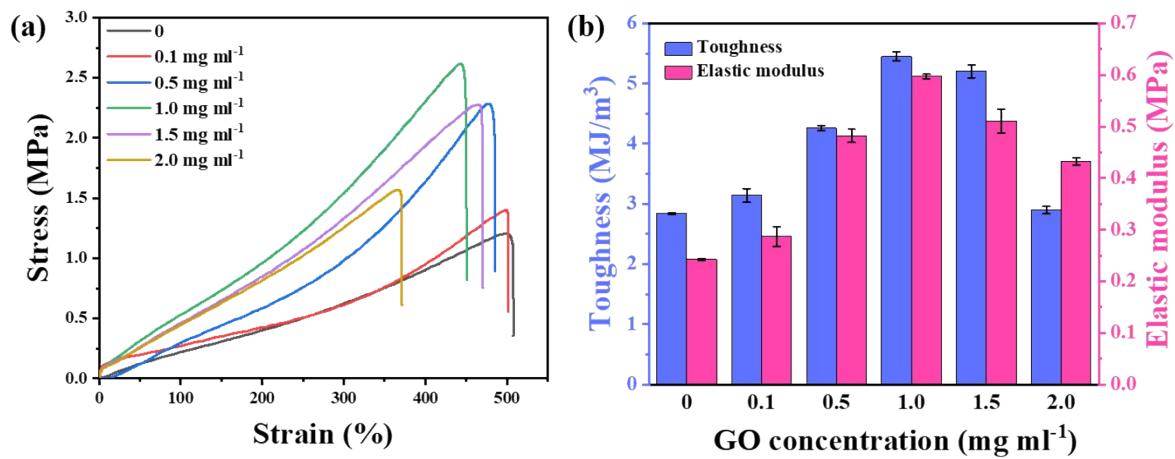
**Fig. S1** Tensile curves (a) and (b) elastic modulus and toughness of PVA/TA-1.8/GO-0.5 hydrogel at different freezing time.



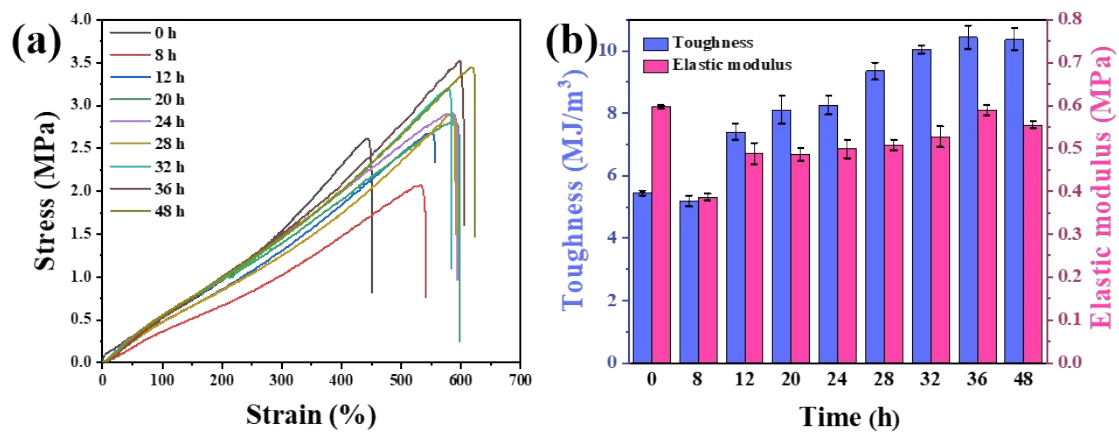
**Fig. S2** PVA/TA-1.8/GO-0.5 hydrogels of different GL concentrations (0, 30%, 40%, 50% and 60%) prepared from freezing for 8 h and curing for 8 h: (a) Stress-strain curve, (b) elastic modulus and toughness.



