

In-situ triboelectric nanogenerator for energy self-cycling electrochemical systems in wastewater treatment

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Abstract

Enhancing energy efficiency in wastewater treatment is essential for achieving carbon neutrality in the water sector. However, the potential and feasibility to recover in-situ mechanical energy from the complex and multidirectional fluid dynamics of aeration-induced flows remains underexplored. Here we present a self-sustaining treatment system that couples a coronal triboelectric nanogenerator (C-TENG) with membrane capacitive deionisation (MCDI) for energy self-cycling contaminant removal. The tailored C-TENG could harvest low-frequency water wave energy in aeration tanks to directly power the MCDI unit for the treatment of real wastewater. Both simulations and experimental validation were conducted to optimise the system configuration, obtaining sufficient energy recovery from a single 18 cm-diameter C-TENG unit and allowing the subsequent MCDI to effectively remove phosphorus (95%) and a range of metal ions (70%-80% for Fe³⁺, Ni²⁺, Cu²⁺, Cr³⁺, Cd²⁺, and Pb²⁺) from real secondary effluent. Moreover, integrating 75% energy recovery efficiency through self-regeneration reduced MCDI energy consumption to 0.26 kWh/m³, enabling low-energy ion removal and electric energy storage in the C-TENG//MCDI system, while supporting further treatment. This innovation introduces a scalable and sustainable approach that couples fluidic energy harvesting with electrochemical treatment, offering a viable route to upgrade existing wastewater infrastructure.

Keywords: Coronal triboelectric nanogenerator; Membrane capacitive deionisation; Self-sustaining treatment system; Energy self-cycling; Aeration tanks; Energy recovery

1. Introduction

As global efforts toward nutrient neutrality and net-zero targets accelerate, the water sector is undergoing a significant transformation towards more sustainable wastewater treatment and resource recovery (Li et al., 2014; Yang et al., 2020; Gu et al., 2024). Traditional wastewater treatment plants (WWTPs) are increasingly being re-envisioned as resource recovery centres. Notable examples, such as Singapore's Changi NEWater Project, Denmark's Marselisborg WWTP, and China's Yixing WWTP, demonstrate the feasibility of achieving energy self-sufficient in treatment facilities (Mikkelsen and Keiding, 2002; Wang et al., 2019; Qu et al., 2022). Current sustainable energy strategies primarily focus on two pathways, including 1) direct bioenergy production through anaerobic digestion, which converts organic matter into biogas, and 2) energy demand reduction via innovations such as the anammox process, which significantly lowers aeration requirements (Chen et al., 2023; Gupta and Khatiwada, 2024).

The aforementioned approaches largely depend on the biochemical energy embedded in the organic fraction of wastewater. This energy potential varies significantly across wastewater types, often requiring additional capital investment and substantial modifications to existing treatment flowsheets (Rani et al., 2022). A critical and underexplored opportunity lies in harnessing the mechanical energy inherent to treatment operations, particularly within aeration tanks, where the cause of turbulent water motion accounts for over the half of a WWTP's total energy consumption (Maktabifard et al., 2018; Hao et al., 2024). Exploiting this otherwise wasted hydraulic energy could pave a new way for power generation without altering existing bioprocess flow configurations. Recent advancements in triboelectric nanogenerator (TENG) technology offer a promising avenue for this purpose. TENGs operate through the coupled effects of triboelectrification and electrostatic induction, enabling highly sensitive, self-powered energy harvesting (Wang, 2013; Ye et al., 2021). Their efficacy has been demonstrated in harvesting energy from dynamic environments with periodic and high-amplitude water waves, such as oceans and lakes (Zhao et al., 2024). Nevertheless, their application within WWTPs remains limited due to the fundamentally different hydrodynamic conditions (Gong et al., 2025). Unlike natural wave environments, WWTPs are engineered for stable and controlled operation, resulting in low-amplitude and weakly fluctuating water flows. Even in aeration units, the most hydrodynamically active sections of WWTPs, the kinetic energy is distributed across complex multiphase flows driven by gas-liquid turbulence and irregular surface disturbances (Dong et al., 2022; Gu et al., 2023; Yao et al., 2025; Chen et al., 2025). Therefore, it is essential to develop TENG devices that are not only mechanically and chemically robust but also capable of high energy conversion efficiency and adaptive output control in wastewater treatment scenario.

The subsequent challenge in energy recovery from wastewater treatment processes lies in ensuring compatibility between electricity storage and utilisation, in a way that supports or enhances the existing treatment functions (Liu et al., 2021; Han et al., 2025). TENGs can convert mechanical energy from water flows into current signals by generating alternating current pulses, with hydrodynamic

forces serving as the driver (Cao et al., 2016). However, similar to other on-site energy recovery approaches, the output from TENGs typically requires stabilisation via external components such as capacitors or rectifiers to ensure consistent and usable electrical energy in WWTPs (Zuo et al., 2023; Magni et al., 2025). Along with the contemporary WWTP development, advanced technologies such as Membrane Capacitive Deionization (MCDI) (Zhu et al., 2024), Electrooxidation (EO) (Ajam et al., 2025), and Electrodialysis (ED) (Hajalifard et al., 2023), have been deployed to effectively utilise electricity to remove a range of pollutants, including nutrients, chemical, and biological micropollutants. Among these, MCDI is particularly well-suited to intermittent power sources. Moreover, the system can utilise ion exchange membranes (IEMs) to facilitate selective ion removal while enhancing the in-situ capacitive behaviour of the electrodes (Liu et al., 2020; Zhu et al., 2024). During operation, electrodes are charged to extract ions from the influent stream and can subsequently release stored energy during the regeneration phase (Długołęcki and van der Wal, 2013; Kang et al., 2014). This mechanism offers potential synergy with TENGs, yet its practical performance in storing and cycling TENG-derived energy within the wastewater treatment context remains underexplored.

In this study, we proposed and evaluated a pioneering integrated system based on the concept of 'self-powered and energy self-cycling' wastewater treatment. The prototype combines a coronal triboelectric nanogenerator (C-TENG) with an MCDI unit (C-TENG//MCDI). A low-friction C-TENG was developed to accommodate the low-intensity, low-frequency hydrodynamic conditions typical of wastewater treatment environments. The performance assessments included characterising the electrical output and generation efficiency of the C-TENG, along with stability testing to ensure that its power density is sufficient to continuously drive the electrochemical processes of the MCDI. Furthermore, the wastewater treatment performance was validated using real secondary effluent from a municipal WWTP in order to support its practical applicability.

2. Materials and methods

2.1. Design, fabrication, and experimental evaluation of the C-TENG system

The C-TENG consists of three main components: a 3D-printed porous hollow sphere, 18 TENG units, and an acrylic enclosure (Fig. 1a). FEP tube in each TENG unit is tightly sealed with silicone plugs at both ends to ensure complete airtightness. Copper tape wrapped around the tube serves as the friction electrode material. The salt solution in the tube is NaCl solution. A linear motor was used to operate the C-TENG in linear modes. Solution's high fluidity enables it to generate electricity by moving in various directions within the pipeline (Fig. S1). The parallel configuration of multiple C-TENG units enhances overall power output. The output performance was measured using a Keithley 6514 electrometer (USA). The rectifier circuit converts alternating current (AC) generated by the TENG into pulsed direct current (DC) to power the MCDI system. The self-powered C-TENG system maintains a low operation cost of 8.23 \$ (Fig. S2), with zero electricity cost due to independence from the power grid.

2.2. Statistical analysis and parameter optimization of the C-TENG system

Experimental data were organized and analyzed using RSM. A polynomial fitting equation is established to determine the optimal range of independent variables through single-factor experiment. Optimal parameters for constructing the C-TENG prototype were identified using a three-level, three-factor BBD method. The independent variables were salt solution concentration (*A*), copper electrode length (*B*), and salt solution volume (*C*). The response variables, representing the combination of these independent variables, were peak current, peak voltage, and transferred charge. The second-order polynomial model commonly used in RSM is expressed as (Nie et al., 2020):

$$Y = A_0 + \sum_{i=1}^n A_i X_i + \sum_{i=1}^n A_{ii} X_i^2 + \sum_{i=1}^n \sum_{j=i+1}^n A_{ij} X_i X_j \quad (1)$$

where *Y* is the response variable (peak current, peak voltage, and transferred charge), *A*₀, *A*_{*i*}, *A*_{*ii*}, and *A*_{*ij*} are the regression coefficients of the intercept term, linear term, quadratic term, and interaction term, respectively. *X*_{*i*} and *X*_{*j*} represent the independent variables (*i* ≠ *j*). Experimental data analysis and parameter optimization were performed using Design Expert software 8.0.6 (trial version, State-Ease Inc., Minneapolis, MN, USA). Analysis of variance (ANOVA) was used to assess the impact and interactions of each variable and the statistical significance of the model. The fitness of the polynomial model equation was expressed by the determination coefficient *r*₂. The *F*-test was used to test the statistical significance of regression coefficients with probabilities (*P*) of 0.001, 0.01, and 0.0523. The optimum parameters for the C-TENG operation were estimated through regression analysis and visualized using 3D RSM diagram.

2.3. Design of the MCDI device

The ion removal experiments were conducted in a symmetric two-electrode MCDI cell with two plexiglass plates (90 mm×90 mm, thickness: 35 mm) and two titanium plates (90 mm×90 mm, thickness: 1 mm) serving as current collectors. Each titanium plate was equipped with an activated carbon cloth electrode (50 mm×50 mm). IEMs were positioned facing each other, with a polyester gasket (90 mm×90 mm, thickness: 1 mm) placed between them to ensure uniform solution distribution within the 5mm channel and to prevent short circuit. A peristaltic pump introduced the feed solution into the lower inlet of the MCDI device. The electric energy generated by the C-TENG was stored in an external capacity to supply power to the MCDI. Before electroadsorption, the feed solution was circulated through the MCDI unit until the effluent's ion concentration and pH matched those of the inlet water, achieving physical adsorption equilibrium.

2.4. Ion removal experiments and performance metrics of the C-TENG//MCDI system

The feed solution was buffered with sodium phosphorus ions to maintain a stable pH without additional acids or bases, minimizing the risk of increased total dissolved solids (TDS). Buffers containing NaH₂PO₄ and Na₂HPO₄ with a total phosphorus content of 10 mg ([PO₄²⁻]=31.1 mg/L) were prepared to investigate their impact on phosphorus removal. The MCDI experiments were conducted using a continuous flow mode, where the feed solution was continuously pumped

through the MCDI cell at a flow rate of 2 mL/min. The desired pH value (6.6-7.8) was achieved by adjusting the ratio of these two chemicals. Treated water was collected every 50 s in three consecutive trials. All samples were then digested using a total phosphorus detection kit, and the total phosphorus concentration was determined utilizing a HACH DR3900 bench visible spectrophotometer (USA). The performance metrics for the C-TENG//MCDI system are calculated using the following formulas (2)-(6) (Suss et al., 2015; Zhang et al., 2023).

Phosphorus ions removal efficiency (R_p):

$$R_p(\%) = \frac{\int_0^t Q(C_0 - C_d)dt}{\int_0^t Q C_0 dt} \times 100\% \quad (2)$$

where Q is the volume flow rate (mL/min), C_0 is the initial concentration (mM), C_d is the concentration at time t .

Phosphorus ions adsorption capacity (C_p):

$$C_p(\text{mg/g}) = \frac{Q \times \int_0^t \Delta C dt \times M}{m} \quad (3)$$

where M is the molar mass of salt (mg/mmol), m is the total electrode mass (g).

Average adsorption rate (AR_p):

$$AR_p(\text{mg/g} \cdot \text{min}) = \frac{C_p}{\Delta t} \quad (4)$$

where Δt is the time difference between the start and any given time.

Charge efficiency (CE):

$$CE(\%) = \frac{zFQ \int_0^t (C_0 - C_e)dt}{\int_0^t I dt} \times 100\% \quad (5)$$

where z is the charge number of ions, F is Faraday's constant (96,500 C/mol), I is the current (mA).

