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Supplementary information

Stimulation of ambient energy generated electric field on crop plant growth

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Supplementary Information for

Stimulation of ambient energy generated electric field on crop plant growth

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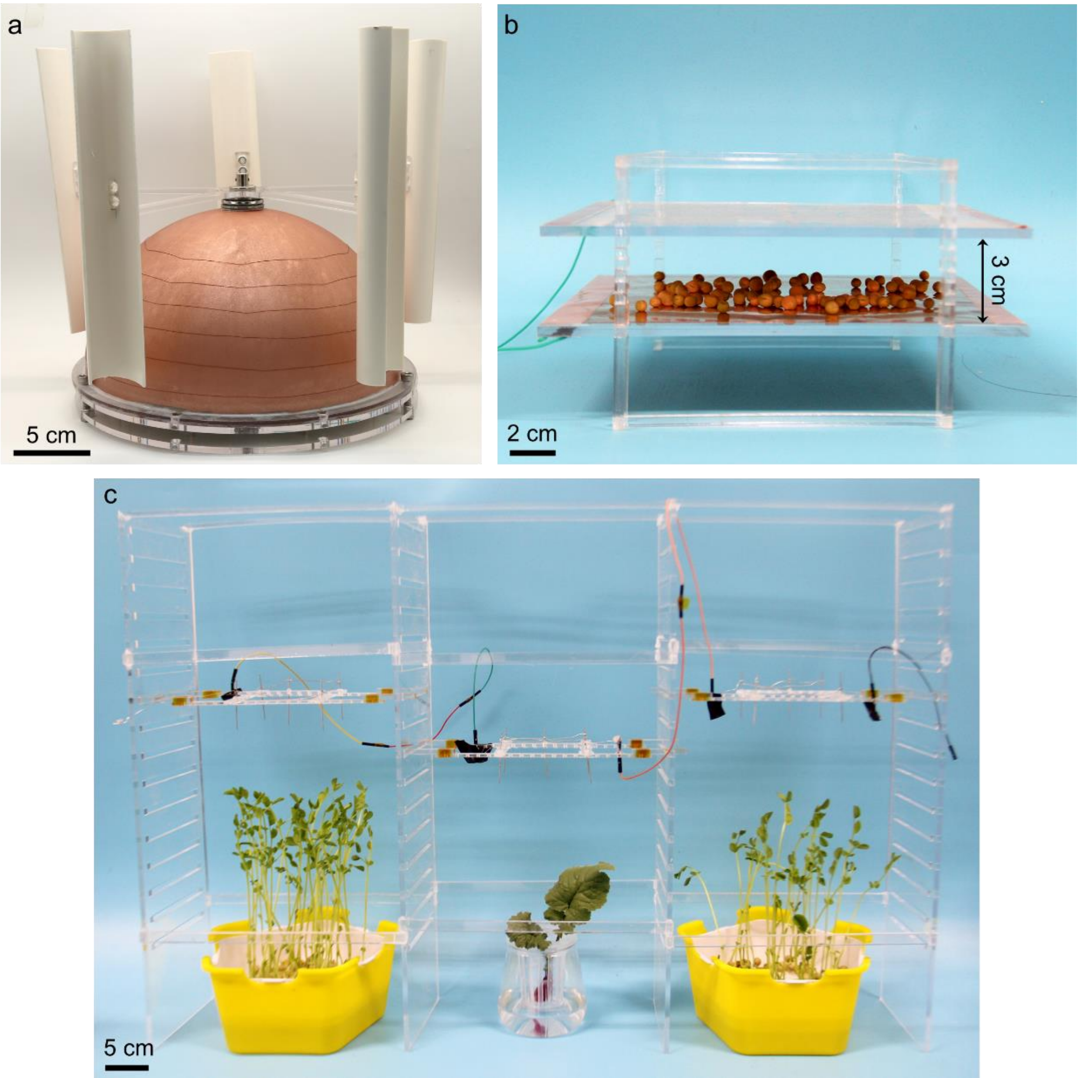
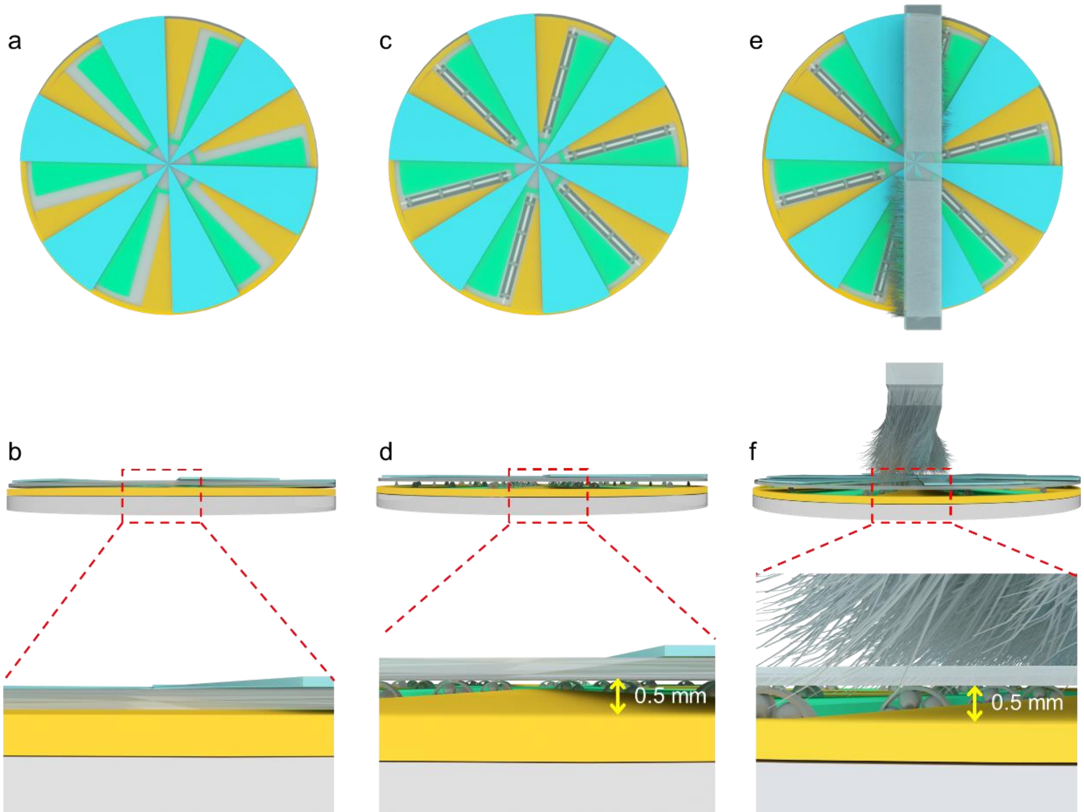
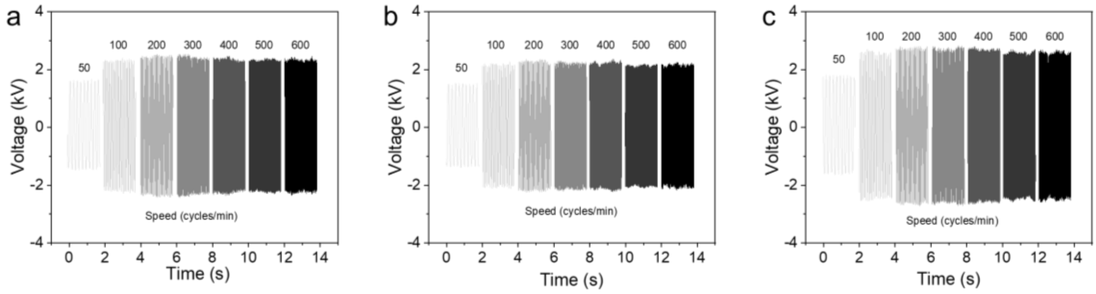
Supplementary Figures



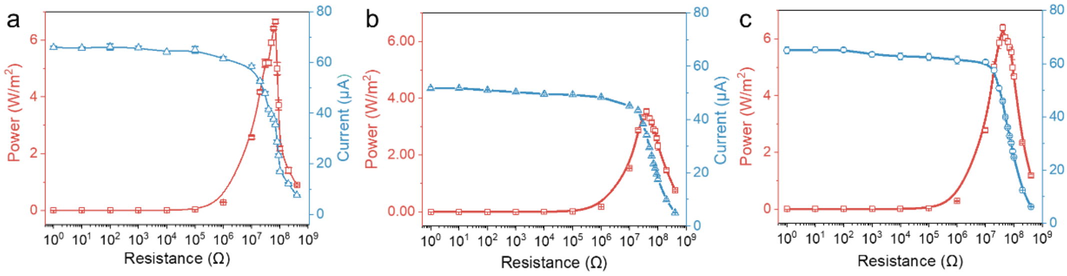
Supplementary Fig. 1 Photographs of the (**a**) AW-TENG, and electric field generators for (**b**) germination promoting and (**c**) growth acceleration. The detailed design and fabrication of them were presented in the section of "Methods".



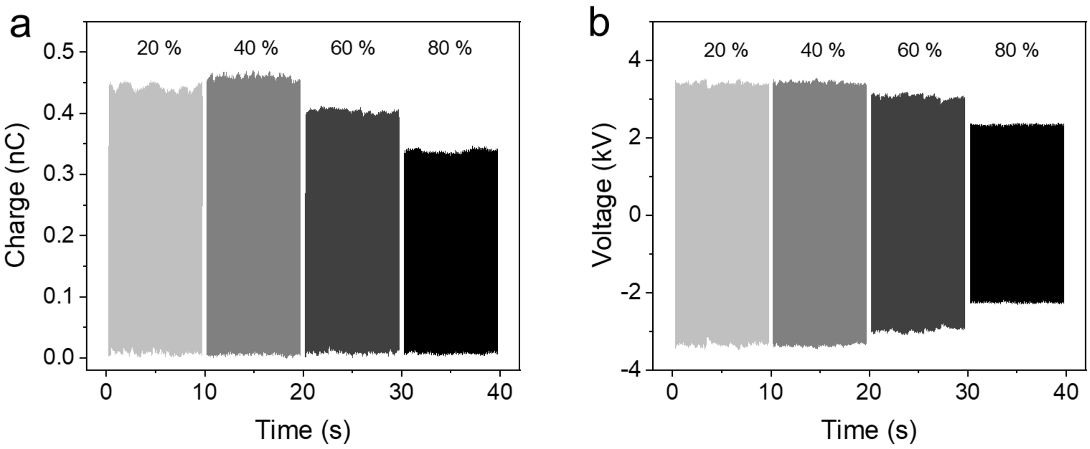
Supplementary Fig. 2 Overlooking, side-viewing, and corresponding detailed structures of the (**a**, **b**) traditional rotation-mode TENG, (**c**, **d**) B-TENG, and (**e**, **f**) BH-TENG.