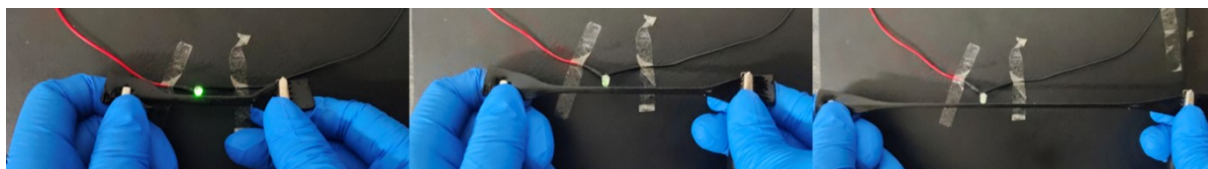
**Fig. S3** PVA/TA-x/GO-0.5 hydrogels of different TA concentrations prepared from freezing for 8 h and curing for 8 h: (a) Stress-strain curve, (b) elastic modulus and toughness. x = 0, 0.05, 1.1, 1.8, 2.5, 3.3 and 4.3, respectively.



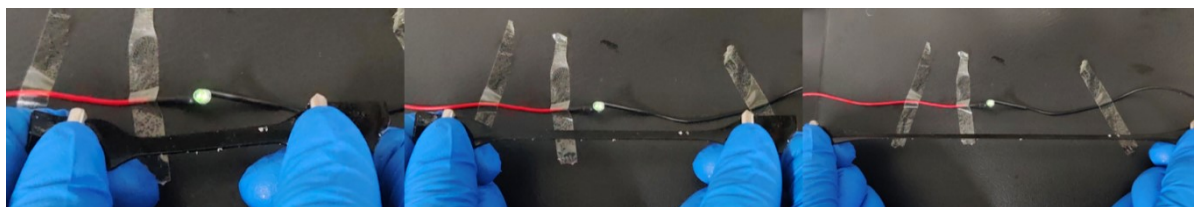
**Fig. S4** PVA/TA-1.8/GO-y hydrogels of different GO concentrations prepared from freezing for 8 h and curing for 8 h: (a) Stress-strain curve, (b) elastic modulus and toughness. y = 0, 0.1, 0.5, 1.0, 1.5 and 2.0 mg mL<sup>-1</sup>, respectively.



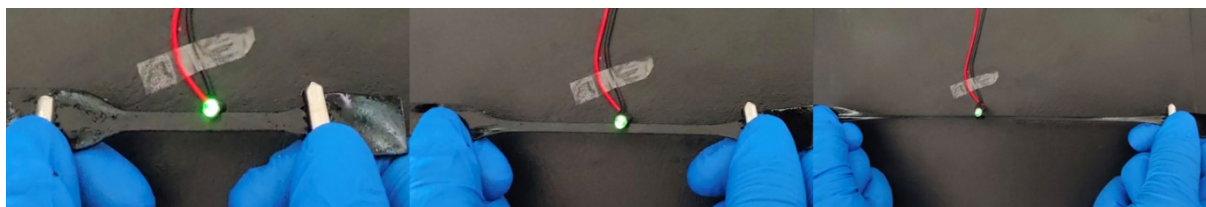
**Fig. S5** PVA/TA-1.8/GO-1 hydrogels of different curing times (0 h, 8 h, 12 h, 20 h, 24 h, 28 h, 32 h, 36 h, 48 h) prepared from freezing for 8 h.