Molar energy consumption (E_m):

$$E_m(\text{kJ/mol}) = \frac{MV \int_0^t I dt}{Q \int_0^t (C_0 - C_e) dt} \quad (6)$$

where, V is the voltage (V).

The energy parameters, including energy consumption (E_c), energy recovery (E_r), and energy recovery rate (η) during the charging cycle, were calculated as follow (Długołęcki and van der Wal, 2013; Rommerskirchen et al., 2018).

Energy consumption (E_c):

$$E_c(w \cdot h) = \int_{t_0}^{t_{\text{charging}}} V_{\text{charging}}(t) I_{\text{charging}}(t) dt \quad (7)$$

where t_{charging} is the charging cycle time (h), V_{charging} is the charging voltage (V), and I_{charging} is the change current (A). The charging voltage is constant in CV mode.

Energy recovery (E_r):

$$E_r(w \cdot h) = I_{\text{discharging}} \int_{t_{\text{discharging}}}^{t_{\text{ending}}} V_{\text{charging}}(t) dt \quad (8)$$

where $I_{\text{discharging}}$ is the discharge current (A), $t_{\text{discharging}}$ is the start time of the discharge cycle (h), and t_{ending} is the end time of the discharge period (h).

Energy recovery rate (η):

$$\eta = \frac{E_r}{E_c} \quad (9)$$

2.5. Numerical simulation: two-fluid model

To assess the influence of bubble swarms and macroscopic flow characteristics in gas-liquid two-phase systems (aeration units) on C-TENG motion, simulations were conducted using the commercial CFD package ANSYS® Fluent® with a coupled solver and the standard k- ϵ turbulence model. The CFD model employs the Euler-Euler two-fluid approach to simulate the flow fields of the dispersed and continuous phase, assuming mutual interaction between dispersed phase (a) and continuous phase (b). The model integrates Euler's multiphase model with dynamics theory and is mathematically described by the conservation equations for mass and momentum (Shang et al., 2020). Specifically, the momentum conservation equation for each phase can be formulated as follows:

$$\frac{\partial(\alpha_p \rho_p u_p)}{\partial t} + \nabla \cdot (\alpha_p \rho_p u_p u_p) = \alpha_p \rho_p g - \alpha_p \nabla p + \nabla \cdot \tau_p + F_{\text{interact}} \quad (10)$$

where α_p , ρ_p , u_p , and τ_p represent the volume fraction, density, velocity, and stress tensor of a generic phase, g is the gravitational acceleration, p is the pressure, and F_{interact} is the interphase force.

The energy equation for each phase is given by:

$$\frac{\partial(\alpha_p \rho_p E_p)}{\partial t} + \nabla \cdot (\alpha_p \rho_p u_p E_p) = \alpha_p \rho_p u_p \cdot g - \alpha_p u_p \cdot \nabla p + \nabla \cdot (\tau_p \cdot u_p) + q_p + S_{E, \text{interact}} \quad (11)$$

where E_p and q_p represent the aggregate energy and the thermal conduction flux of each phase, and $S_{E, \text{interact}}$ signifies the interphase energy exchange term.

The volume fraction equation for each phase is:

$$\frac{\partial \alpha_p}{\partial t} + \nabla \cdot (\alpha_p u_p) = 0 \quad (12)$$

The density equation for each phase is expressed as:

$$\frac{\partial f}{\partial t} + \nabla \cdot (f u_p) + \frac{\partial (f m_p)}{\partial m_p} = S_f \quad (13)$$

where f and m_p represent the concentration distribution function and mass change rate of each phase, and S_f is the source term of each phase formation or disappearance.

The Grace drag model is used to describe flow past a single bubble. The drag coefficient in the distorted particle regime is given by (Dang and Chen, 2015; Shang et al., 2020):

$$C_{d,dist} = \frac{4}{3} \frac{g d_p}{u_t^2} \frac{\Delta \rho}{\rho_f} \quad (14)$$

where the terminal velocity u_t is:

$$u_t = \frac{\mu_f}{\rho_f d_p} M_o^{(-0.149)} (J - 0.857) \quad (15)$$

where $J = 0.94 H^{0.757} (2 < H \leq 59.3)$, $J = 3.42 H^{0.441} (H > 59.3)$, and M_o is the Morton number calculated by:

$$M_o = \frac{\mu_f^4 g \Delta \rho}{\rho_f^2 \sigma^3} \quad (16)$$

with

$$H = \frac{4}{3} E_0 M_o^{-0.149} \left(\frac{\mu_f}{\mu_{f,ref}} \right)^{-0.14} \quad (17)$$

Here, $\mu_{f,ref} = 9.0 \times 10^{-4} [\text{Pa s}]$ is the molecular viscosity of water at 25°C and 1 bar, and ρ_f is the continuous phase density. In the above equations, subscript f refers to the continuous phase.

The lift force, which arises from the interaction of the dispersed phase with the shear stress of the continuous phase, is partially responsible for the lateral distribution of the dispersed phase. The lift coefficient C_l is defined as (Dang and Chen, 2015; Shang et al., 2020):

$$C_l = f(S_r, Re) - f(E_0') \quad (18)$$

Here, $f(S_r, Re)$ is calculated as:

$$f(S_r, Re) = \left(\left(\frac{6}{\pi^2} \cdot \frac{1}{(Re \cdot S_r)^{1/2}} \cdot \frac{2.255}{(1 + 0.2 \epsilon^{-2})^{3/2}} \right)^2 + \left(0.5 \frac{Re + 16}{Re + 29} \right)^2 \right)^{1/2} \quad (19)$$

The Reynolds number, Re is defined as:

$$Re = \frac{\rho_f \left| \vec{V}_f - \vec{V}_q \right| d_b}{\mu_f} \quad (20)$$

The Strouhal number S_r is defined as:

$$S_r = \frac{d_b \gamma}{\left| \vec{V}_f - \vec{V}_q \right|} \quad (21)$$

The ϵ is defined as:

$$\epsilon = \left(\frac{S_r}{Re} \right)^{1/2} \quad (22)$$

where V_f and V_q are the continuous and dispersed phase velocities respectively, d_b is bubble diameter, and γ is the shear stress.

$f(E_0')$ is a correction for ellipsoidal bubbles expressed as:

$$f(E_0') = \frac{\ln(1 + \exp(-12(G)))}{12} \quad (23)$$

with

$$G = 0.11 \frac{\ln(1 + \exp(4(E_0' - 5.6)))}{4} - 0.14(E_0' - 5.2) - 0.44 \quad (24)$$

The k - ϵ Standard wall function model is used for near-wall turbulence simulation, capturing the turbulent flow behavior close to solid boundaries accurately. The turbulent kinetic energy distribution is described as (Dang and Chen, 2015; Kumar and Rao, 2021):

$$\frac{\partial(\rho_f k)}{\partial t} + \frac{\partial}{\partial x_i} \left[\left(\mu_{f,ref} + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_i} \right] + G_k + G_b - \rho_f \epsilon - Y_M + S_k \quad (25)$$

where σ_k is the turbulent Prandtl number, G_k is the generation of turbulent kinetic energy due to mean velocity gradient. G_b is a turbulent kinetic energy generation phase due to buoyancy. ϵ is the turbulent dissipation rate; Y_M is the contribution of fluctuating dilatation. S_k is a user-defined source term.

The equation for turbulent dissipation rate is:

$$\frac{\partial(\rho \epsilon)}{\partial t} + \frac{\partial(\rho u_i \epsilon)}{\partial x_i} = \frac{\partial}{\partial x_i} \left[\left(\mu + \frac{\mu_t}{\sigma_{k\epsilon}} \right) \frac{\partial \epsilon}{\partial x_i} \right] + C_{1\epsilon} \frac{\epsilon}{k} (G_k + C_{3\epsilon} G_b) - C_{2\epsilon} \rho \frac{\epsilon^2}{k} + S_\epsilon \quad (26)$$

where $C_{1\epsilon}$, $C_{2\epsilon}$, and $C_{3\epsilon}$ are empirical constants, with typical values of $C_{1\epsilon}=1.44$, $C_{2\epsilon}=1.92$, and $C_{3\epsilon}=1.0$, S_ϵ is a custom source term.

Turbulent viscosity (μ_t) is given by:

$$\mu_t = \rho C_\mu \frac{k^2}{\epsilon} \quad (27)$$

where the C_μ is assigned a value of 0.09.

In the wall function model, the logarithmic law describes the velocity distribution in the near-wall region:

$$U^+ = \frac{1}{K} \ln(y^+) + B \quad (28)$$

where U^+ represents the dimensionless velocity ($U^+ = \frac{U}{u_\tau}$), y^+ is the dimensionless distance

($y^+ = \frac{y u_\tau}{\nu}$), u_τ is the friction velocity ($u_\tau = \sqrt{\frac{\tau_w}{\rho}}$), K is the von Karman constant (typically 0.41), and

B is a constant, usually 5.2.

The logarithmic law is employed in the region where $y^+ > 30$, instead of addressing the underlying viscosity layer directly.

2.6. Numerical algorithm for the coupled CFD solver

The simulations were conducted using a coupled solver, which facilitates fully coupled pressure-velocity calculations suitable for complex multiphase flows. The Euler-Euler two-fluid model was employed to simulate bubble dynamics (Kumar and Rao, 2021). Geometry construction was performed using the FLUENT Design modeler, while 2D and 3D meshes were generated in ICEM CFD, with all meshes being unstructured. The mesh employed was tetrahedral with a refined wall region and a mesh size of 0.0010625 m. In the second iteration, the flow equation and turbulence model are solved. The computed flow field, volume fraction, and turbulence characteristics serve as essential inputs for determining the convergence and fragmentation kernel and solving the Euler model equations. The presence of bubbles in the fluid flow is recognized as an additional source term, necessitating modifications to the two-fluid turbulence model (Shang et al., 2020). The CFD solver directly represents the particle size distribution, and the resulting control population balance equation is treated as a prototypical convection-diffusion problem. The existing numerical schemes based on the finite volume method can effectively discretize transient terms (e.g., Euler explicit/implicit schemes), convective terms (e.g., high order upwind TVD schemes), and diffusion terms (first/second order central difference schemes).

3. Results and discussion

3.1. Composition and output performance of the C-TENG system

Fig. S3 illustrates the application scenario of the coronal C-TENGs, specifically designed to harvest kinetic energy from aeration, for powering a low-voltage MCDI system in advanced wastewater treatment. The generator features a spherical architecture (Fig. 1a), with a photograph of the fabricated device shown in Fig. S3. Internally, the C-TENG system comprises of 18 thumb-shaped TENG units arranged in parallel. Each unit consisted of salt solution (positive triboelectric material), a fluorinated ethylene propylene (FEP) tube (negative triboelectric material), and two copper sheets as electrodes. Charge generation occurred at the solid-liquid interface through contact electrification and electrostatic induction, which was induced by counterion motion during two types of external mechanical stimuli (Xu et al., 2020), including vertical contact separation and planar sliding (Fig. 1b). The synergistic effect of independent module operation (with negligible mutual coupling) and maximized spatial utilization within the spherical shell leads to a substantial increase in the overall volumetric power density. As the C-TENG rotates under the hydrodynamic excitation from aeration, negative charges accumulate on the FEP films until saturation, due to different electron affinities. The FEP surface exhibited a static contact angle (SCA) of 99°, with advancing and receding contact angles (ACA and RCA) of 122° and 88°, respectively. The electronegativity disparity between the salt solution and the FEP tube led to charge transfer, generating a potential difference (Le et al., 2021; Cheng and Wang, 2023), enabling electricity generation under mechanical movement from various directions (Fig. S4, Video 1). The power generation mechanism in single cycle is schematically depicted in Fig. 1c, using one TENG unit as a representative model. In the initial state, the device maintains in electrical equilibrium, with the salt solution symmetrically distributed between Electrode-A and Electrode-B. As the C-TENG rotates or oscillates, this symmetry is broken. An asymmetric distribution of the positively charged solution develops, inducing a potential difference across the copper electrodes. This potential drives electron flow from Electrode-B to Electrode-A via the external circuit, generating a current pulse. The continuous, periodic transfer of these induced charges between the electrodes generates a stable alternating current (AC) output. Numerical simulations of potential-electric field (Fig. 1c) further elucidate the working principle of the C-TENG, illustrating the dynamic variation in open-circuit voltage (U_{oc}) during operation. The maximum U_{oc} occurred when one electrode was completely covered by the salt solution, while the opposite electrode remained dry. As the solution moved between electrodes, the U_{oc} gradually decreased, reversed polarity, and stabilised when both electrodes reached equal coverage (electrostatic equilibrium). The electrical output of the rolling spherical TENG can be quantitatively characterized by the following model equation (Jiang et al., 2024):

$$P = \frac{1}{2} CV^2 f_a \quad (29)$$

where P is the power output, C is the capacitance, V is the voltage, and f_a is the aeration-driven frequency.