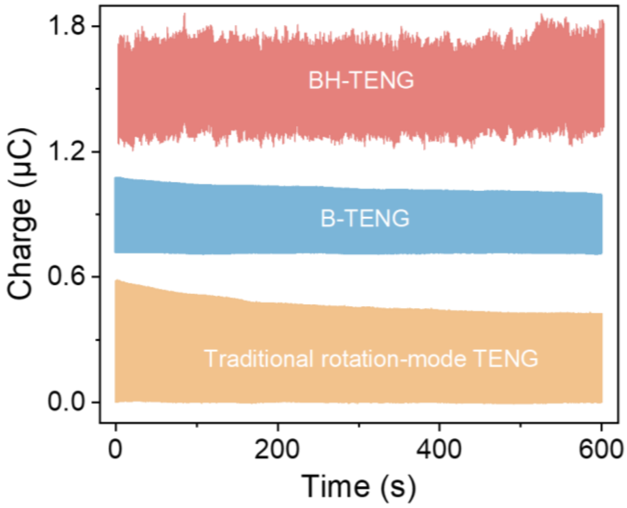
Supplementary Fig. 3 The output voltage of (**a**) the traditional rotation-mode TENG, (**b**) B-TENG, and (**c**) BH-TENG under different rotating speeds. Ambient relative humidity was set as ~40% and the gap height in B-TENG and BH-TENG was 0.5 mm.



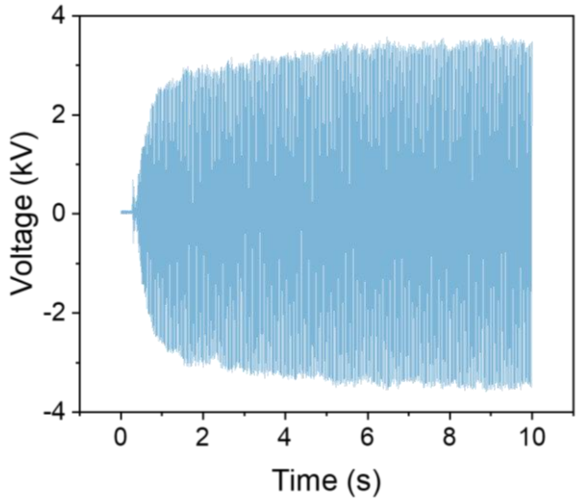
Supplementary Fig. 4 Instantaneous output power density and output current of (**a**) the traditional rotation-mode TENG, (**b**) B-TENG, and (**c**) BH-TENG. Ambient relative humidity was set as ~40%. Rotating speed was set as 400 r/min and the gap height in BH-TENG was 0.5 mm. Values are means ± s.d. (n = 3 independent tests).



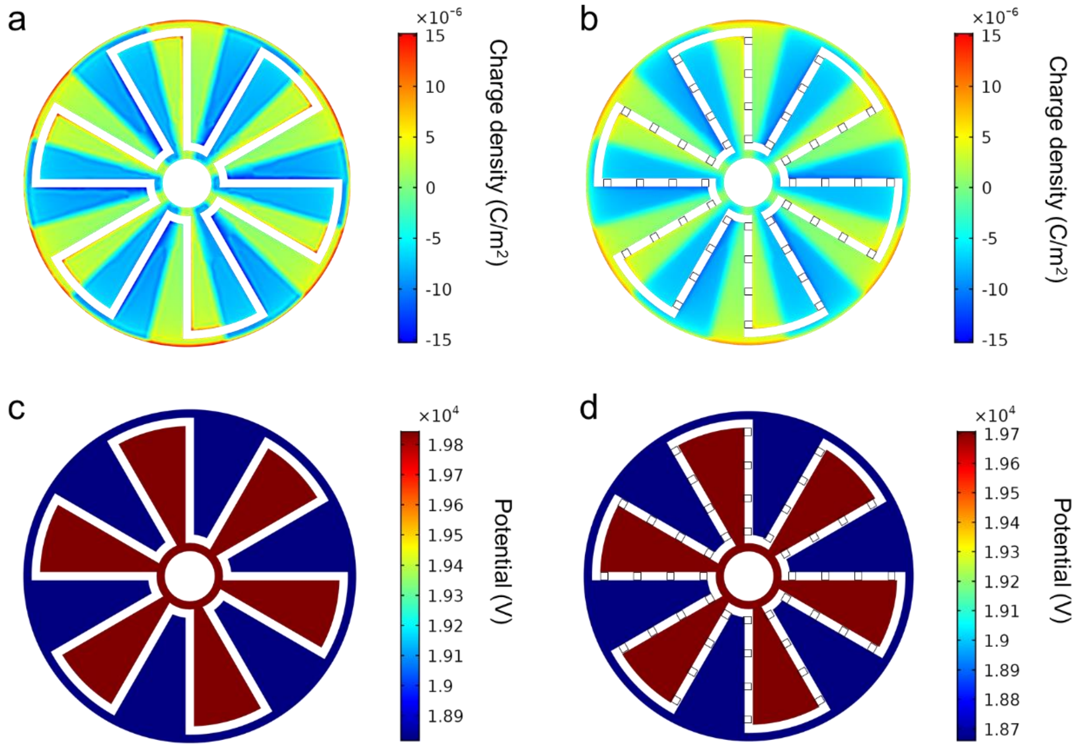
Supplementary Fig. 5 (**a**) Transfer charge and (**b**) output voltage of BH-TENG under different humidity. Rotating speed was set as 400 r/min and the gap height in BH-TENG was 0.5 mm.



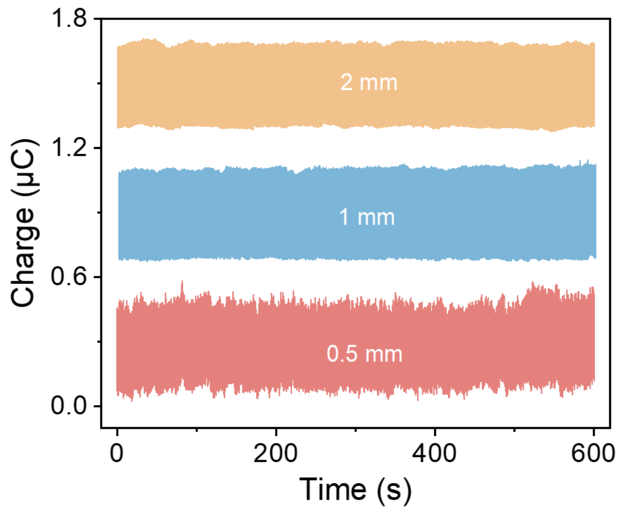
Supplementary Fig. 6 Output stability of the BH-TENG, B-TENG, and traditional rotation-mode TENG under the rotating speed of 400 r/min. Ambient relative humidity was set as ~40%. The gap height in B-TENG and BH-TENG was 0.5 mm.



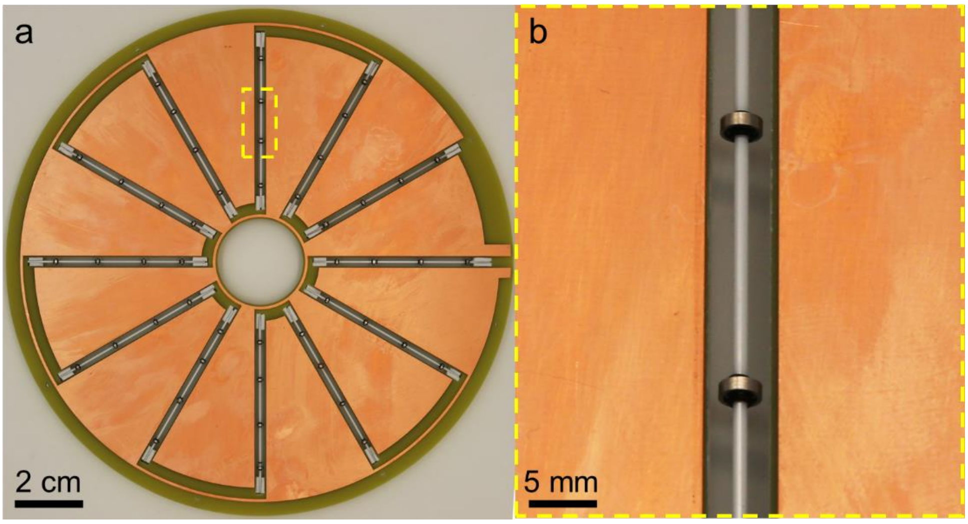
Supplementary Fig. 7 The output voltage of the BH-TENG within 10 s after startup under the rotating speed of 400 r/min. Ambient relative humidity was set as ~40% and the gap height in BH-TENG was 0.5 mm.



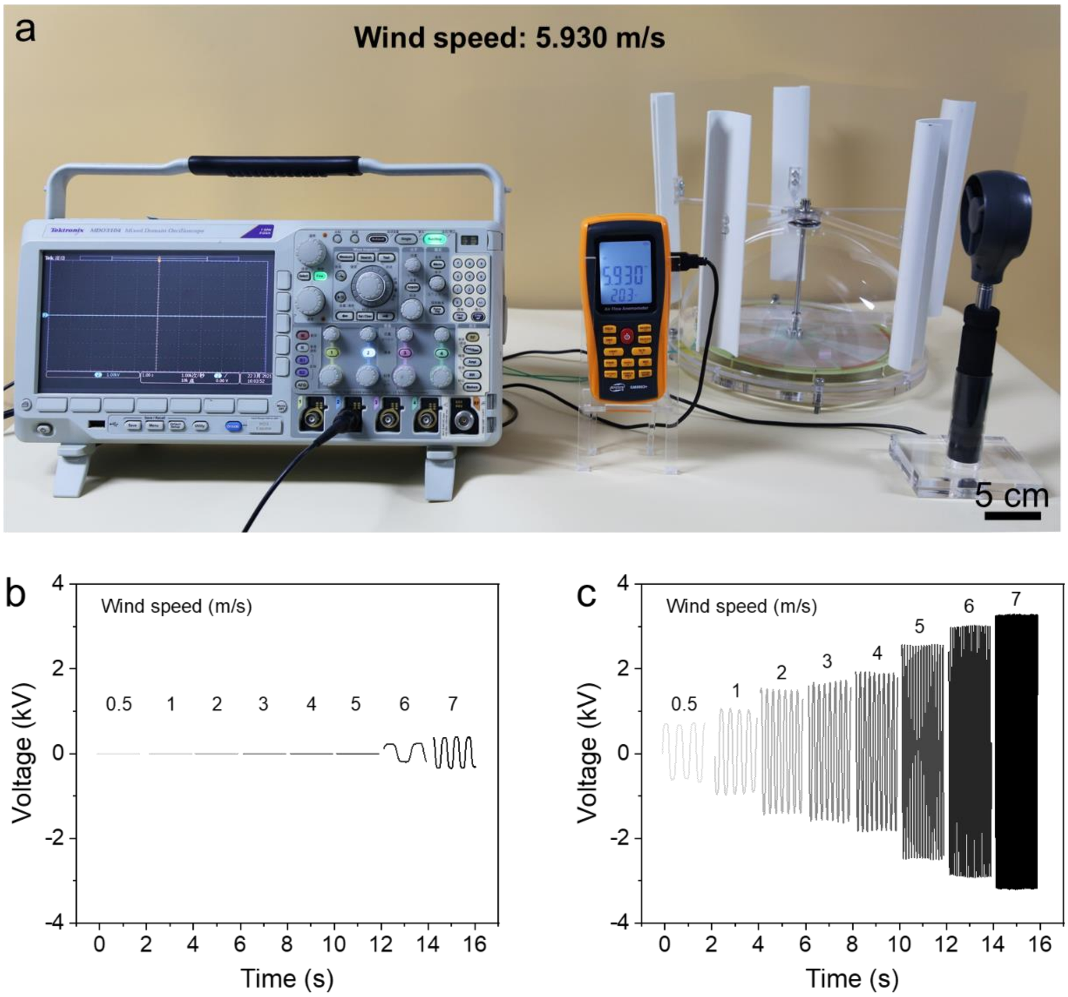
Supplementary Fig. 8 a,**b,** Surface charge density and (**c**, **d**) potential simulation of the traditional rotation-mode TENG and BH-TENG by COMSOL software.