**Fig. S6** Conductive behavior of PVA/TA-1.8/GO-1 hydrogel after one months of exposure to air.



**Fig. S7** Conductive behavior of PVA/TA-1.8/GO-1 hydrogel after two months of exposure to air.



**Fig. S8** Conductive behavior of PVA/TA-1.8/GO-1 hydrogel after three months of exposure to air.



## References

- 1 J. Lan, Y. Gong, B. Lin, A. Xu and R. Liu, *Microchem J.*, 2024, 205, 111272.
- 2 A. Xu, T. Sun, R. Liu, L. Li, Y. Gong and Z. Xiao, *Green Chem.*, 2024, **26**, 3926.
- 3 H. Zhu, J. Xu, X. Sun, Q. Guo, Q. Guo, M. Jiang, K. Wu, R. Cai and K. Qian, *J. Mater. Chem. A*, 2022, **10**, 23366–23374.
- 4 S. Zhang, Y. Li, H. Zhang, G. Wang, H. Wei, X. Zhang and N. Ma, *ACS Mater. Lett.*, 2021, **3**, 807–814.
- 5 X. L. Qi, X. Y. Hu, W. Wei, H. Yu, J. J. Li, J. F. Zhang and W. Dong, *Carbohydr. Polym.*, 2015, **118**, 60–69.
- 6 J. Wen, J. Tang, H. Ning, N. Hu, Y. Zhu, Y. Gong, C. Xu, Q. Zhao, X. Jiang, X. Hu, L. Lei, D. Wu and T. Huang, *Adv. Funct. Mater.*, 2021, **31**, 2011176.
- 7 M. Songa, H. Yua, J. Zhua, Z. Ouyanga, S. Y. H. Abdalkarima, K. C. Tam and Y. Li, *Chem. Eng. J.*, 2020, **398**, 125547.
- 8 H. Lei and D. Fan, *Chem. Eng. J.*, 2021, **421**, 129578.
- 9 C. H. Luo, A. D. Guo, Y. F. Zhao and X. X. Sun, *Carbohydr. Polym.*, 2022, **286**, 119268.
- 10 G. Li, K. Huang, J. Deng, M. Guo, M. Cai, Y. Zhang and C. F. Guo, *Adv. Mater.*, 2022, **34**, 2200261.
- 11 R. Liu, Y. Liu, S. Fu, Y. Cheng, K. Jin, J. Ma, Y. Wan and Y. Tian, *Small*, 2024, 20(24), e2308092.
- 12 X. Gao, Y. Wang, J. Wu, Z. Xue, C. Yan, H. Zhang, Y. Wang, Y. Zhang, M. Jiang and Y. Zhao, *ACS Sustainable Chem. Eng.*, 2024, **12**, 41, 15159–15172.
- 13 X. Jiang, N. Xiang, H. Zhang, Y. Sun, Z. Lin and L. Hou, *Carbohydr. Polym.*, 2018, **186**, 377.
- 14 R. Zhang, A. Yang, Y. Yang, Y. Zhu, Y. Song, Y. Li and J. Li, *Int. J. Biol. Macromol.*, 2023, **245**, 125469.
- 15 Y. Qin, J. Mo, Y. Liu, S. Zhang, J. Wang, Q. Fu, S. Wang and S. Nie, *Adv. Funct. Mater.*, 2022, 32, 2201846.
- 16 W. J. Yang, R. Zhang, X. Guo, R. Ma, Z. Liu, T. Wang and L. Wang, *J. Mater. Chem. A*, 2022, 10, 23649.
- 17 X. Huang, X. Ao, L. Yang, J. Ye and C. Wang, *RSC Adv.*, 2023, **13**, 527.
- 18 X. Li, S. Zhang, X. Li, L. Lu, B. Cui, C. Yuan, L. Guo, B. Yu and Q. Chai, *Carbohydr. Polym.*, 2023, **320**, 121262.
- 19 X. Dong, Y. Ge, K. Li, X. Li, Y. Liu, D. Xu, S. Wang and X. Gu, *Soft Matter*, 2022, **18**, 9231.