The crown-shaped spherical TENG demonstrates enhanced output stability over other designs, owing to an integrated multi-tube solid-liquid structure that increases the interfacial contact area and reduces frictional losses. These features improve the response frequency and energy conversion efficiency. The charge transfer at the solid–liquid interface is described by the surface charge density (Jiang et al., 2020):

$$\sigma_s = \frac{Q_c}{A} \quad (30)$$

$$C = \frac{\epsilon_d A}{d} \quad (31)$$

where Q_c is the total charge, A is the contact area, d is the contact distance, and ϵ_d is the dielectric constant. The liquid velocity (v_l) affects the charge transfer rate:

$$v_l = \frac{d}{\dot{\phi}_d} \quad (32)$$

According to Eq. (1)-(4), the power output can be described by:

$$P = \frac{1}{2} \sigma^2 v A f_a \quad (33)$$

The output performance of the C-TENG system was influenced by multiple factors, including mechanical frequency, electrode dimensions, and solution concentration. To optimise performance, a combination of single-factor experiments and response surface methodology (RSM) based on the Box-Behnken design (BBD) was employed. The key output metrics, i.e., open-circuit voltage (U_{oc}), short-circuit current (I_{sc}), and transferred charge (Q), were used to evaluate performance across different conditions (Fig. S5-S12). The driving frequency of the linear motor was varied from 0.25 to 1 Hz, aligning with the primary frequency range (0.2-1.5 Hz) of pressure fluctuations at the free liquid surface in aeration units (Fig. S5). At lower frequencies, salt solution oscillation within the FEP tube was insufficient, leading to diminished charge generation. At higher frequencies, the charge transfer process accelerated, which had minimal effect on Q and U_{oc} but caused a slight decline in I_{sc} , likely due to splashing losses. The C-TENG efficiently harvests triboelectric power from water wave agitation across a broad frequency range, markedly improving energy conversion efficiency and broadening its applicability to diverse environmental conditions. An array of 18 TENG units yielded approximately ten times the output of a single unit under identical excitation conditions (Fig. S6). The parallel arrangement ensures synchronous contact and separation among TENG cells. Due to the continuous charge accumulation on the stacked parallel TENG units, its voltage (U_{oc}) increases from 3.6 V to 77 V. The enhanced charge and voltage of the stacked TENG facilitate a higher load voltage (Text S3). Moreover, the greater copper electrode width, the higher charge transfer efficiency could be achieved (Fig. S7). Changes in salt concentration affected performance in a non-linear manner. At higher concentrations, output declined due to ion accumulation at the interface, which

introduced shielding effects that hindered electron transfer (Fig. S8) (Nie et al., 2020). Larger FEP tube dimensions, including length (Fig. S9) and diameter (Fig. S10), allowed greater contact area and fluid mobility, both of which contributed to higher charge accumulation. The elongation length of the linear motor actuator was found to influence output by improving the internal flow dynamics of the salt solution (Fig. S11). An increase in salt solution volume (Fig. S12) also enhanced performance by expanding the effective contact area and increasing surface charge. However, once the volume exceeded half of the tube's capacity, limited fluid mobility reduced the frequency of movement between electrodes, ultimately lowering output performance (Zhao et al., 2025).

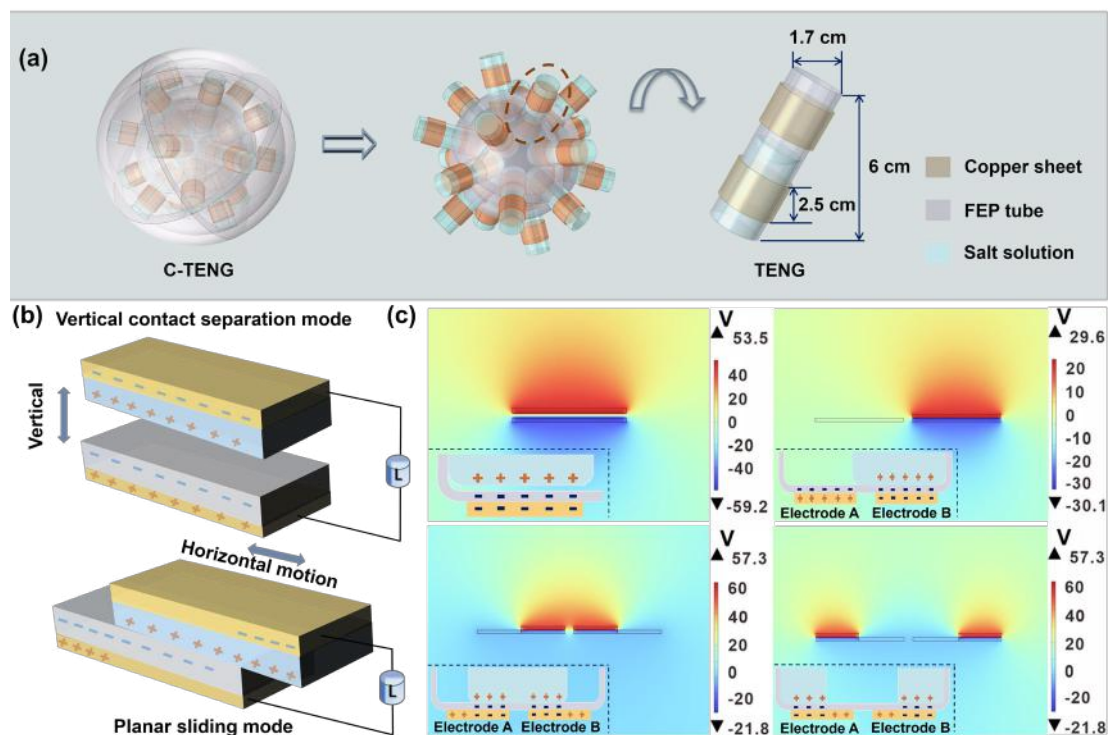


Fig. 1. Design, capacity verification, and performance analysis of the C-TENG. (a) Schematic diagram of the C-TENG. (b) Illustration of two solid-liquid interaction modes within a TENG unit. (c) Simulated dynamic variation in open-circuit voltage via finite element modelling.

Fig. 2 (a)-(i) provides a comprehensive analysis of the primary factors influencing C-TENG performance (U_{OC} , I_{SC} , and Q). Based on initial experimental observations, three variables (i.e., salt solution concentration, solution volume, and copper electrode width) were selected for optimisation using RSM. Corresponding settings and data analyses are outlined in Table S1. The ANOVA results (Tables S2 and S3) indicated that solution volume (factor B) exerts a highly significant influence on peak voltage ($P < 0.001$), with both salt concentration (factor A) and volume (factor B) showing strong individual effects ($P < 0.01$). Significant contributions were also observed from the quadratic terms A^2 and B^2 . The regression model demonstrated strong statistical significance ($P < 0.0001$), with a minimal difference between adjusted and predicted R^2 values (0.005), and a signal-to-noise ratio of 37.513, well above the acceptable threshold of 4 (Table S4). These findings confirmed the suitability of the second-order model for performance optimisation. The RSM and contour plots (Fig. S13) illustrate the interactions between the three factors and C-TENG output. For

voltage output, regions of high intensity (represented in faint yellow) indicate optimal conditions, with the peak corresponding to the maximum predicted voltage within the tested parameter space. Steep gradients in the contour plots suggest strong sensitivity to changes in the respective variable (Pouladi et al., 2019). Optimal voltage output was associated with a salt solution volume approximately equal to half the internal volume of the FEP tube. In contrast, higher salt concentrations reduced electron transfer efficiency, likely due to enhanced ionic shielding effects at the solid-liquid interface. Overall, C-TENG performance outcomes are largely dependent on transferred charge, where larger electrode dimensions contribute to improved space utilisation and increased charge transfer efficiency, resulting in higher overall output.

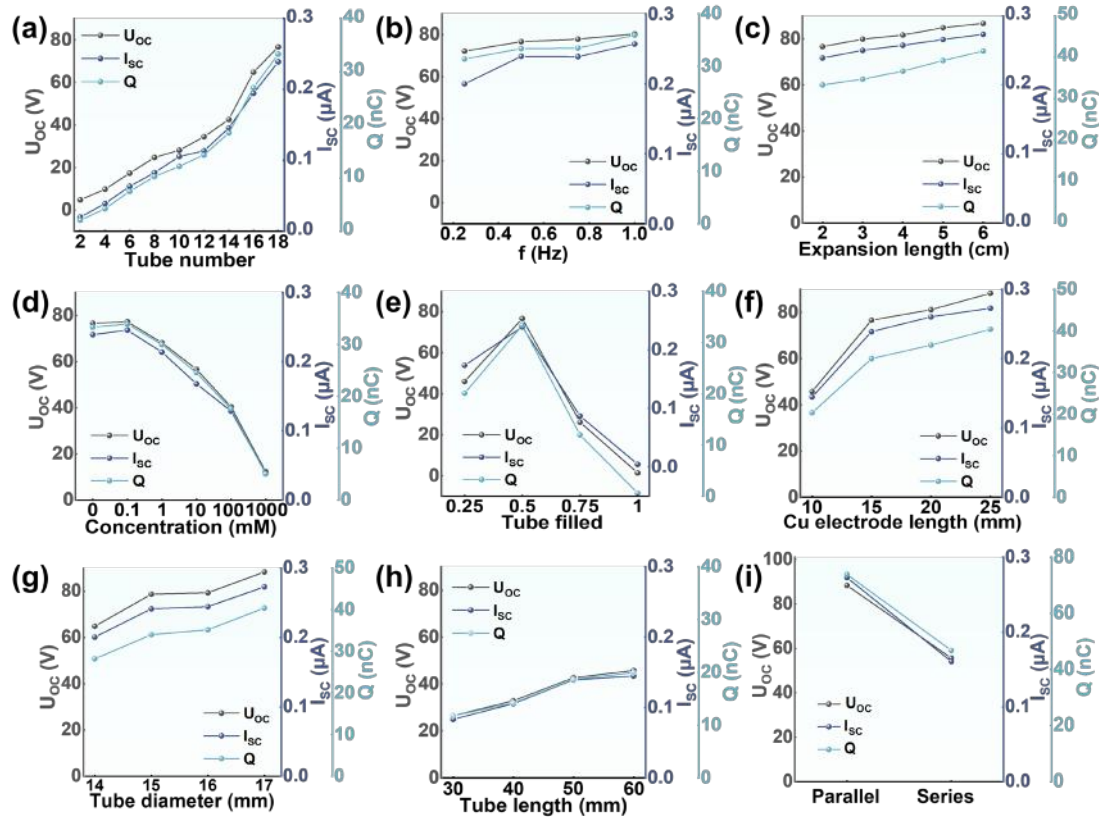


Fig. 2. (a-i) Output performance (I_{sc} , Q , and U_{oc}) of the C-TENG under various operating conditions.