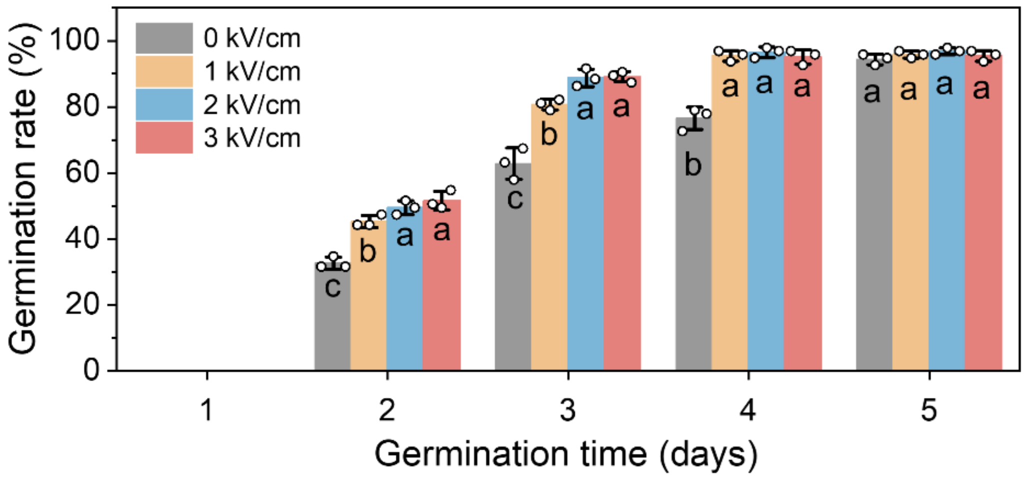
Supplementary Fig. 9 Output stability of BH-TENG with bearing spacers of different heights (0.5 mm, 1mm, and 2 mm) under the rotating speed of 400 r/min. Ambient relative humidity was set as ~40%.



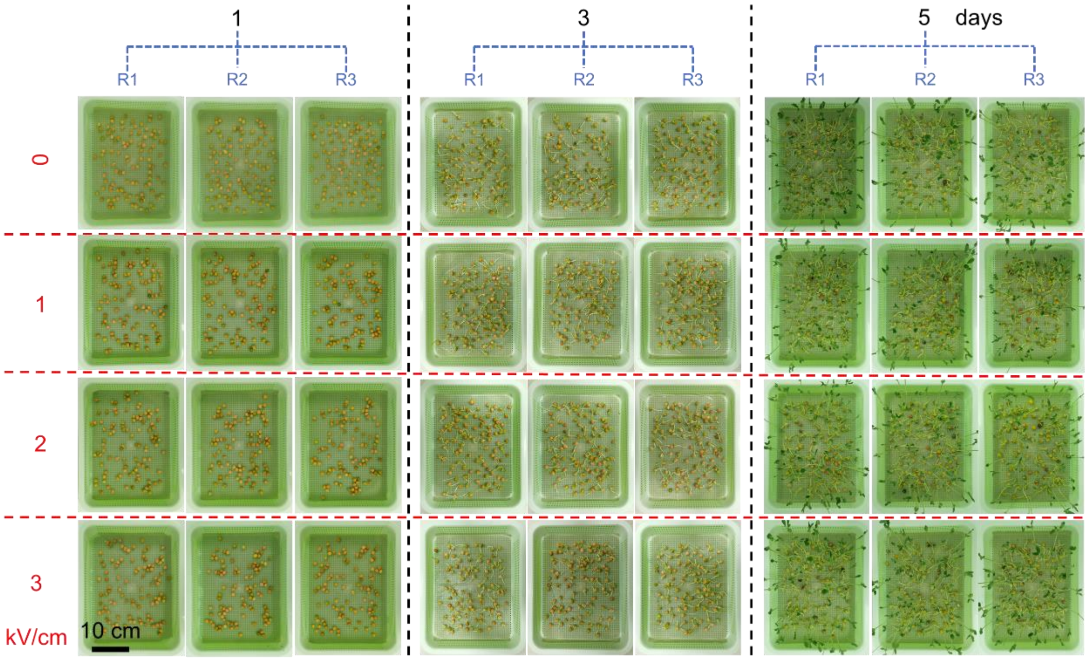
Supplementary Fig. 10 a, A photograph of the stator in BH-TENG and (**b**) the detailed structure of bearing spacers. Detailed structure design was shown in the section of “Methods”.



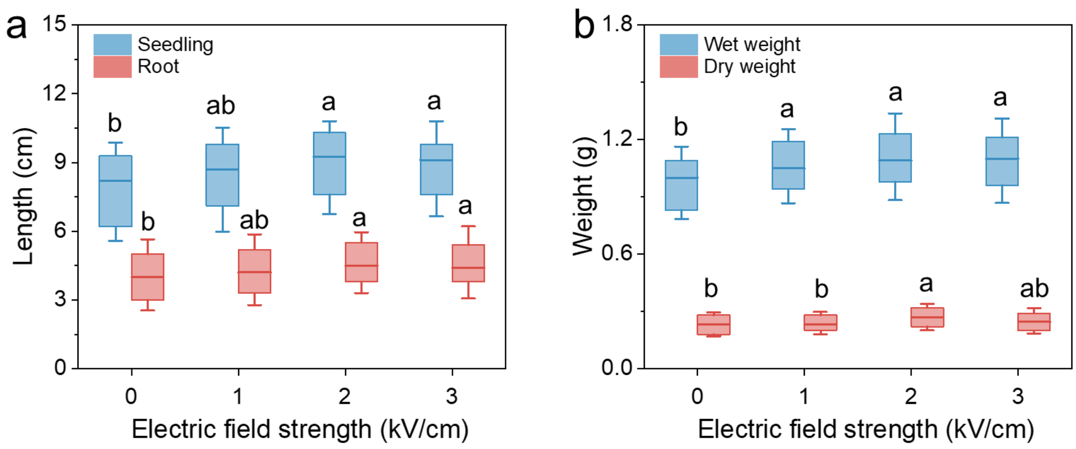
Supplementary Fig. 11 a, Operation status of traditional rotation-mode TENG under a wind speed of 5.930 m/s. The output voltage of the (**b**) traditional rotation-mode TENG and (**c**) BH-TENG under different wind speeds. Ambient relative humidity was set as ~40% and the gap height in BH-TENG was 0.5 mm. The wind was induced by an air blower, and the distance between the air blower and BH-TENG was ~1 m.



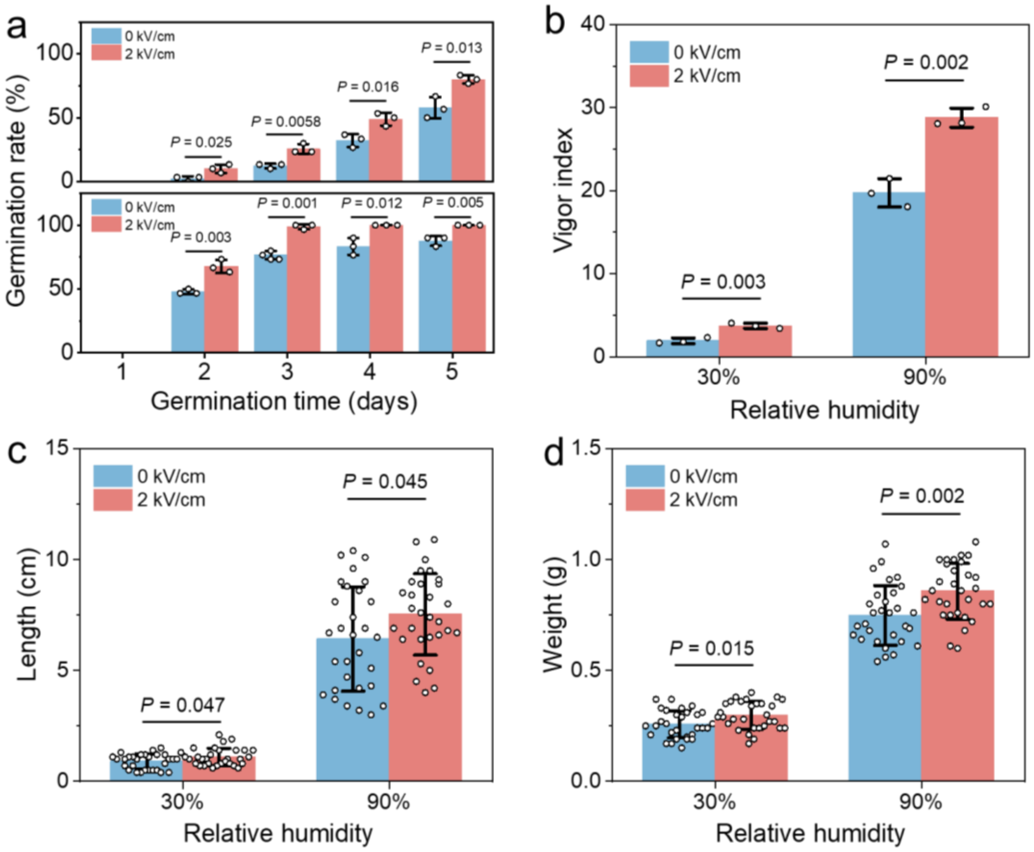
Supplementary Fig. 12 Germination rate of pea seeds treated with the self-powered electric field of different field strengths after different days. Values are means ± s.d. (n = 3 independent experimental groups; each group contained 95 independent seeds). The data were analysed by ANOVA one-way comparison followed by LSD test. Different letters in bars indicate a significant difference at $P < 0.05$. The P value of data in second day versus the 0 kV/cm for 1 kV/cm is 1.0×10^{-4}, for 2 kV/cm is 1.2×10^{-5}, and for 3 kV/cm is 5.0×10^{-6}. The P value of data in third day versus the 0 kV/cm for 1 kV/cm is 7.3×10^{-5}, for 2 kV/cm is 5.0×10^{-6}, and for 3 kV/cm is 4×10^{-6}. The P value of data in fourth day versus the 0 kV/cm for 1 kV/cm is 8.0×10^{-6}, for 2 kV/cm is 6.0×10^{-6}, and for 3 kV/cm is 1.0×10^{-5}. The P value of data in fifth day versus the 0 kV/cm for 1 kV/cm is 0.24, for 2 kV/cm is 0.06, and for 3 kV/cm is 0.37.