- 20 Z. Wang, F. Cheng, H. Cai, X. Li, J. Sun, Y. Wu, N. Wang and Y. Zhu, *Carbohydr. Polym.*, 2021, **259**, 117753.
- 21 J. Ren, Y. Liu, Z. Wang, S. Chen, Y. Ma, H. Wei and S. Lü, *Adv. Funct. Mater.*, 2021, **32**, 2107404.
- 22 R. Liu, K. Chen, H. Liu, Y. Liu, R. Cong, J. Guo and Y. Tian, *ACS Appl. Mater. Inter.*, 2022, **14**, 51341.
- 23 L. Li, Y. Zhang, H. Lu, Y. Wang, J. Xu, J. Zhu, C. Zhang and T. Liu, *Nature Commun.*, 2020, **11**, 62.
- 24 Y. Xu, M. Pei, J. Du, R. Yang, Y. Pan, D. Zhang and S. Qin, *New J. Chem.*, 2023, **47**, 13721.
- 25 S. Zhang, Y. L. Li, H. J. Zhang, G. J. Wang, H. Wei, X. Y. Zhang and N. Ma, *ACS Mater. Lett.*, 2021, **3**, 807-814.
- 26 S. Zhang, Y. H. Zhang, B. Li, P. Zhang, L. Kan, G. J. Wang, H. Wei, X. Y. Zhang and N. Ma, *ACS Appl. Mater. Interfaces*, 2019, **11**, 32441-32448.
- 27 M. T. Hua, S. W. Wu, Y. F. Ma, Y. S. Zhao, Z. L. Chen, I. Frenkel, J. Strzalka, H. Zhou, X. Y. Zhu and X. M. He, *Nature*, 2021, **590**, 594–599.
- 28 S. W. Wu, M. T. Hua, Y. Alsaïd, Y. J. Du, Y. F. Ma, Y. S. Zhao, C.-Y. Lo, C. R. Wang, D. Wu, B. W. Yao, J. Strzalka, H. Zhou, X. Y. Zhu and X. M. He, *Adv. Mater.*, 2021, **33**, 2007829.
- 29 T. Q. Liu, C. Jiao, X. Peng, Y. N. Chen, Y. Y. Chen, C. C. He, R. G. Liu and H. L. Wang, *J. Mater. Chem. B*, 2018, **6**, 8105-8114.
- 30 Y. Y. Chen, C. Jiao, X. Peng, T. Q. Liu, Y. Q. Shi, M. Liang and H. L. Wang, *J. Mater. Chem. B*, 2019, **00**, 1-3.
- 31 Y. B. Feng, H. Liu, W. H. Zhu, L. Guan, X. T. Yang, A. V. Zvyagin, Y. Zhao, C. Shen, B. Yang and Q. Lin, *Adv. Funct. Mater.*, 2021, **31**, 2105264.
- 32 J. R. Huang, S. J. Han, J. D. Zhu, Q. R. Wu, H. J. Chen, A. B. Chen, J. Y. Zhang, B. Huang, X. X. Yang and L. H. Guan, *Adv. Funct. Mater.*, 2022, **32**, 2205708.
- 33 Y. Zhou, C. J. Wan, Y. S. Yang, H. Yang, S. C. Wang, Z. D. Dai, K. J. Ji, H. Jiang, X. D. Chen and Y. Long, *Adv. Funct. Mater.*, 2018, **29**, 1806220.
- 34 J. M. Wu, Q. Ma, Q. K. Pang, S. S. Hu, Z. H. Wan, X. F. Peng, X. Cheng and L. H. Geng, *Carbohydr. Polym.*, 2023, **321**, 121282.
- 35 G. Ge, Y. Z. Zhang, J. J. Shao, W. J. Wang, W. L. Si, W. Huang and X. C. Dong, *Adv. Funct. Mater.*, 2018, **28**, 1802576.
- 36 S. Sun, Y. Z. Xu and X. Maimaitiyiming, *Int. J. Biol. Macromol.*, 2023, **249**, 125978.
- 37 Z. X. Zhou, W. Z. Yuan and X. Y. Xie, *Mater. Chem. Front.*, 2022, **6**, 3359–3368.
- 38 H. L. Fan, J. H. Wang and Z. X. Jin, *Macromolecules*, 2018, **51**, 1696-1705.