3.2. Operational stability simulation and experimental validation

The current-source equivalent circuit of the C-TENG was simulated using Multisim 14.0, with the load characteristic curve derived based on experimental parameters outlined in Table S5. Fig. 3a and 3c illustrate the simulation circuits for series and parallel configurations, respectively. In the constant current region under resistive load, current remained relatively stable while voltage increased linearly (Fig. 3b). The maximum power region was characterised by a sharp increase in voltage and a rapid decline in current. The intersection of voltage and current curves indicated the point of peak load power (Zhao et al., 2021). In the constant voltage region, output voltage approximated the open-circuit voltage and remained nearly constant, whereas the output current gradually decreased. In contrast, capacitive load conditions resulted in an inverse trend, where voltage increased more gradually while current dropped more significantly (Fig. 3d). The comparative analysis (Fig. S14) indicated that the parallel configuration (77 V and 0.13 μA) reduced internal resistance and provided

superior output compared to the series configuration (57 V and 0.082 μA).

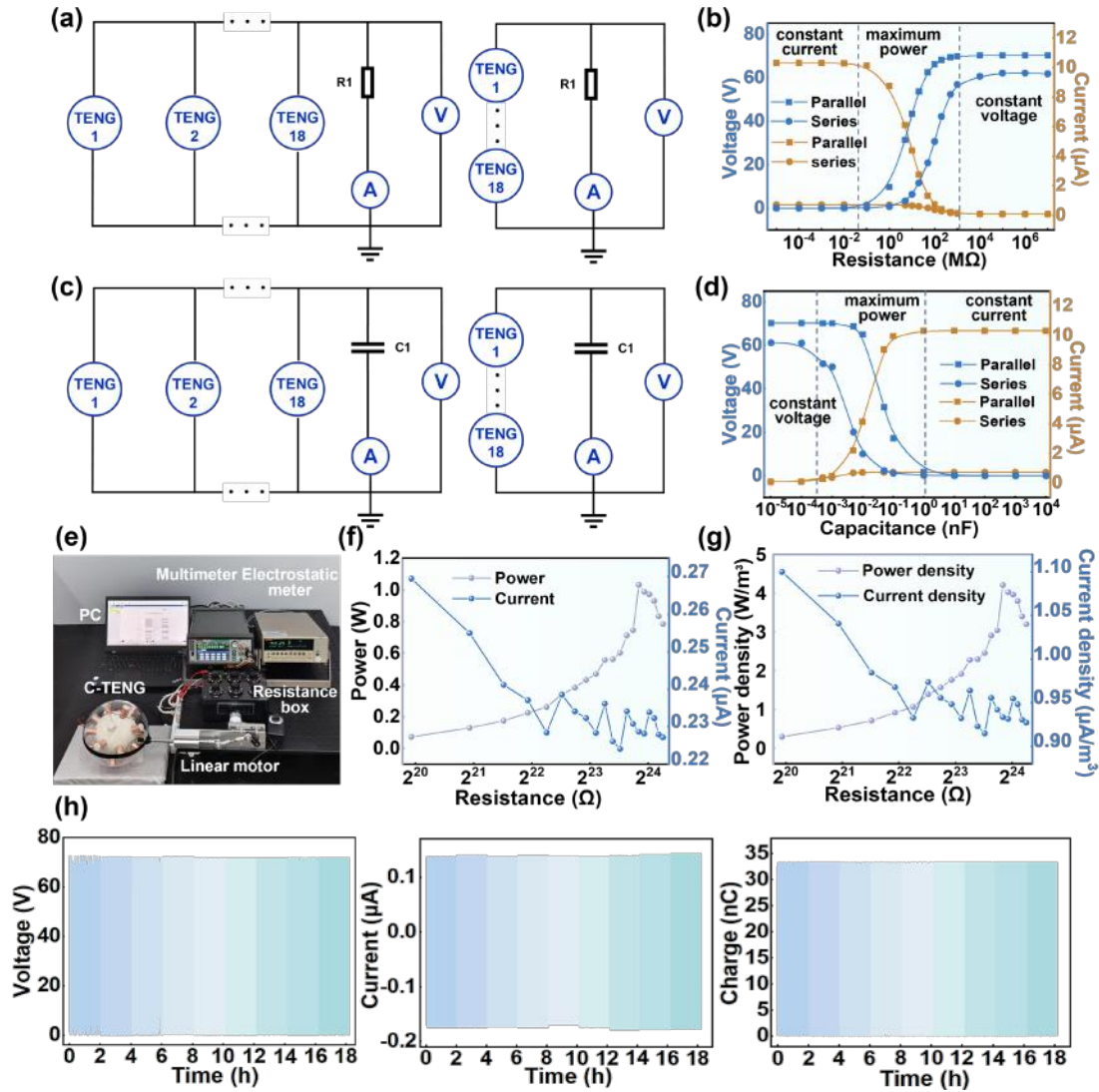


Fig. 3. Electrical performance verification and stability experiment of C-TENG. The series and parallel simulation circuits, respectively, under resistive load (a) and capacitive load (c). (b) and (d) Load curves under resistive and capacitive loading. (e) Self-powered system for C-TENG driven by a linear motor. (f) and (g) Variation in power output and power density for C-TENG. (h) Consistent C-TENG output for 18 hours under external excitation (with hourly measurements).

The self-powered C-TENG prototype (approximately 460 g) was experimentally evaluated using a linear stepper motor (Fig. 3e and Video 2) with the optimal structural parameters: i.e., a salt solution concentration of 0.147 mM, a solution volume equivalent to 50.6% of the FEP tube capacity, and a copper electrode width of 20.566 mm. This design offers two critical advantages: (1) it allows the internal power-generating module to oscillate free within the external housing under wave excitation; and (2) it maximizes the volumetric power density of the device. Performance characterisation under varying load resistances (Fig. 3f and 3g) showed a maximum power density of 4.212 W/m^3 at 16 G Ω and an average power density of 2.287 W/m^3 at 11 G Ω . Under the operational conditions, predicted peak current, peak voltage, and transferred charge were 0.255 μA ,

78.937 V, and 35.401 nC, respectively. Experimental validation confirmed the reliability of the RSM-derived model. To facilitate practical applications, these conditions were slightly adjusted to 0.1 mM salt concentration, 50% solution volume, and a 20 mm electrode width. Corresponding experimental results yielded an average peak current of 0.239 μ A, average peak voltage of 76.669 V, and transferred charge of 33.334 nC. To evaluate long-term stability and compare C-TENG power output with MCDI energy demand, various capacitors were charged by the C-TENG (Fig. S15). Charging rate decreases with increasing capacitor capacitance. As shown in Fig. S16, a 1000 μ F capacitor was charged, followed by voltage decay as stored energy powered the MCDI. During 18 hours of continuous operation under external mechanical excitation (with hourly measurements), the C-TENG maintained consistent electrical output, achieving 97% performance retention over 18 hours of operation (Fig. 3h), which demonstrates reliable energy harvesting from low-frequency vibrations and good agreement with model predictions.

3.3. Flow-structure interaction and dynamic response of the C-TENG in an aeration unit

A transient model for gas-liquid two-phase systems (aeration units) was developed based on a two-dimensional axisymmetric Euler-Euler approach (Fig. 4a). This numerical model was employed to more accurately simulate the behavior of bubble dynamics and macroscopic flow characteristics, with a particular focus on their impact on the motion of the C-TENG. This model captured the interaction between multiscale flow fields and the C-TENG interface. Experimental validation was carried out in a pilot-scale aeration tank using an initial bubble diameter of 0.002 m, consistent with CFD input parameters. Detailed physical properties and operating conditions are listed in Table S6.

Fig. 4b and 4c depict the bubble plume development at a superficial velocity of 0.01 m/s. After air injection through the diffuser, bubbles ascended from the central plane of the aeration zone. During the initial 20 s of aeration, the airflow followed an approximately linear path, producing symmetrical vortices. At 25 s, the bubble column became curved, and staggered vortices emerged. As aeration continued, the bubble column exhibited increasing instability, ultimately reaching a periodic oscillation state. The recorded footage (Video 3) confirmed that the CFD model effectively reproduced the complex multiphase flow behaviour within the aeration zone. Gas-liquid velocity distributions and mixing patterns were evaluated over a 13 s interval (Fig. S17 and S18), revealing kinetic energy generation in the range of 12-15 N under quasi-steady conditions. According to Archimedes' principle ($F = \rho g v$), the buoyancy force acting on the C-TENG prototype was approximately 4.6 N (self-weight), significantly lower than the energy imparted by ascending bubbles (Kumar and Rao, 2021). The formation of symmetrical vortices induced local gas aggregation, lateral water displacement, and upward bubble migration, collectively contributing to the radial and axial movement of the C-TENG (Lai et al., 2023). The lift force altered local velocity fields and gas holdup, while drag forces decreased as bubble-induced kinetic energy increased (Ren et al., 2022). Near the water surface or the C-TENG interface, buoyancy diminished, resulting in a reduction in bubble velocity (Fig. S19). The validation results confirmed that hydrodynamic energy from bubble motion was sufficient to drive C-TENG displacement and facilitate electrical energy generation.

We further applied a three-dimensional Euler-Euler method to analyse multiscale flow dynamics and surface tension effects at the gas-liquid interface, thereby validating the fluid-structure interaction involving the C-TENG. As bubble clusters reached the surface region, they had significant radial diffusion and triggered liquid level fluctuations, resulting in observable velocity gradients and flow trajectory deviations (Fig. 4d). Analysis of the vorticity field and velocity streamlines associated with low-frequency wave motion revealed a strong positive (counterclockwise) vortex at 3.6 s. The shedding frequency of this vortex was aligned with the natural frequency of the C-TENG structure. Initially, this vortex suppressed the tilting motion of the C-TENG, however, it soon reversed, generating a strong negative vortex. As this vortex drove the C-TENG leftward, it also induced a flipping motion, with the flipping angle progressively decreasing at subsequent time points (3.8 and 4.2 s). The vertical buoyant force acting on the C-TENG followed a wave-like decline (Fig. S20). This reduction in buoyancy resulted from partial conversion of the C-TENG's gravitational potential energy into surface waves, while the kinetic energy of the surrounding water was redistributed into radial, axial, and rotational motion, thus facilitating the C-TENG's dynamic response.

Force analysis further confirmed the C-TENG's tilting behaviour (Fig. 4e). The magnitude of the tilting force was determined by the tangential force at the point of contact with the spherical surface. Assuming rotational motion of the sphere on the water surface, the tangential force (F_T) was composed of contributions from the vorticity-induced force (F_v), water viscosity (F_w), buoyancy (F_b), and interfacial surface tension (F_s). This net tangential force induced the observed overturning motion (Fig. S21, Video 4). Simulated velocity components and angular velocities enabled the calculation of contact angles (Fig. 4e, Table S7) and water surface height (h). At 3.6 s, 3.8 s, and 4.2 s, the tangential forces were 2.449 N, 2.572 N, and 2.775 N, corresponding to contact angles of 75°, 72°, and 80°, respectively. These results demonstrated that variations in angular velocity and contact angle directly influenced the tangential force and water surface height, thereby affecting the C-TENG's tilting dynamics. In summary, the simulation results provided robust theoretical evidence supporting the C-TENG's capability to harvest multi-directional hydrodynamic energy under low-frequency excitation in aeration systems.