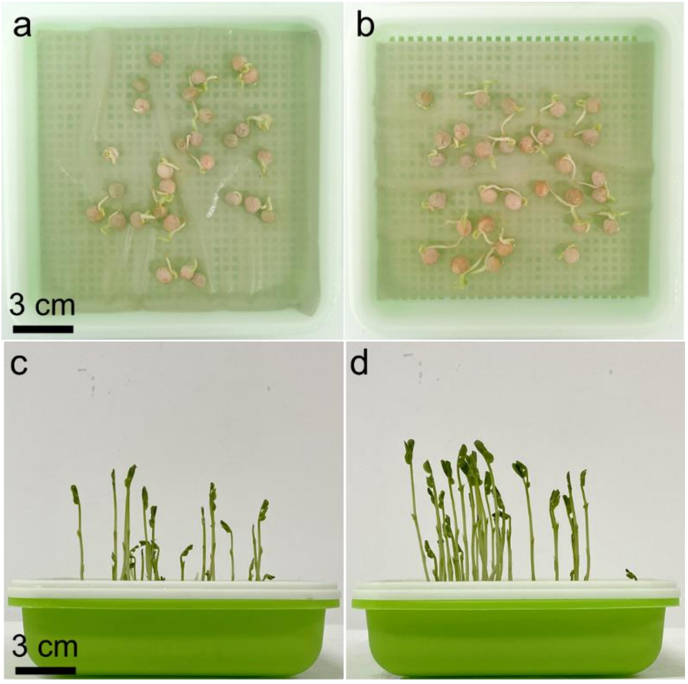
Supplementary Fig. 13 Detailed germination status of seeds treated with the self-powered electric field of different field strengths in 5 days. The letters of R1, R2, and R3 indicate 3 repeats and each repeats contained 95 independent seeds. The germination of seeds was performed in a dark room, and the ambient temperature and relative humidity were maintained at 25 °C and 60% by using an air conditioner and humidifier.



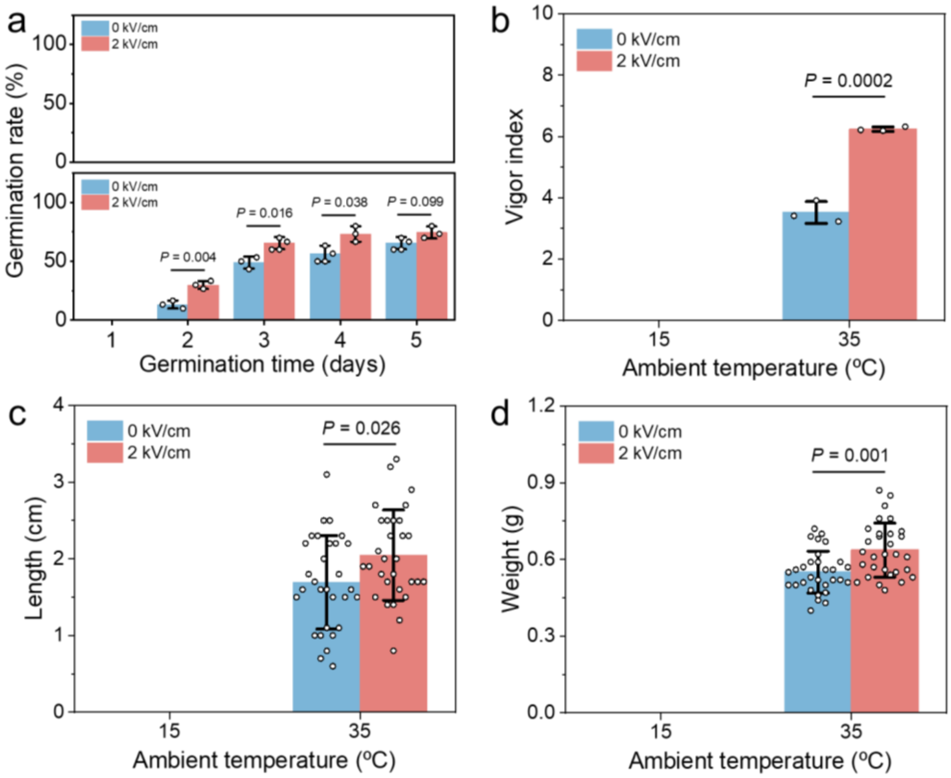
Supplementary Fig. 14 a, Average length of seedling and root, and (**b**) average fresh wet and dry weight of seeds treated with the self-powered electric field of different field strengths after 5-days germination. Values are means ± s.d. (*n* = 3 independent experimental groups; each group contains 30 independent seedlings). The box plots show median (solid line), 25th and 75th percentile (top and bottom of boxes) and SD (whiskers).The data were analysed by ANOVA one-way comparison followed by LSD test. Different letters in bars indicate a significant difference at $P < 0.05$. The P value of seedling data in (**a**) versus the 0 kV/cm for 1 kV/cm is 0.1, for 2 kV/cm is 0.001, and for 3 kV/cm is 0.0017. The P value of root data in (**a**) versus the 0 kV/cm for 1 kV/cm is 0.31, for 2 kV/cm is 0.018, and for 3 kV/cm is 0.015. The P value of wet weight data in (**b**) versus the 0 kV/cm for 1 kV/cm is 0.006, for 2 kV/cm is 1.6×10^{-5}, and for 3 kV/cm is 2.6×10^{-4}. The P value of dry weight data in (**b**) versus the 0 kV/cm for 1 kV/cm is 0.52, for 2 kV/cm is 0.0001, and for 3 kV/cm is 0.051.



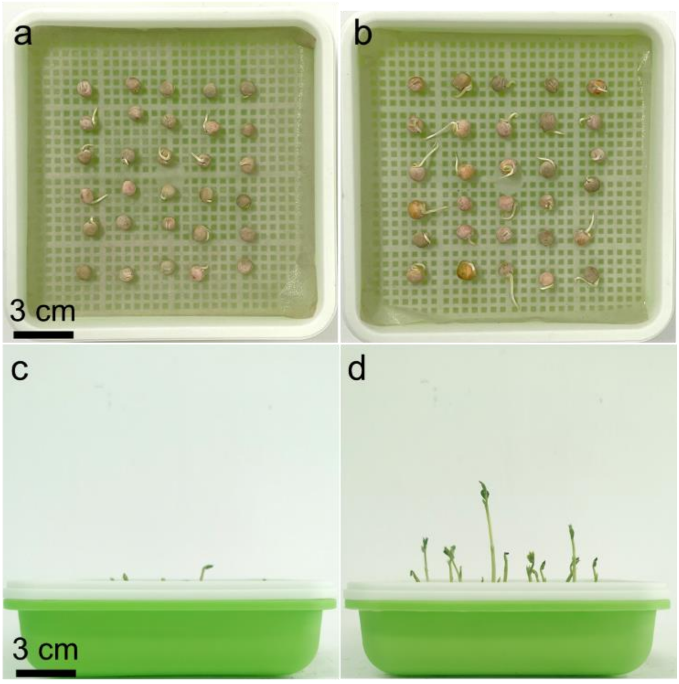
Supplementary Fig. 15 **a**, Germination rate of pea seeds untreated or treated with the self-powered electric field of 2 kV/cm after different days. Upper: Pea seeds germinated under the ambient relative humidity of 30%. Lower: Pea seeds germinated under the ambient relative humidity of 90%. Values are means ± s.d. (n = 3 independent experimental groups; each group contained 30 independent seeds). **b**, Vigor index of the pea seeds treated with the self-powered electrical field of different strengths after 5-days germination under different ambient relative humidity. Values are means ± s.d. (n = 3 independent experimental groups; each group contained 30 independent seeds; their calculation refers to Supplementary Note 3). **c**, Average seedling length and (**d**) fresh wet weight of seeds untreated or treated with the self-powered electric field of 2 kV/cm after 5-days germination under different ambient relative humidity. Values are means ± s.d. (n = 3 independent experimental groups; each group contains 10 randomly selected independent seedlings). The germination of seeds was performed in a dark room and the ambient temperature was set as 25 °C. P values are based on two-tailed, two-sample t-tests.



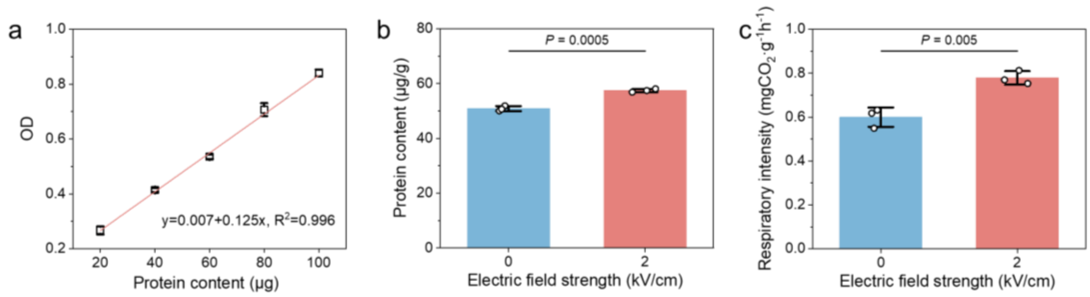
Supplementary Fig. 16 Germination status of peas (**a**) untreated and (**b**) treated with the self-powered electrical field of 2 kV/cm after 5-days germination under the ambient relative humidity of 30%. Germination status of peas (**c**) untreated and (**d**) treated with the self-powered electrical field of 2 kV/cm after 5-days germination under the ambient relative humidity of 90%. The germination of seeds was performed in a dark room and the ambient temperature was set as 25 °C.