- 39 Y. Hui, R. Liu, T. Sun, L. Li, Y. Gong, Z. Xiao, A. Xu and X. Wei, *Macromolecules*, 2024, **57**, 4737–4746.
- 40 Y. Hui, R. Liu, Y. Gong, J. Lan, Y. Chen, L. Wu and A. Xu, *Sensor. Actuat. B-Chem.*, 2024, **419**, 136346
- 41 M. Gong, X. Wang, Z. Wu, L. Yue, Q. Chen, H. Li, X. Lin, L. Zhang and D. Wang, *Small*, 2024, **20**(30), e2400161.
- 42 Y. Liu, H. Yu, G. Zhou and M. Peng, *ACS Sens.*, **2024**, 9(9), 4617–4625.
- 43 Y. Yin, R. Xie, Z. Sun, T. Jiang, B. Zhou, Y. Yu, H. Ding, S. Gai and P. Yang, *Nano Lett.*, 2024, **24**(17), 5351–5360.
- 44 H. Liu, Z. Chen, X. Lin, X. Zhang, Y. Cai, Y. Zhang, B. Sun, X. Mei, W. Lyu, R. B. Kaner, M. Zhu and Y. Liao, *Chem. Mater.*, 2024, **36**, 12, 6100–6113.
- 45 R. Wang, C. Liu, Z. Li, Y. Li and X. Yu, *ACS Sens.*, 2024, **9**(10), 5322–5332.
- 46 X. Jiang, S. Wei and J. Wang, *ACS Appl. Mater. Interfaces*, 2024, **16**(1), 1380–1393.
- 47 Y. Zhu, D. Yao, X. Gao, J. Chen, H. Wang, T. You, C. Lu and X. Pang, *ACS Appl. Mater. Interfaces*, 2024, **16**(25), 32466–32480.
- 48 H. N. Fath Dehghan, A. Abdolmaleki, M. Pourahmadi, S. Hozori, E. Gaeini, S. Y. Mousavi, A. Arvaneh and M. Sadat-Shojai, *Polym. Test.*, 2024, **140**, 108607.
- 49 C. Liu, H. Wu, R. Wang, Y. Li and X. Yu, *Eur. Polym. J.*, 2024, **217**, 113312.
- 50 W. Zhu, Y. Zhang, S. Huang, L. Geng, J. Wu, G. Mao, X. Peng and Y. Cheng, *Chem. Eng. J.*, 2024, **497**, 154409.
- 51 X. Liu, H. Shi, F. Song, W. Yang, B. Yang, D. Ding, Z. Liu, L. Hui and F. Zhang, *Int. J. Biol. Macromol.*, 2024, **257**, 128800.
- 52 X. Fan, L. Wang, S. Bai, H. Wang, X. Zhu, L. Liu, N. Li, C. Xue and S. Hu, *Eur. Polym. J.*, 2024, 221, 113573.
- 53 T. Lei, Y. Wang, Y. Feng, X. Duan, Q. Zhang, A. Wan, Z. Xia, W. Shou and J. Fan, *J. Colloid Interface Sci.*, 2025, **678**, 726–741.
- 54 W. Zhu, S. Wang, Y. Lu, W. Yang, S. Ge, Z. Lou, S. He, S. Jiang and J. Han, *Ind. Crops Prod.*, 2024, **222**, 119598.
- 55 M. Gao, J. Li, S. Zhao and G. Li, *Chem. Eng. J.*, 2024, **496**, 153881.
- 56 C. Yang, J. Liu, P. Liu, W. Wang, H. Chen, L. Bai, H. Yang, L. Yang and D. Wei, *Chem. Eng. J.*, 2024, **493**, 152276.
- 57 Y. Zhou, H. Liu, X. Zhou, X. Lin, Y. Cai, M. Shen, X. Huang, H. Liu and X. Xu, *Int. J. Biol. Macromol.*, 2024, **265**, 131143.
- 58 H. Zhang, Y. Zhu, T. Fu, C. Hao, Y. Huang, H. Ren, N. Yan and H. Zhai, *Chem. Eng. J.*, 2024, **485**, 150105.

59 D. Chen, H. Bai, H. Zhu, S. Zhang, W. Wang and W. Dong, *Chem. Eng. J.*, 2024, **480**, 148192.