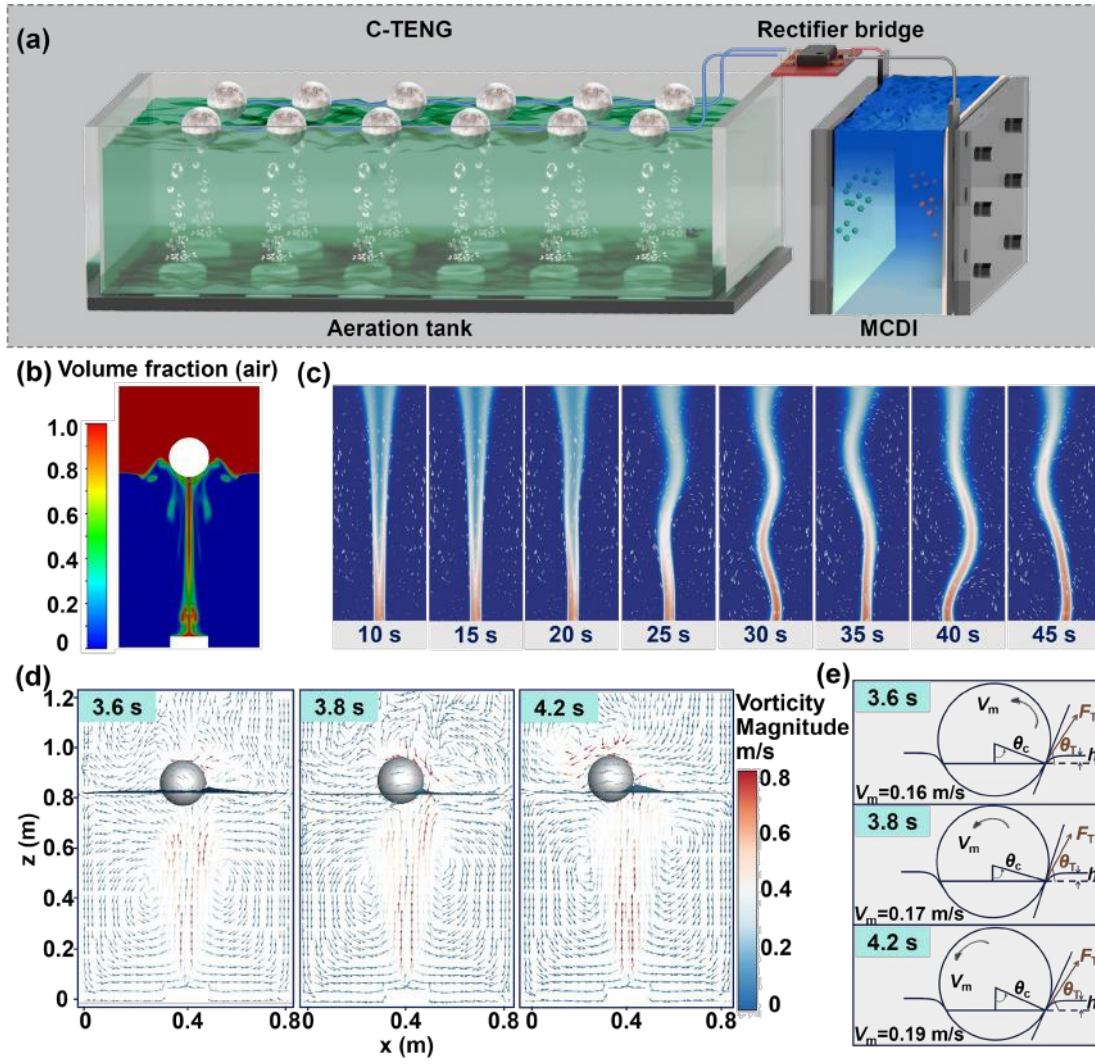


Fig. 4. CFD simulation of bubble swarm and macroscopic flow characteristics in gas-liquid two-phase systems. (a) Self-powered C-TENG//MCDI system driven by aeration induced surface waves. (b) Simulation of bubble plume dynamics. (c) Temporal evolution of plume behaviour (10-45 s). (d) Trends in velocity and vorticity over time (3.6 s, 3.8 s, and 4.2 s). (e) Force analysis of the C-TENG.

3.4. Applicability evaluation of the integrated C-TENG//MCDI system

The C-TENG exhibits significant potential for harvesting wave energy. As shown in Fig. 5, its alternating current (AC) output can power MCDI systems through two distinct energy supply pathways (Fig. 5a, b). The generated AC power is first rectified, enabling charging of energy storage devices (e.g., capacitors) or direct powering of electronic components (MCDI). Here, the integrated C-TENG//MCDI system was installed in an aeration tank and comprises a C-TENG, rectifier bridge, and MCDI reactor (Fig. 5b).

To validate the application potential of the designed C-TENG, a series of experiments systematically evaluated its performance. All ion removal experiments were powered solely by the C-TENG. The energy-intensive nature of conventional seawater desalination presents a major barrier to addressing global water scarcity. Previous studies have shown that TENGs are capable of successfully converting water wave energy into electrical energy (Wang et al., 2013). As an example, we deployed

this novel C-TENG in an aeration tank for self-powered phosphorus removal. By harvesting inherent hydrodynamic energy, it generated a peak voltage of 40 V (Fig. 5c), far exceeding the 1.2 V required for MCDI electrosorption. Further validation in a pilot-scale aeration tank showed stable 40 V output over 15 minutes (Fig. S21 and S22), confirming reliable, long-term power generation in dynamic wastewater environments.

MCDI experiments used single-pass continuous flow mode, with feed solution pumped through the cell once during adsorption without recirculation. Upon applying the harvested electric potential in MCDI within 10 minutes, the phosphorus concentration in the feed solution at pH 6.6 drops by 94.8%, with phosphorus decreasing from 1.0 to 0.052 mg/L (Fig. S23a). This process highlights the importance of equilibrium mechanisms (HPO_4^{2-} and H_2PO_4^-) in achieving high phosphorus removal efficiency (Fig. S24 and Fig. 5d). During a complete charge-discharge cycle (electrode regeneration), the pH and phosphorus concentration in the dephosphorized dilute brine vary with initial pH conditions (Fig. 6a and 6b). The results show enhanced phosphorus adsorption at lower initial pH levels. Correspondingly, the phosphorus adsorption capacity (C_p) increases over time, confirming efficient ion removal under the applied voltage (Fig. 6c). Furthermore, the trade-off between C_p and AR_p in the corresponding Ragone plot of the MCDI system further suggests that at pH = 6.6, the system is located in the upper-right region, exhibiting higher phosphorus removal capacity and adsorption rate (Fig. 6d). Under acidic conditions, H_2PO_4^- (0.302 nm) predominates and has a smaller hydration radius than HPO_4^{2-} (0.327 nm), enabling more efficient transfer from the aqueous phase to the electrode micropores (Fig. 5d) (Hassanvand et al., 2018). As the concentration of coexisting freshwater ions decreases, internal resistance within the MCDI system increases, leading to a stable decline in current (Fig. S23b). According to unipolar ion conduction theory, the phosphorus removal capacity of MCDI is primarily governed by the diffusion and migration of H_2PO_4^- and HPO_4^{2-} ions (Fig. 5d), which can rapidly respond to reversible reactions in equilibrium. When H_2PO_4^- dominates, each ion consumes only one electron, increasing the requirement for phosphorus ions to balance surface charges at the carbon electrode, thereby enhancing the system's total adsorption capacity.

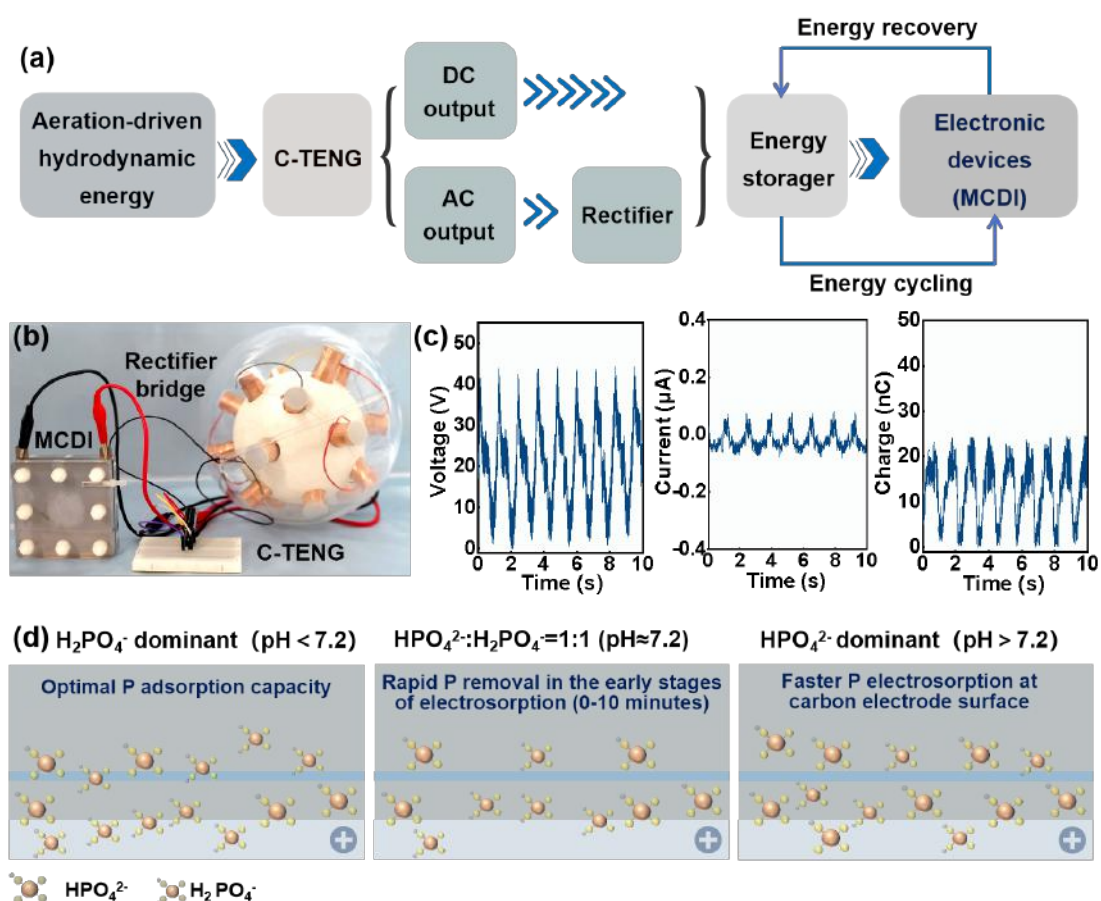


Fig. 5. (a) Schematic diagram of power supply mode of the C-TENG. (a) Schematic of the prototype coupling system comprising C-TENG and MCDI. (b) Output performance of the TENG in the aeration tank, showing voltage, current, and transferred charge. (c) Adsorption mechanism of phosphorus by the carbon electrode at different pH values.

In the absence of Faradaic reactions, voltage bias and electromigration dominate the ion transport mechanisms within the MCDI system. Under the applied electric field, disordered ions in the channel were symmetrically adsorbed onto the electrodes, reaching saturation rapidly and producing the maximum operational current (Fig. S23b). The inclusion of ion-exchange membranes (IEMs), which are in direct contact with the electrodes, effectively suppresses co-ion discharge by guiding ions into regions with high current gradients. This ensures that co-ions transport a balanced charge to maintain overall electro-neutrality. As a result, ion adsorption predominantly occurs in the ion enrichment zones formed between the anion-exchange membrane (AEM) and the cation-exchange membrane (CEM). The continuous supply of phosphorus ions in the vicinity of the porous carbon electrode significantly enhances adsorption efficiency. In these zones, ion accumulation promotes effective electro-adsorption, thereby facilitating phosphorus ion removal. Performance metrics, including removal efficiency (R_p), current efficiency (CE), adsorption capacity (C_p), average adsorption rate (AR_p), and molar energy consumption (E_m), are used to assess the system's overall efficacy (Fig.6e). At pH 6.6, the phosphorus ions electrolyte achieved a C_p of 5.45 mg/g, reflecting strong electro-adsorption at the electrode interface and elevated local phosphorus ions concentrations near the IEM-enriched zones. Although increased resistance in ion-depleted areas

was observed, the optimisation of ion migration pathways led to a notable reduction in E_m (He et al., 2024). Additionally, the presence of electrical double-layer capacitance and Faradaic pseudo-capacitance at the electrode surface results in enhanced ion consumption, with CE values exceeding 100%. A peak current efficiency of 107.17% was observed under these operating conditions, indicating highly efficient charge utilisation. Furthermore, the water recovery rate can reach up to 80%. Optimization experiments identified an effluent flow rate of 2 mL/min as the ideal operating parameter for MCDI unit (Fig. S25). This confirms the feasibility of the C-TENG//MCDI system for efficient phosphorus removal. In addition, this study further explored the system's capability to remove heavy metal ions from a solution containing multiple coexisting species, including various metal chlorides (10 mg/L each) and NaCl (100 mg/L). Replicate experiments demonstrated removal efficiencies of 78.97%, 76.55%, 69.25%, 81.27%, 67.41%, 72.71%, and 60.8% for Fe^{3+} , Ni^{2+} , Cu^{2+} , Cr^{3+} , Cd^{2+} , Pb^{2+} , and Na^+ , respectively, with all removal rates surpassing 60% and an average efficiency of approximately 72.42% (Fig. S26, Table S8). These results underscore the potential of C-TENG//MCDI system for effective treatment of low-concentration industrial wastewater.