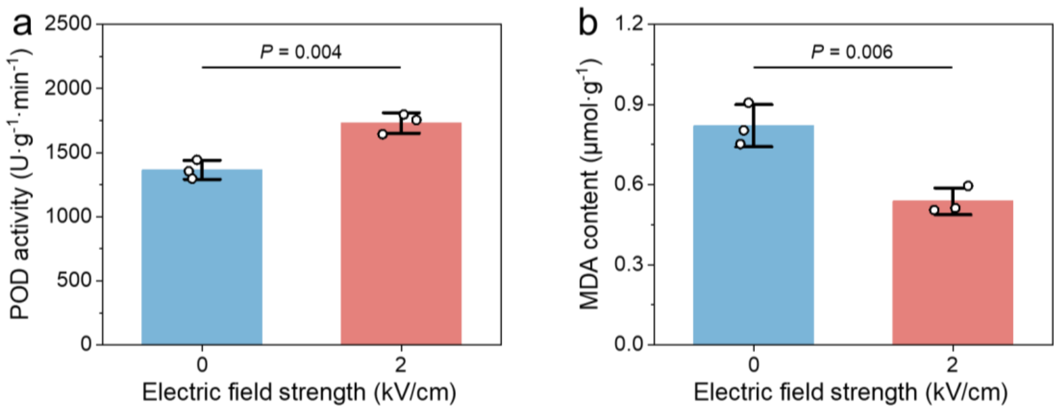
Supplementary Fig. 17 a, Germination rate of pea seeds untreated or treated with the self-powered electric field of 2 kV/cm after different days. Upper: Pea seeds germinated under the ambient temperature of 15 °C. Lower: Pea seeds germinated under the ambient temperature of 35 °C. Values are means ± s.d. (*n* = 3 independent experimental groups; each group contained 30 independent seeds). **b**, Vigor index of the pea seeds treated with the self-powered electrical field of different strengths after 5-days germination under different ambient temperatures. Values are means ± s.d. (*n* = 3 independent experimental groups; each group contained 30 independent seeds; their calculation refers to Supplementary Note 3). **c**, Average seedling length and (**d**) fresh wet weight of seeds untreated or treated with the self-powered electric field of 2 kV/cm after 5-days germination under different ambient temperatures. Values are means ± s.d. (*n* = 3 independent experimental groups; each group contains 10 randomly selected independent seedlings). The germination of seeds was performed in a dark room and the ambient relative humidity was set as 60%. *P* values are based on two-tailed, two-sample t-tests. It is worth noting that the 5-day growth data of seeds at low temperature (15 °C) are missing because the low temperature significantly reduced the seed germination speed, and only roots but no shoots still grew even on the fifth day.



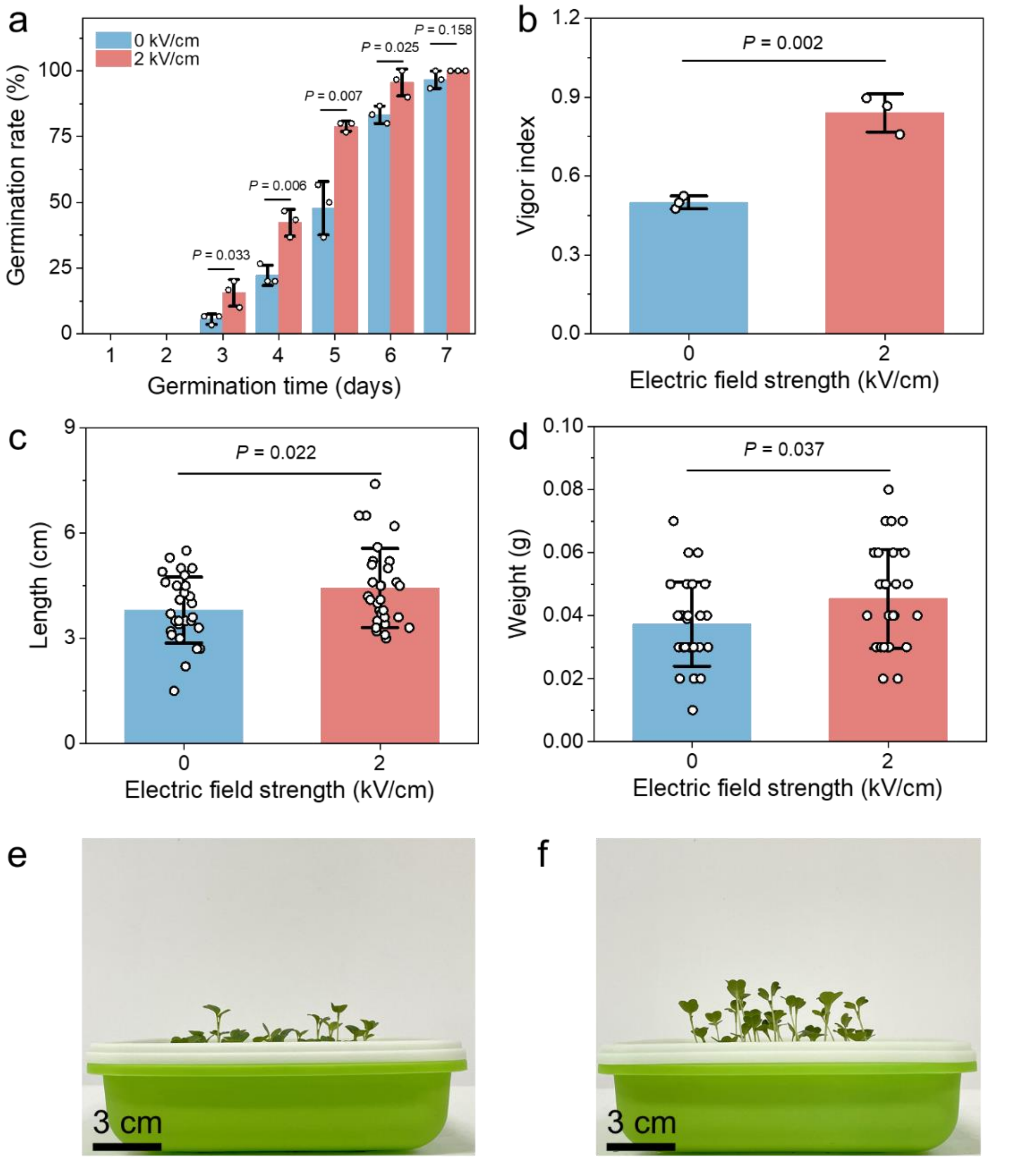
Supplementary Fig. 18 Germination status of peas (**a**) untreated and (**b**) treated with the self-powered electrical field of 2 kV/cm after 5-days germination under the ambient temperature of 15 °C. Germinatin status of peas (**c**) untreated and (**d**) treated with the self-powered electrical field of 2 kV/cm after 5-days germination under the ambient temperature of 35 °C. The germination of seeds was performed in a dark room and the ambient relative humidity was set as 60%.



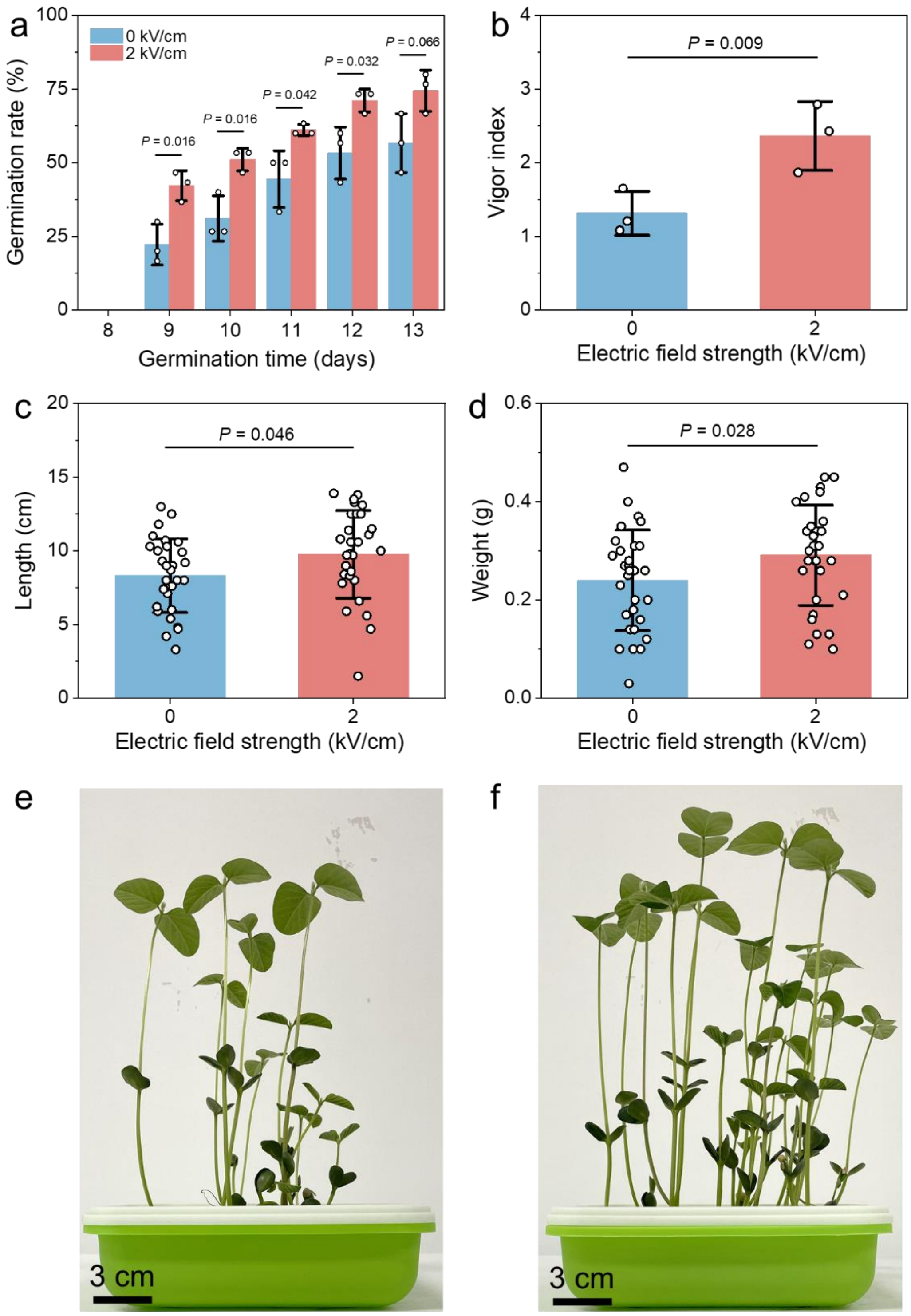
Supplementary Fig. 19 a, The standard curve for soluble protein content calculating and (**b**) soluble protein content of the seeds treated with the self-powered electric field of different field strengths after 5-days germination. **c**, Respiratory intensity of the seeds treated with the self-powered electric field of different field strengths after 5-days germination. Values are means ± s.d. (n = 3 independent tests; their calculation refers to Supplementary Note 4 and Note 5). P values are based on two-tailed, two-sample t-tests.



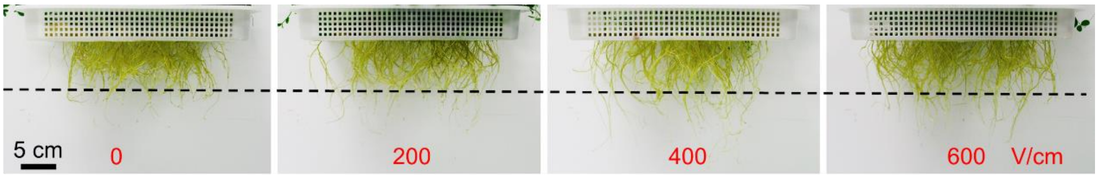
Supplementary Fig. 20 **a**, POD activity and (**b**) MDA content of the seeds treated with the self-powered electric field of different field strengths after 5-days germination. Values are means ± s.d. (n = 3 independent tests; their calculation refers to Supplementary Note 6 and Note 7). P values are based on two-tailed, two-sample t-tests.