We further evaluated the practical efficacy of the integrated system in removing phosphorus from secondary effluent of a municipal WWTP in *Changchun, China*, achieving a removal efficiency exceeding 100% (Fig. S27). To assess long-term viability, the system's regeneration performance and cycling stability were examined through repeated charge-discharge cycles using actual secondary effluent, powered solely by the C-TENG at 1.2 V. Notably, phosphorus removal capacity retention remained at 98.31% after 20 cycles (Fig. 6f). This robust stability was supported by real-time conductivity profiles, which showed no significant degradation, thereby indicating consistent and superior conductivity reduction during the MCDI process, even in complex multi-ion environment (Fig. S28). Collectively, these observations emphasize the system's potential for effective pollutant removal in low-concentration industrial wastewater laden with diverse metal contaminants.

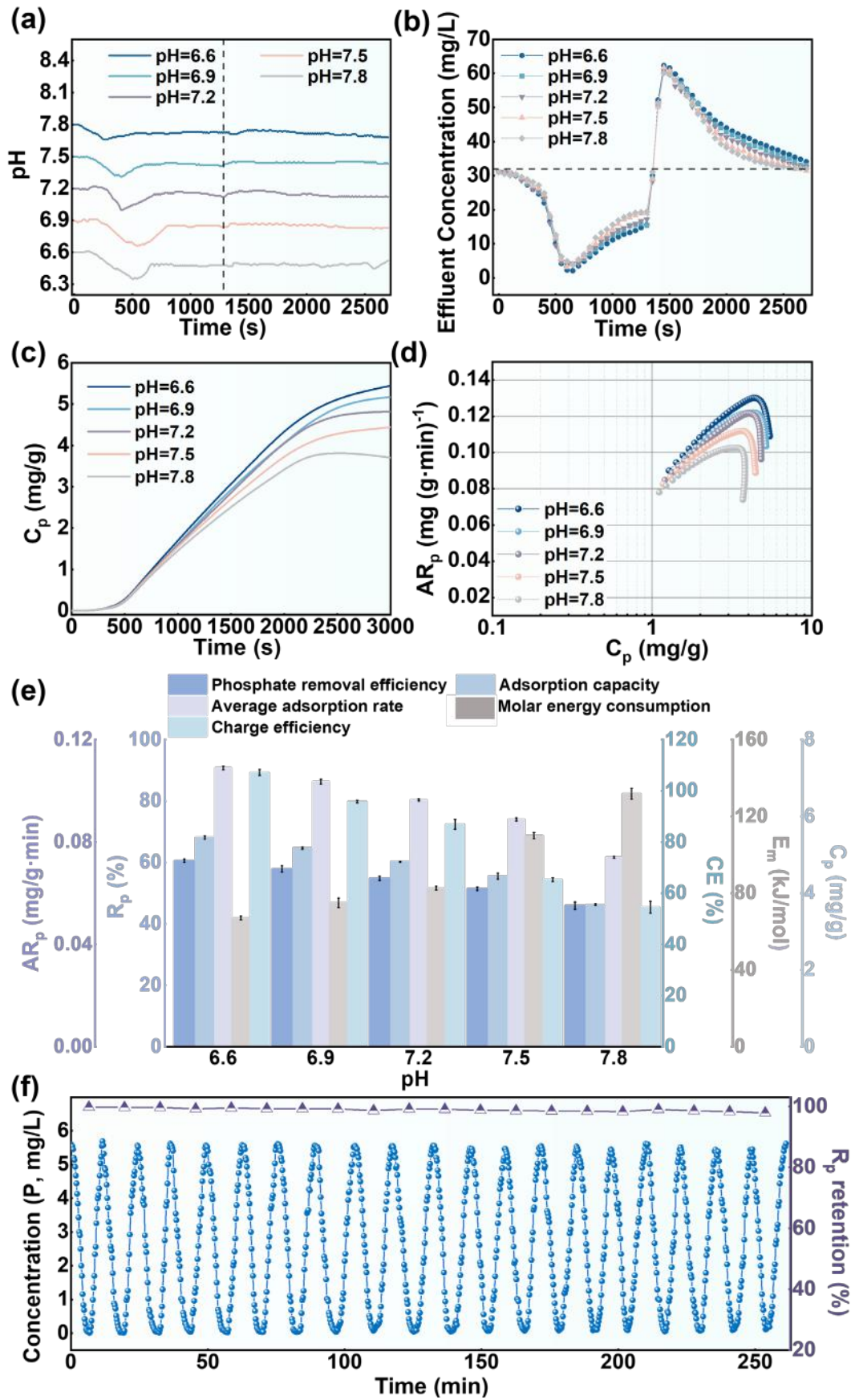


Fig. 6. Investigation of the self-powered C-TENG//MCDI phosphorus removal system. (a) and (b), Charge-discharge cycle of MCDI, variations in pH, and concentration of the dephosphorized brine at different pH values. (c) Time-dependent variation of the C_p . (d) Ragone plots. (e) The values of R_p , C_p , AR_p , CE , and E_m in

MCDI (performance metrics calculation). (f) Phosphorus removal and regeneration profiles of the C-TENG//MCDI in secondary effluent from real-life wastewater.

3.5. Energy balance in the C-TENG//MCDI system

Energy consumption is a critical metric in evaluating the performance of MCDI and comparing it with other electrochemical water treatment technologies. All such systems inevitably consume more energy than the theoretical minimum due to unavoidable losses, including those associated with ion transport and water molecule movement. A key advantage of MCDI lies in its ability to temporarily store a portion of the energy required for ion removal within the electric double layers (EDLs) formed at the carbon-water interface during adsorption (Długołęcki and van der Wal, 2013; Kang et al., 2014). Due to the inherent capacitive nature, the energy consumed during ion removal can be partially recovered during subsequent regeneration (Fig. 7a). Harvested energy can either power another MCDI cell in its purification cycle or be stored in an energy storage medium, such as a supercapacitor, for later use. This dual function—delivering purified water while storing energy—significantly enhances the overall energy efficiency. Therefore, this section aims to establish a direct energy recovery system by integrating an MCDI module with a supercapacitor. Fig. 7b shows the schematic circuit of a C-TENG//MCDI-based energy recovery system coupled with a supercapacitor. The voltage gradient between the MCDI cell and the supercapacitor serves as the primary driving force for energy transfer. Energy dissipation within the MCDI module results from distinct ohmic losses in carbon electrodes (Electrode), IEMs (Membrane), and the dilute chamber (Chamber), as well as non-ohmic contributions from the Stern potential in electrode micropores (Electrode_Stern), the Donnan potential at micro-macropore interfaces (Electrode_Donnan), and ion transport potential across IEMs (Membrane_Transport) (Zhang et al., 2023).

Operating in a single-pass mode, this section systematically investigates the influence of applied voltage on MCDI performance in constant voltage (CV) mode, focusing on energy consumption, energy recovery efficiency, and the potential for energy reuse. We analysed both energy dissipation and recovery across charging and discharging cycles, identifying key factors that influence recovery performance. A range of constant charging voltages (0.4, 0.6, 0.8, 1.0, and 1.2 V) were applied, while discharge was conducted at a fixed current of 0.01 A and a controlled pH of 6.6. At the onset of the charge-discharge cycles (Fig. 7c), a voltage drop was observed due to internal resistance losses. When the charging voltage was 1.2 V, the discharge voltage decreased to 1.044 V, while at 0.4 V, it fell to 0.355 V. These reductions reflect energy losses during the discharge phase, partly due to internal resistance and partly due to energy used for residual ion desorption. The voltage gradually declines over time, reflecting the desorption of ions from the electrodes as energy is released for external storage. Thus, energy reuse efficiency is influenced by both the ion adsorption capacity of the electrode and the kinetics of energy recovery (Długołęcki and van der Wal, 2013). Concurrently, the voltage of the supercapacitor increased from zero (Fig. 7d), indicating effective energy flow transfer from the MCDI cell. The energy originally consumed during desalination in the charging step was liberated during ion desorption in the discharge step, with a portion captured by the supercapacitor via a converter. Fig. S29 shows the current profile during the charging process. At a

charging voltage of 1.2 V, the current initially peaked at 1.94 mA and sharply decreased to 0.826 mA within the first three minutes, followed by a slower decline. At lower charging voltages, such as 0.4 V, the initial current was significantly lower (1.22 mA), indicating a positive correlation between charging voltage and current magnitude. These trends confirm that higher charging voltages lead to increased energy input, encompassing both resistive losses and energy stored in the EDLs. Energy dissipation occurs across multiple components, including the current collector, activated carbon fibre electrodes, IEMs, and inter-electrode spacers. Consequently, the energy recovery rate is determined not only by the total energy consumed but also by the fraction that can be effectively reclaimed during discharge.

The energy recovery efficiency of the MCDI system is defined as the ratio of energy recovered during the discharge phase to the energy consumed during the charging phase (Fig. 7e). As the applied charging voltage increases, more energy is stored in the system, resulting in longer discharge durations and an enhanced capacity for energy recovery. At 0.4 V, the recovery efficiency is approximately 28.15%, increasing significantly to 60.0% at 1.0 V. However, a further increase to 1.2 V results in a slight decrease to 57.6%, suggesting that higher voltages impose greater demands in overcoming internal resistance, thereby reducing net recovery gains. In this study, energy consumption is classified into two categories: recovered energy and dissipated energy. Recovered energy represents the portion transferred to external loads during discharge, while dissipated energy includes losses attributed to ohmic and non-ohmic resistance, as well as energy consumed by internal processes like phosphorus removal ([Rommerskirchen et al., 2018](#)). The energy recovery efficiency achieved in this self-powered MCDI system exceeds that reported for conventional MCDI setups (Table S9). To further illustrate performance, the absolute energy recovered reaches a maximum of 0.27 W·h at 1.2 V, approximately fivefold greater than the value at 0.4 V (Fig. 7e). However, dissipated energy also increases with charging voltage, nearly tripling at 1.2 V compared to 0.4 V. This highlights the inherent trade-off between enhanced energy recovery and increased energy loss at higher voltages.

Overall, the findings demonstrated that a substantial proportion of the energy used during electrode charging for phosphorus removal can be effectively recovered during subsequent regeneration. This is achieved through controlled electrode charging and discharging under constant voltage conditions. By integrating energy recovery into MCDI operation, net energy consumption for clean water production is reduced to as low as 0.26 kW·h/m³, while simultaneously contributing to phosphorus removal. The coupled C-TENG//MCDI module with a supercapacitor achieves low-energy ion removal while simultaneously enabling efficient energy storage, reaching an energy storage efficiency of 75%. This integration not only ensures effluent meets discharge standards but also harnesses hydrodynamic energy from the aeration tank, significantly reducing energy consumption and operational costs in wastewater treatment, providing valuable insights for the design of future energy recovery systems.

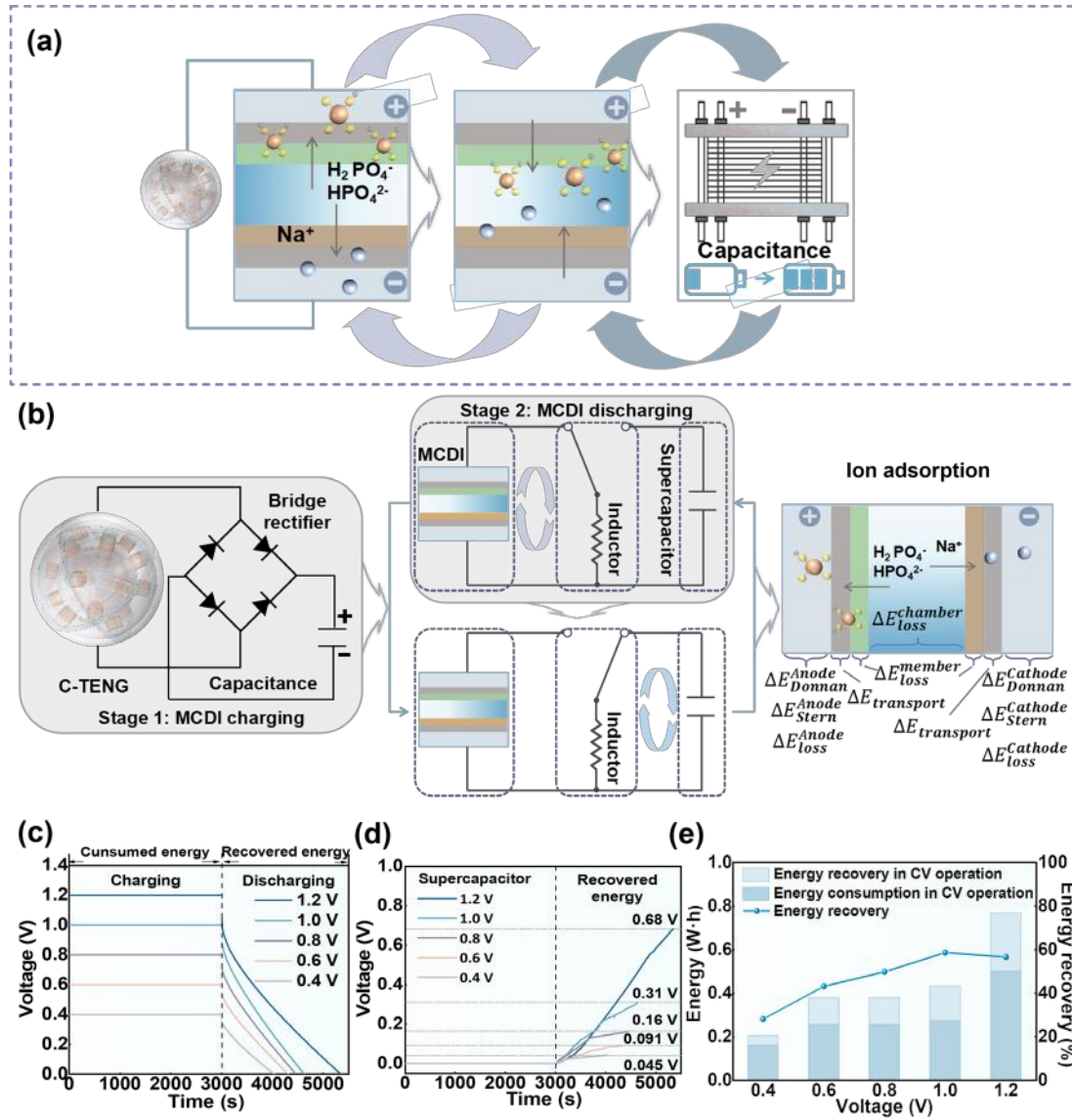


Fig. 7. Energy recovery in C-TENG//MCDI. (a) Corresponding energy flow pathway of the MCDI cell. (b) Schematic representation of a directly energy-recoverable MCDI system, comprising the charging step driven by a C-TENG and the energy recovery step facilitated by a supercapacitor (during energy recovery, Stage 1 and Stage 2 operate sequentially until the MCDI module is fully discharged) and the potential energy losses of the MCDI module. (c) The voltage change during the charge and discharge cycle. (d) The supercapacitor voltage profile in one cycle during MCDI operation with energy recovery. (e) Energy recovery, energy consumption, and energy recovery efficiency of the MCDI.

3.6. Implications for large-scale MCDI deployment: balancing water and energy demands

The C-TENG is designed to directly harness otherwise-dissipated hydrodynamic energy from aeration-induced turbulence, without requiring modifications to existing WWTP infrastructure. This design facilitates seamless integration into operational aeration tanks, substantially reducing capital costs—a benefit enhanced by its modular scalability and synergistic coupling with MCDI for self-powered purification. However, real-world WWTPs present additional complexities. The system's energy input is susceptible to fluctuations arising from the diversity of aerator layouts in different WWTPs, biofouling, airflow rates, and seasonal conditions, which were not fully replicated in our

controlled experiments. Compared to existing energy supply technologies (Fig. S30), conventional grid power provides stable and scalable supply (typically 0.3-0.65 kWh/m³) but lack on-site recover, posing sustainability challenges. Renewable alternatives, while promising, have their own limitations: solar power offers high peak density (>100 W/m²) but intermittent, weather dependent, and space-intensive (e.g., requiring rooftops or land); wind power requires large turbines and consistent winds (>5 m/s), often infeasible in urban or space-constrained WWTPs (Dong et al., 2022; Perdana et al., 2025; Zahmatkesh et al., 2022). Thus, C-TENG's in-situ, low-impact harvesting positions it as competitive for WWTP upgrades.

The levelized cost of water (LCOW) for the developed MCDI system, as presented in Text S6 and Table S10, ranges from 0.35 to 0.53 USD/m³, which is lower compared to conventional fiber filtration (FF)-ultrafiltration (UF)-reverse osmosis (RO) processes (0.58 USD/m³). Field trials have shown that MCDI operation requires lower maintenance, particularly concerning chemical consumption. Note that the labor cost assumptions detailed in Table S10 are specific to this trial location, where capital and operating expenditures account for approximately 54% and 46% of the total cost, respectively. Furthermore, the low DC voltage operation of MCDI electrodes makes them highly compatible with in-situ C-TENG self-powering, enabling deployment in remote areas without grid connection, and potentially further reducing operation and maintenance costs. As shown in Fig. 8, the developed dual-energy-driven system effectively mitigates the need for an external power supply for MCDI systems by harnessing the aeration energy collected by the C-TENG and the energy stored in the electrodes during the MCDI charging phase for ion removal. Under pilot-scale conditions, 15 C-TENG units connected in parallel were sufficient to support 10 hours of daily operation for the MCDI unit. The energy consumption of the MCDI unit ranged from 0.4 to 0.53 kWh/m³ in CV mode. Additionally, we designed and fabricated an energy storage circuit capable of delivering a high-current discharge (~mA range). Theoretical calculations predicted that after 40 minutes of continuous charging by the 15 C-TENGs, the circuit could deliver a mA-level DC output for 6 minutes of operation. This performance was then experimentally verified; charge-discharge tests demonstrated a stable, mA-level current sufficient for both our laboratory-scale needs and for powering other engineering devices that require a steady supply (Fig. S31). Integration of the dual-energy system enabled a significant reduction in electricity consumption, with net values achieving as low as 0.01 kWh/m³, thereby further decreasing the LCOW. Indeed, electrode replacement is the main cost driver in MCDI operations, with IEMs being significantly more expensive than carbon electrodes. Consequently, as electrode replacement frequency increases, the associated costs become a dominant factor in the LCOW, underscoring the critical need to enhance electrode durability. Future research should therefore prioritize understanding electrode aging mechanisms, particularly focusing on the impact of fouling and feedwater composition, to improve the long-term performance and economic feasibility of MCDI in industrial applications.

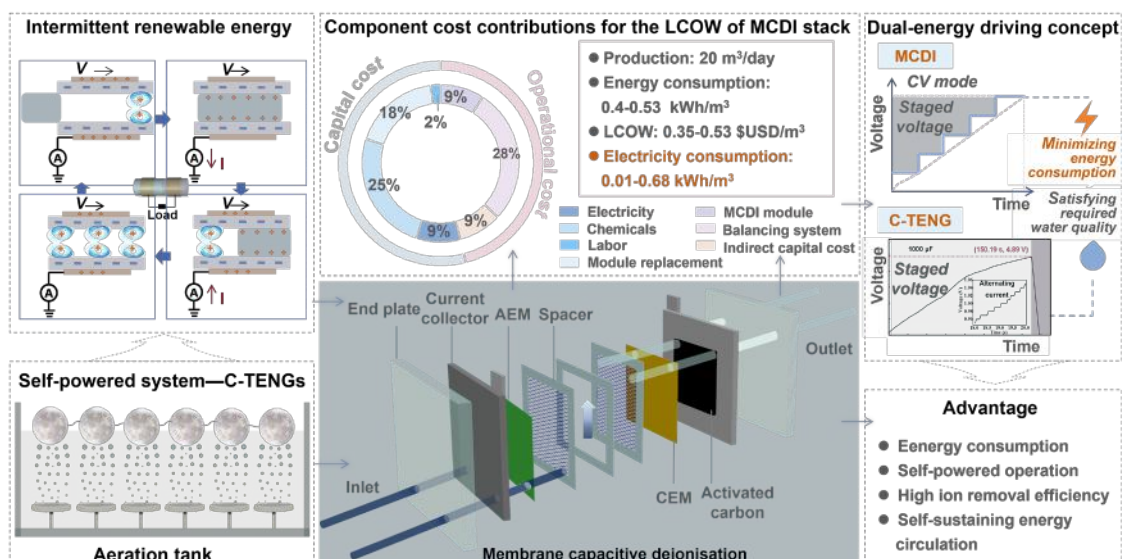


Fig. 8. Conceptual framework of the dual-energy system integrating C-TENG// MCDI.

4. Conclusions

This study assessed an innovative C-TENG//MCDI system that integrates self-powered operation with energy self-cycling through bidirectional dynamic energy management. Both simulations and experimental validation confirmed the effective conversion of multidirectional fluid dynamics, driven by aeration-induced bubble motion, into radial, axial, and tangential motions, which enabled efficient energy harvesting and achieved 97% performance retention over 18 hours of operation. Experimental results demonstrated the exceptional phosphorus removal capabilities of the self-powered C-TENG//MCDI system, which exhibited high current efficiency and effective energy recovery during electrode regeneration, achieving up to 60% recovery and an overall energy storage efficiency of 75%. The system's capacity for continuous energy recovery while maintaining stable pollutant removal performance highlights its promise for scalable wastewater treatment applications, from fixed installations to modular units. The dual-energy driving concept establishes a novel framework for advancing electrochemical wastewater treatment technologies, aligning energy sustainability with environmental performance. Future work should focus on innovations in electrode materials and system structure optimisation to enhance its resilience and applicability in more complex water matrices.

CRedit authorship contribution statement

Y. Li: Methodology, Investigation, Writing – Original Draft. **S. Wang:** Date curation, Investigation. **W. Gao:** Methodology, Software. **L. He:** Visualization, Methodology. **J. Xi:** Investigation, Formal analysis. **Y. Huo:** Writing – Review & Editing. **W. Fan:** Methodology, Writing – Review & Editing. **T. Lyu:** Date curation, Writing – Review & Editing. **M. Huo:** Resources.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data available within the article and its supplementary materials.