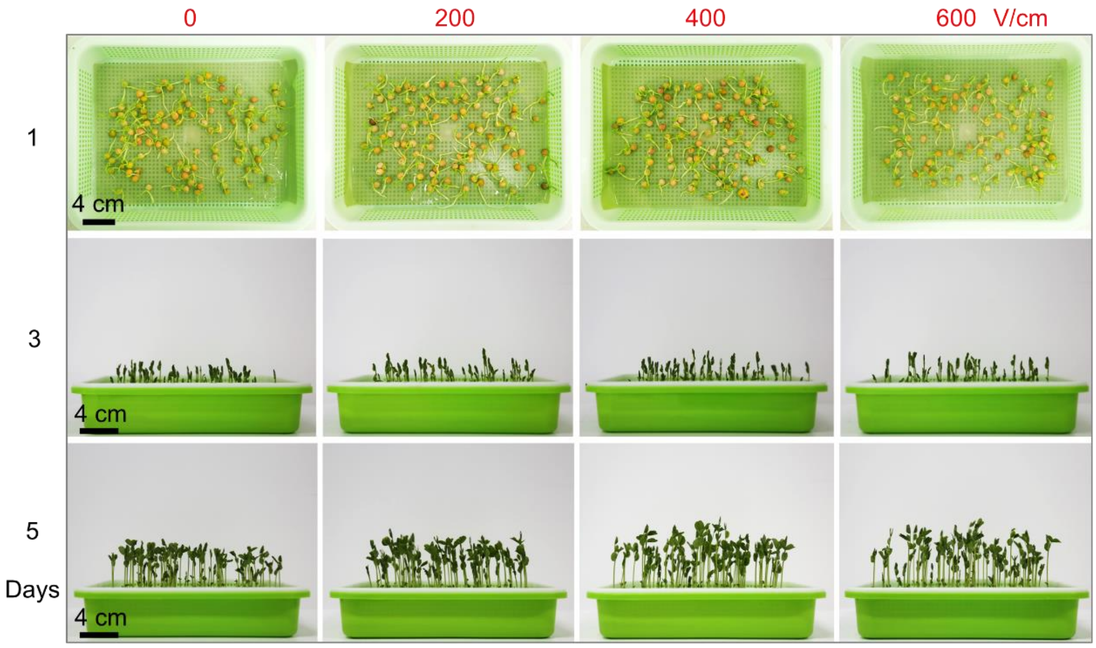
Supplementary Fig. 21 a, Germination rate of Chinese cabbage seeds untreated or treated with the self-powered electric field of 2 kV/cm after different days. Values are means ± s.d. (n = 3 independent experimental groups; each group contained 30 independent seeds). **b**, Vigor index of the Chinese cabbage seeds treated with the self-powered electrical field of different strengths after 7-days germination. Values are means ± s.d. (n = 3 independent experimental groups; each group contained 30 independent seeds; their calculation refers to Supplementary Note 3). **c**, Average seedling length and (**d**) fresh wet weight of seeds untreated or treated with the self-powered electric field of 2 kV/cm after 7-days germination. Values are means ± s.d. (n = 3 independent experimental groups; each group contains 10 randomly selected independent seedlings). Germination status of (**e**) Chinese cabbage seeds untreated and (**f**) treated with the self-powered electrical field of 2 kV/cm after 7-days germination. The germination of seeds was performed in a dark room. The ambient temperature and relative humidity were set as 25 °C and 60%, respectively. *P* values in (**a-d**) are based on two-tailed, two-sample t-tests.



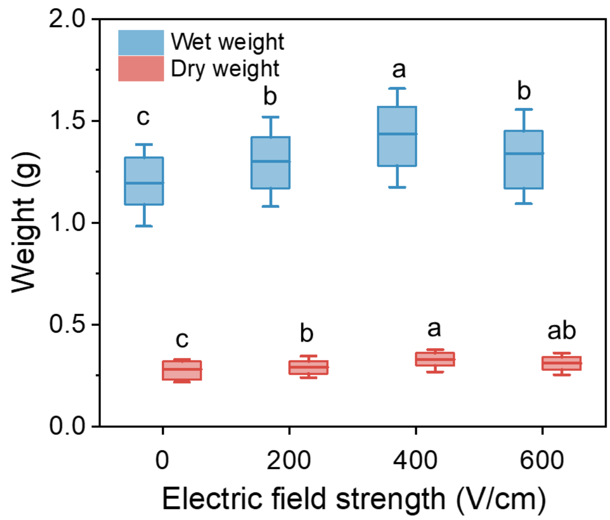
Supplementary Fig. 22 a, Germination rate of soybean seeds untreated or treated with the self-powered electric field of 2 kV/cm after different days. Values are means ± s.d. (n = 3 independent experimental groups; each group contained 30 independent seeds). **b**, Vigor index of the soybean seeds treated with the self-powered electrical field of different strengths after 13-days germination. Values are means ± s.d. (n = 3 independent experimental groups; each group contained 30 independent seeds; their calculation refers to Supplementary Note 3). **c**, Average seedling length and (d) fresh wet weight of seeds untreated or treated with the self-powered electric field of 2 kV/cm after 13-days germination. Values are means ± s.d. (*n* = 3 independent experimental groups; each group contains 10 randomly selected independent seedlings). Germination status of (**e**) soybean seeds untreated and (**f**) treated with the self-powered electrical field of 2 kV/cm after 13-days germination. The seedling heights refer to the height of soybean sprouts. The germination of seeds was performed in a dark room. The ambient temperature and relative humidity were set as 25 °C and 60%, respectively. *P* values in (**a**-**d**) are based on two-tailed, two-sample t-tests.



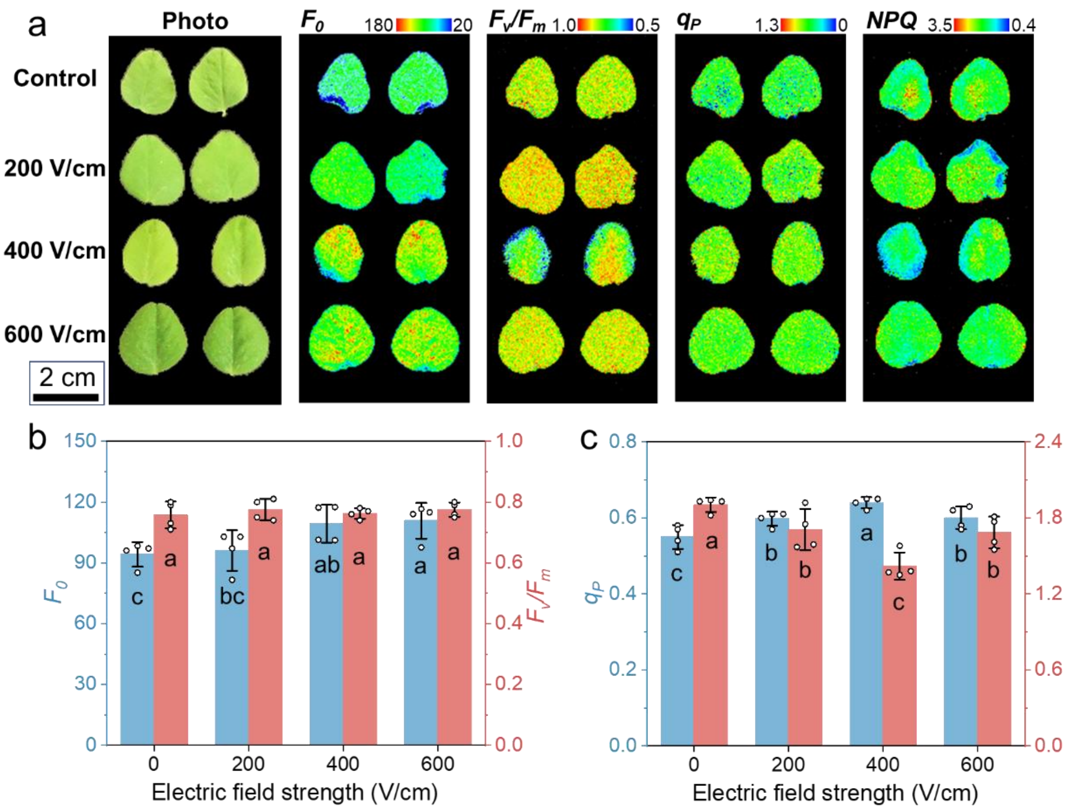
Supplementary Fig. 23 Photographs of roots of the pea seedlings treated with the self-powered electric field of different field strengths for 7 days. The light of plants was provided by full-spectrum LEDs with a strength of 4000 Lux for 12 h every day, and the ambient temperature and relative humidity were maintained at 25 °C and 60% by using an air conditioner and humidifier.



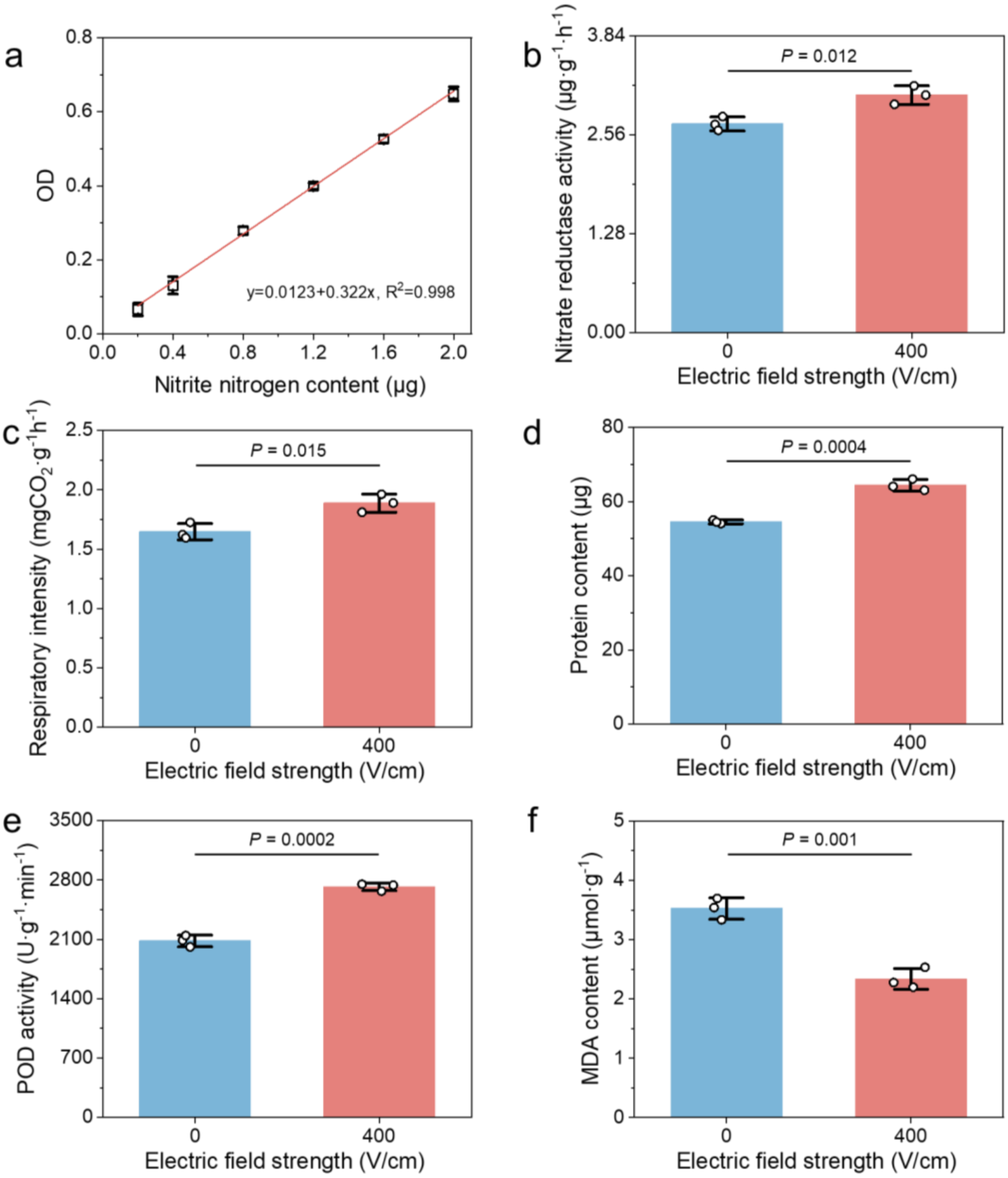
Supplementary Fig. 24 The growth status of the pea seedlings treated with the self-powered electric field of different field strengths for different days. The light of plants was provided by full-spectrum LEDs with a strength of 4000 Lux for 12 h every day, and the ambient temperature and relative humidity were maintained at 25 °C and 60% by using an air conditioner and humidifier.



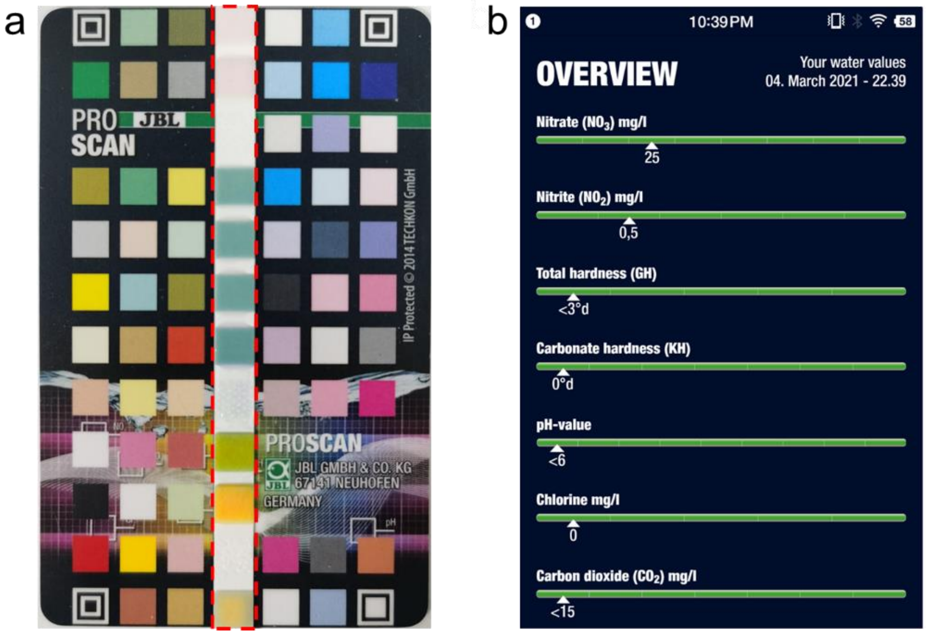
Supplementary Fig. 25 The wet and dry weight of pea seedlings treated with the self-powered electric field of different field strengths for 7 days. Values are means ± s.d. (n = 3 independent experimental groups; each group contains 30 independent seedlings). The data were analysed by ANOVA one-way comparison followed by LSD test. Different letters above boxes indicate a significant difference at $P < 0.05$. The box plots show median (solid line), 25th and 75th percentile (top and bottom of boxes) and SD (whiskers). The P value of wet weight data versus the 0 V/cm for 200 V/cm is 0.0006, for 400 V/cm is 1.5×10^{-11}, and for 600 V/cm is 3×10^{-5}. The P value of dry weight data versus the 0 kV/cm for 200 V/cm is 0.014, for 400 V/cm is 1.5×10^{-9}, and for 600 V/cm is 2.3×10^{-5}.



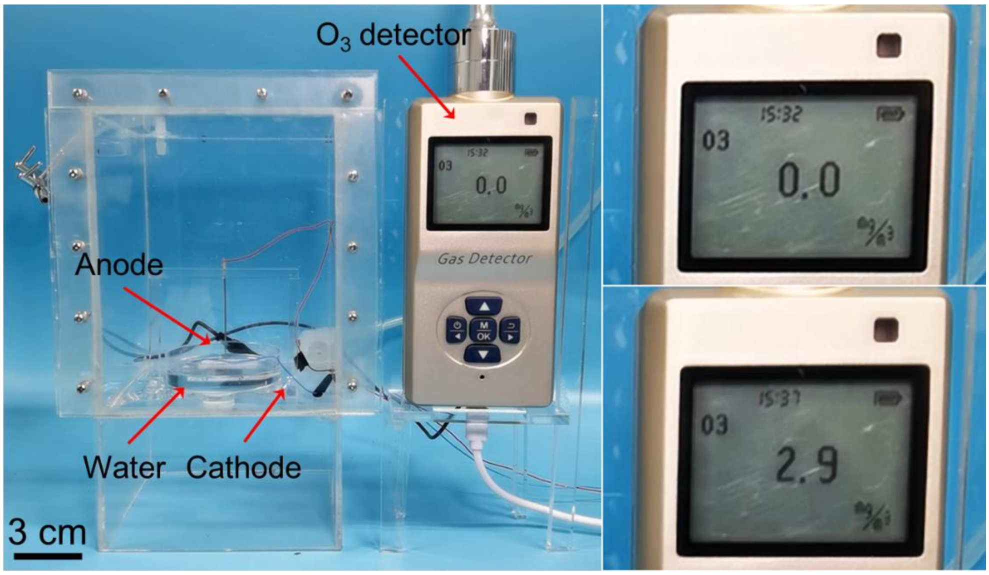
Supplementary Fig. 26 a, Chlorophyll fluorescence images correspond to *Fo*, *Fv/Fm*, q_p, and *NPQ* of pea leaves under different strength of electric fields. Average values of (**b**) *Fo*, *Fv/Fm*, (**c**) q_p, and *NPQ* calculated from related chlorophyll fluorescence images. Values in (**b**) and (**c**) are means ± s.d. (n = 4 independent leaves; the measurement refers to Supplementary Note 9). The data were analysed by ANOVA one-way comparison followed by LSD test. Different letters in bars indicate a significant difference at $P < 0.05$. The P value of F_0 data in (**b**) versus the 0 V/cm for 200 V/cm is 0.76, for 400 V/cm is 0.03, and for 600 V/cm is 0.019. The P value of F_v/F_m data in (**b**) versus the 0 V/cm for 200 V/cm is 0.452, for 400 V/cm is 0.829, and for 600 V/cm is 0.452. The P value of q_P data in (**c**) versus the 0 V/cm for 200 V/cm is 0.018, for 400 V/cm is 0.0002, and for 600 V/cm is 0.014. The P value of *NPQ* data in (**c**) versus the 0 V/cm for 200 V/cm is 0.037, for 400 V/cm is 0.0001, and for 600 V/cm is 0.023.



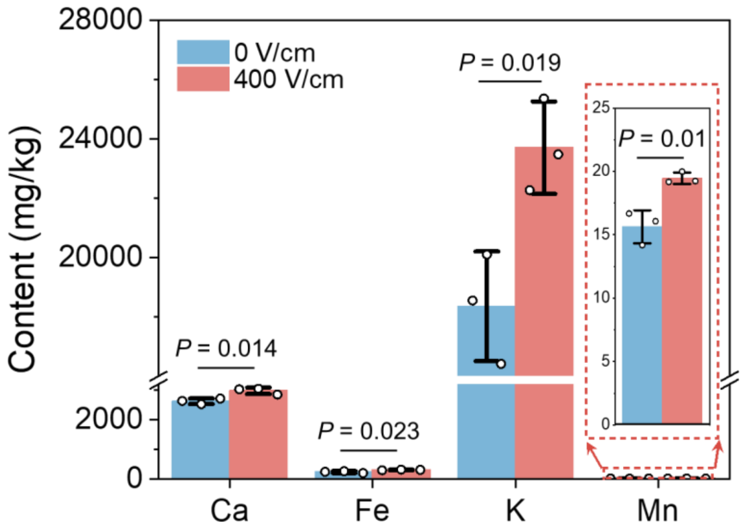
Supplementary Fig. 27 **a**, Standard curve for nitrate reductase activity of pea seedlings calculating and (**b**) nitrate reductase activity of the pea seedlings untreated and treated with the self-powered electric field for 7 days. **c**, Respiratory intensity, (**d**) soluble protein content, (**e**) POD activity, and (**f**) MDA content of the pea seedlings untreated and treated with the self-powered electric field for 7 days. Values are means ± s.d. (n = 3 independent tests; their calculation refers to Supplementary Note 4 to Note 7, and Note 10). P values in (**b-f**) are based on two-tailed, two-sample t-tests.



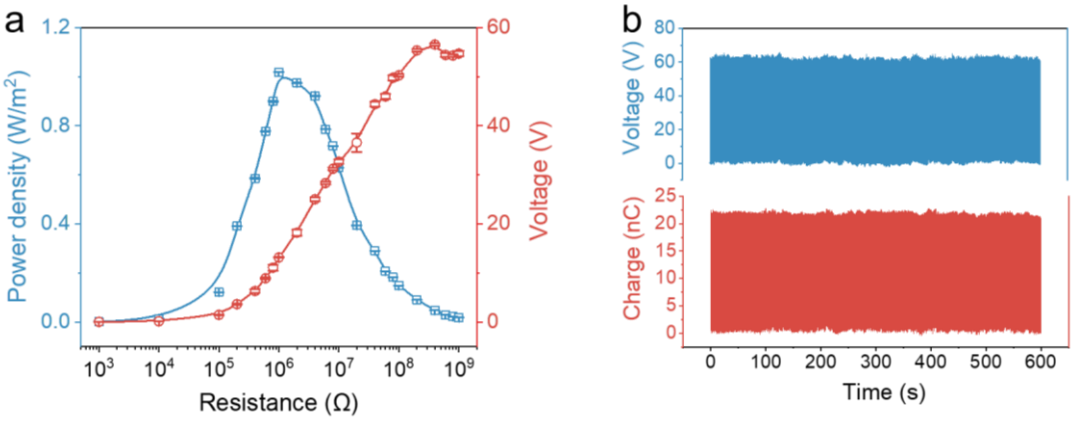
Supplementary Fig. 28 a, Photograph of the test card for testing the concentration of nitrogen oxides dissolved in water. **b**, The concentration of the nitrogen oxides dissolved in water. The test card (JBL PROSCAN Color Card) for NO_x was purchased from JBL GmbH & Co. KG. After full contact with the solution, the color on the card can be identified and analyzed by the relevant phone to calculate the concentration of NO_x in the solution.



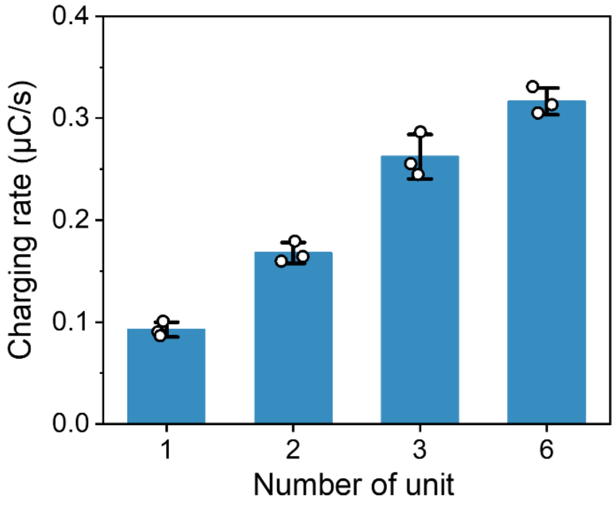
Supplementary Fig. 29 The concentration of O_3 produced by SAPIS in the container after 5 min. The device consists of a homemade closed chamber, a pump suction-type O_3 detector, and a needle for air ionizing.



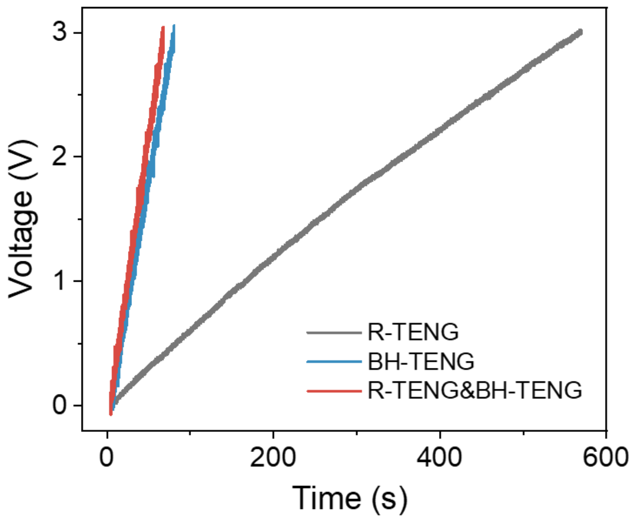
Supplementary Fig. 30 Trace element (Ca, Fe, K, and Mn) content of the pea seedlings treated with the self-powered electric field of different field strengths for 7 days. Values are means ± s.d. (n = 3 independent tests; their calculation refers to Supplementary Note 11). P values are based on two-tailed, two-sample t-tests.



Supplementary Fig. 31 a, Instantaneous output power density and output voltage of the R-TENG with a single unit-array outer electrode. Values are means ± s.d. (n = 3 independent tests) **b**, Output stability of the R-TENG. Ambient relative humidity was set as ~40% and the gap height in BH-TENG was 0.5 mm. The wind was induced by an air blower, and the distance between the air blower and BH-TENG was ~1 m. DI water was used to drip and the outlet inner diameter is 1.69 mm. The dripping height was 14 cm and the dripping frequency was 2 Hz.



Supplementary Fig. 32 Charging rate of the R-TENG of different electrode unit numbers to charge a capacitor of 10 μF to 5 V. The dripping height was 14 cm and the dripping frequency was 2 Hz. The number of dripping points varies according to the unit number of the R-TENG. Values are means ± s.d. ($n = 3$ independent tests).



Supplementary Fig. 33 Charging voltage curves to a capacitor of 1000 μF for the R-TENG with 6 units-array outer electrode, BH-TENG, and R-TENG&BH-TENG. DI water was used to drip and the outlet inner diameter is 1.69 mm. The dripping height was 14 cm and the dripping frequency was 2 Hz. The rotating speed of BH-TENG was 400 r/min. Ambient relative humidity was set as ~40%.

Supplementary Notes

Supplementary Note 1. Germination potential calculation of pea seeds.

The germination potential is positively associated with the physiological activity intensity of seeds[1]. Germination potential was calculated by counting the sprouted pea seeds on the third day. Moreover, the standard for seed germination is that the length of the green sprouts reaches half of the diameter of the seeds. The formula for calculating seed germination potential is referred to the following:

Germination potential of seeds (%) $= M_1/M \times 100\%$, where M refers to the number of seeds in every group, and M_1 is the number of sprouted seeds in 3 days in every group.

Supplementary Note 2. Determination of germination index of pea seeds.

The germination index is related to the vigor of the seed[2]. The formula for calculating seed germination index is referred to the following:

Germination index of seeds (GI) $= \Sigma \frac{G_t}{D_t}$, where G_t refers to the number of sprouted seeds per day, and D_t is the number of germination days.

Supplementary Note 3. Determination of vigor index of pea seeds.

Vigor index is a comprehensive reflection of seed germination rate and growth status[3]. The formula for calculating vigor index is referred to the following:

Vigor index of seeds (VI)$= GI \times S_0$, where *GI* refers to the germination index, and S_0 is the wet weight of seeds after 5-day germination.

Supplementary Note 4. Determination of soluble protein content (Coomassie brilliant blue staining method).

The determination method referred to the method proposed by Gasparov[4], and only the extraction method was changed according to the crop subject. 0.4 g of fresh pea samples were ground into homogenate with distilled water and centrifuged for 10 min at the rotational speed of 3000-4000 r/min. Then, 1 mL of supernate was put into the tube (repeated twice for each sample) and 5 mL Coomassie brilliant blue reagent (Sinopharm Group Co., Ltd) was added and placed for 2 min. The absorbance of the mixture in every group was determined by a fluorescence spectrophotometer (UV-3600, SHIMADZU Co., Ltd) to build a standard curve, which was used to calculate the soluble protein content in peas. The formula for calculating soluble protein content is referred to the following:

Soluble protein content (mg/g) $= (C \times V_T) / (V_1 \times F_W \times 1000)$, where C refers to the value calculated from the standard curve, V_T refers to the total volume of extract, F_w refers to the fresh weight of samples, and V_1 is the sample volume added during determination.

Supplementary Note 5. Determination of respiratory intensity of peas.

CO_2 volume released by peas is related to respiratory intensity, so the respiratory intensity can be measured by the BA $(OH)_2$ method[5]. The formula for calculating the respiratory intensity of peas is referred to the following:

Respiratory intensity $(mgCO_2 \cdot g^{-1} \cdot h^{-1}) = (V_0 - V_1) / (W \times t)$, where V_0 refers to the value of blank titration, V_1 refers to the value of sample titration, W refers to the fresh weight of samples, and t is the time of the experiment.

Supplementary Note 6. Determination of POD activity of peas.

The determination of peas peroxidase activity was referred to the guaiacol method[6]. The formula for calculating the respiratory intensity of peas is referred to the following:

POD activity $(U \cdot g^{-1} \cdot min^{-1}) = \Delta A470 \times V_T / (0.01 \times T \times V_S \times W)$, which $\Delta A470$ refers to the change of absorbance value during reaction time, V_T refers to the total volume of extraction solution, V_S refers to the volume of enzyme solution for measurement, W refers to the fresh weight of sample, and T is the reaction time.

Supplementary Note 7. Determination of MDA content of pea seedlings.

The concentration of MDA, a lipid peroxidation marker, was determined to investigate the effect induced by the electric field in leaves by spectrophotometric determination following the procedure described by Kumar et al. In each group, 0.5 g of fresh seedling leaves with the same size were randomly cut as the experimental sample, and sampling process was repeated for three times[7]. The formula for calculating the MDA content of pea seedlings is referred to the following:

Concentration of MDA $(C, \mu mol \cdot L^{-1}) = 6.45 \times (OD_{532} - OD_{600}) - 0.56 \times OD_{450}$, *MDA content* $(C, \mu mol \cdot g^{-1}) = C \times V/M$, which OD refers to the absorbance of supernatant at 450 nm, 532 nm, and 600 nm, V refers to the volume of extract volume, and M is the weight of fresh experimental sample.

Supplementary Note 8. Determination of SPAD value of pea seedlings.

The SPAD value was measured by a SPAD measuring instrument (TYS-4N, Zhongkehewei Co. Ltd). 5 fully expanded leaves on the top of each seedling in each group were randomly selected at every noon for measuring in this work[10].

Supplementary Note 9. Chlorophyll fluorescence analysis of pea seedlings.

An enclosed chlorophyll fluorescence imaging system (FluorCam 800-C, P.S. Instruments, Czech Republic) was used to take chlorophyll fluorescence images. Four leaves with the same size were randomly selected from each group for testing. Prior to testing, the leaves were first dark-adapted at room temperature for 20 min. The photochemical light of Actinic2 intensity was 500 μmol m^{-2} s^{-1} and the saturating light intensity was 3000 μmol m^{-2} s^{-1}. The equipment was controlled via a digital interface to a laptop computer to capture fluorescence images of the fixed fluorescence (*Fo*), the maximum photosynthetic efficiency of photosystem II (*Fv/Fm*), photochemical quenching coefficient (*qP*), and non-photochemical quenching (*NPQ*)[11].

Supplementary Note 10. Determination of nitrate reductase activity.

The nitrate reductase activity of the plant can be calculated by the standard curve method[8]. The formula for calculating nitrate reductase activity of pea seedlings is referred to the following:

Nitrate reductase activity ($ug \cdot g^{-1} \cdot h^{-1}$) = $(X \times V_1 \times V_2) / (W \times t)$, which X refers to the total volume of nitrite nitrogen produced by enzyme catalysis in the reaction liquid, V_1 refers to the volume of the buffer added when extracting the enzyme, V_2 Crude enzyme volume added during enzyme reaction, W refers to the sample weight, and t is the reaction time[9].

Supplementary Note 11. Determination of trace element content of pea seedlings.

600 soaked seeds were divided into 2 groups and three parallel samples of 95 were used in every group. These seeds were placed in the dark to germinate for 3 days to obtain the pea seedlings with similar heights. Notably, culture solutions containing certain concentrations of compound fertilizers were used to replace the previous tap water with a concentration of 100 mg/L of Ca and K and 1 mg/L of Fe and Mn. Subsequently, these pea seedlings were treated with the self-powered conical electric field of different strengths for 12 hours a day. After 7-days growth, 1g of leaf tissue was randomly taken from each sample for trace element test.

Supplementary References

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