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Supplementary Material

In-situ triboelectric nanogenerator for energy self-cycling electrochemical systems in wastewater treatment

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Text S1 Chemicals

Disodium Disodium hydrogen phosphate (Na_2HPO_4 , >99%), sodium dihydrogen phosphate (NaH_2PO_4 , >99%), sodium chloride (NaCl , >99%), ferric chloride (FeCl_3 , $\geq 99.9\%$), nickel chloride (NiCl_2 , $\geq 99.9\%$), chromium chloride (CrCl_3 , $\geq 99.9\%$), cadmium chloride (CdCl_2 , $\geq 99.9\%$), lead chloride (PbCl_2 , $\geq 99.9\%$) and copper chloride (CuCl_2 , $\geq 99.9\%$) were purchased from Sinopharm Chemical Reagent Co., Ltd. The chemicals were reagent grade and used as received without any further purification. Carbon cloth (120 g/m^2 , the thickness is $360 \mu\text{m}$), used as electrode material, was purchased from Cetech Co. Ltd., China.

Text S2 Multi-metal ions removal experiments

In order to assess the impact of coexisting ions in C-TENG//MCDI experiments, typical heavy metal ions (Fe^{3+} , Cr^{3+} , Cd^{2+} , Pb^{2+} , Cu^{2+} , and Ni^{2+}) were employed in multi-metal ion solutions to investigate the potential applications of the MCDI unit for the treatment of low-concentration wastewater. The concentrations of these metal ions were quantified through inductively coupled plasma-optical emission spectrometry (ICP-OES, Agilent 720).

Text S3 Parallel characteristic analysis of multiple TENGs—Voltage analysis

' U_{oc} ' represents the open-circuit voltage of multiple TENGs connected in parallel, while ' $U_{oc1} + U_{oc2}$ ' refers to the combined open-circuit voltage of TENG1 and TENG2, and so on. The mathematical model of open-circuit voltage is obtained as follows:

$$U_{oc} \approx \frac{U_{oc1} + U_{oc2} + U_{oc3} + \dots + U_{ocn}}{2} + \frac{U_{ocmax}}{2} \quad (\text{S1})$$

U_{oc} is the open circuit voltage of multiple TENGs in parallel; U_{oc1} is the open circuit voltage of the first TENG; U_{oc2} is the open circuit voltage of the second TENG; U_{ocn} is the open circuit voltage of the nth TENG (U_{ocmax} is the maximum value from U_{oc1} to U_{ocn}).

The parallel stacking of multiple layers further enhances the friction surface area of the TENG units, thus increasing the total surface charge and electrical (voltage) output of the C-TENG. The parallel arrangement in the C-TENG helps the TENG cells contact and separate synchronously to the same extent (Cao et al. (2024)). In an ideal case, the output enhancement of the C-TENG should increase linearly with the increase of the number of stacked layers. In Fig. 2(a), it can be seen that the short-circuit current, transferred charges and output voltage of the C-TENG show an obvious increasing trend, but it is not a linear growth. The reason for this phenomenon may be that the surface of friction materials has reached the state of charge saturation or energy loss in the process of mechanical energy transmission. If the number of stacks continues to increase, the output performance will increase.

Text S4 The output performance parameters of C-TENG were optimized with RSM

According to the results of single-factor experiments and the principles of Box-Behnken experimental design, response surface analysis experiments were conducted at 17 test points with three factors (salt solution concentration, solution volume, and copper electrode length) at three levels. The response variables included peak voltage, peak current, and transferred charge. Among these points, 12 were selected for analysis while 5 served as central points. The factor level analysis is presented in Table S1.

Text S5 Numerical setup—grid Size and time step

The aeration tank geometry and size are illustrated in Fig. S15. Three levels of non-uniform structured grids were employed to evaluate the impact of grid resolution on simulation results, as illustrated in Fig. S16 and S17. The grids were classified as coarse (63 cells in width $\times$ 85 cells in height), medium (72 cells in width $\times$ 103 cells in height), and fine (80 cells in width $\times$ 125 cells in height). Various parameters were incorporated into the model to ensure experimental accuracy and validity, with an aeration rate set at 0.00025 m³/s. A grid resolution test was performed using a CFD model with a gas superficial velocity (U_g) of 0.01 m/s, with simulations running for 45 s across all cases. The variations in gas and liquid phase velocity vectors for both instantaneous and time-averaged flows at a tank height of 0.8 m, across different grid resolutions, are illustrated in Fig. S16 and S17. The results indicate that the deviations among the three grid resolutions are negligible.

Text S6 Economic evaluation of the MCDI stack

In the comparative evaluation of the economic efficiency of various water treatment systems, the economic performance of the MCDI stack was assessed using the parametric model for the levelized cost of water (LCOW, \$/m³ of product water) developed by Liu et al. (2021). The LCOW is considered a crucial metric for the comparative assessment of the economic feasibility of state-of-the-art deionization technologies. The model used to estimate the LCOW incorporates both the net capital and operational costs per unit volume of product water, with particular emphasis on accounting for module replacement due to electrode aging. The LCOW is determined as the following:

$$\text{LCOW (\$/m}^3 \text{ of product water)} = \frac{ATCC + TOC}{V_{total}} \quad (\text{S2})$$

$$ATCC = C_{\text{module}} + C_{\text{balancing system}} + C_{\text{indirect capital cost}} \quad (\text{S3})$$

$$TOC = OC_{\text{electricity}} + OC_{\text{chemical use}} + OC_{\text{material replacement}} + OC_{\text{labor}} \quad (\text{S4})$$

$$V_{total} = \int_{n=1}^{20} \frac{V_{\text{year}}}{(1 + \text{discount rate})^n} \quad (\text{S5})$$

$$OC_{\text{electricity}} = \int_{n=1}^{20} E \times 0.08 \text{ \$USD / m}^3 \times \text{flow rate} \times 365 \times (1 + \text{inflation rate})^n \quad (\text{S6})$$

$$OC_{\text{material replacement}} = \int_{n=1}^{20} \frac{(C_{\text{material replacement}})(1 + \text{inflation rate})^n}{(1 + \text{discount rate})^n} \quad (\text{S7})$$

$$OC_{\text{labor}} = \int_{n=1}^{20} 0.02 \times (C_{\text{module}})(1 + \text{inflation rate})^n \quad (\text{S8})$$

$$OC_{\text{chemical use}} = \int_{n=1}^{20} (C_{\text{chemical use}})(1 + \text{inflation rate})^n \quad (\text{S9})$$

where ATCC is the annualized total capital cost (\$/year) considering the capitalization factor, TOC is the total operating cost (\$/year). The TOC is the summation of the costs from major operating components, including annual module (electrodes) and membrane replacement, maintenance, labor and chemical use; C_{module} , $C_{\text{balancing system}}$, and $C_{\text{indirect capital cost}}$ are the capital costs of modules, balancing system, and indirect capital costs provided by vendors or manufacturers, respectively; $OC_{\text{electricity}}$ is the cost of electricity consumption during operation; $OC_{\text{chemical use}}$, $OC_{\text{material replacement}}$, and OC_{labor} are the operation and maintenance costs for chemical use, material replacement, and labor, respectively; V_{year} and V_{total} are the product volume (m³) in the first year and over twenty years, respectively. All of the cost elements are in the unit of \$USD.

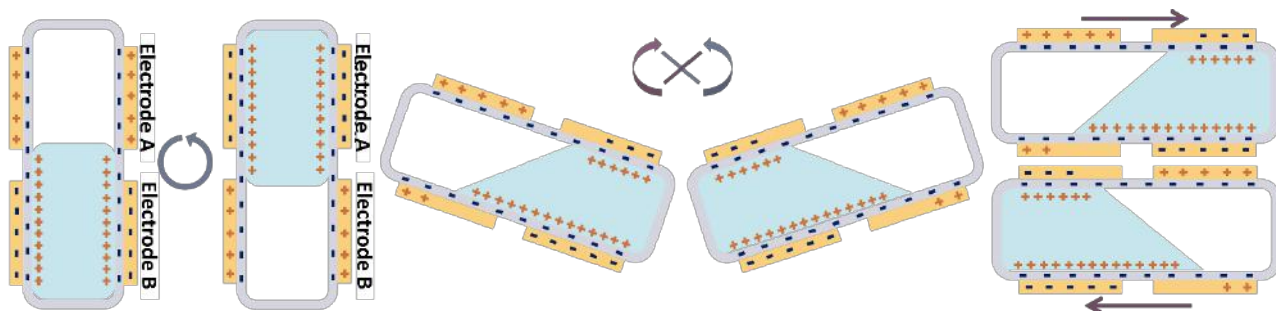


Fig.S1 The omnidirectional movement of the TENG.

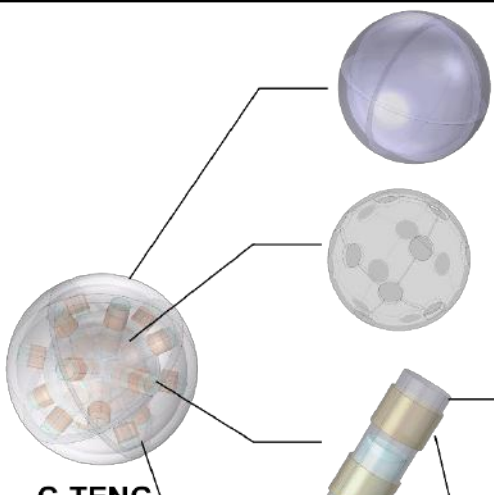
Coste stimate: 8.23 \$	
	Acrylic shell (polymethyl methacrylate PMMA) Diameter: 18 cm, thickness: 2 mm Coste stimate: 2.46 \$
	3D printed support structure (ABS/PLA plastic with a layer of resin) Diameter: 5.5 cm, thickness: 4 mm Coste stimate: 2.32 \$
	FEP tube Diameter: 17 mm, length: 60 mm Coste stimate: 1.5 \$
	Copper sheet and copper conductive tape Length: 17 mm, width: 25 mm Coste stimate: 0.37 \$
	Deionized water pH: 6 ~ 7, resistance: 10~15MΩ/CM, electrical conductivity: ≤2μS/CM Coste stimate: 0.21 \$
	Copper conductor Coste stimate: 1.37 \$

Fig.S2 The cost estimate of C-TENG.

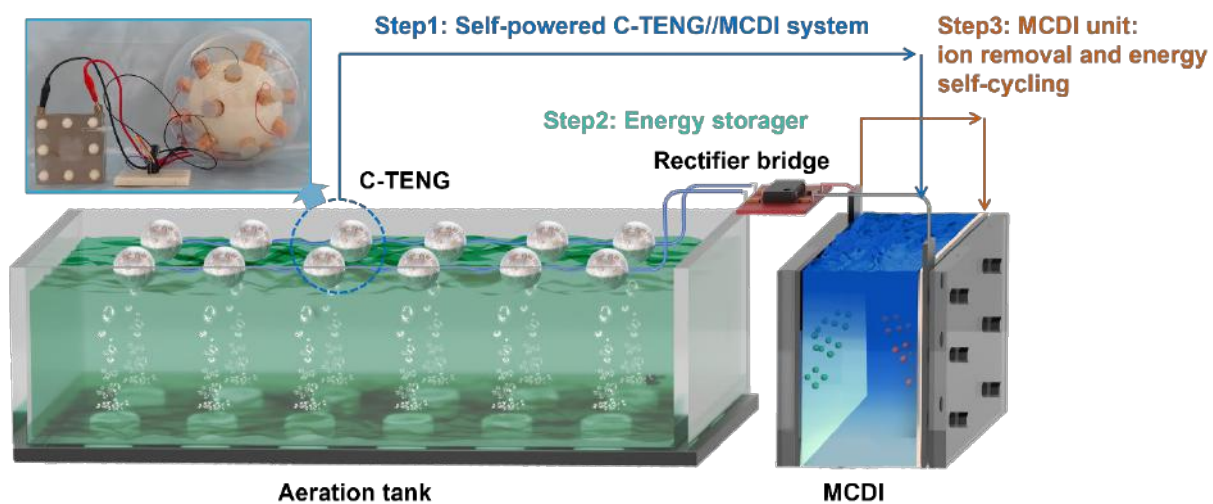


Fig.S3 The application scenario of the coronal C-TENGs.

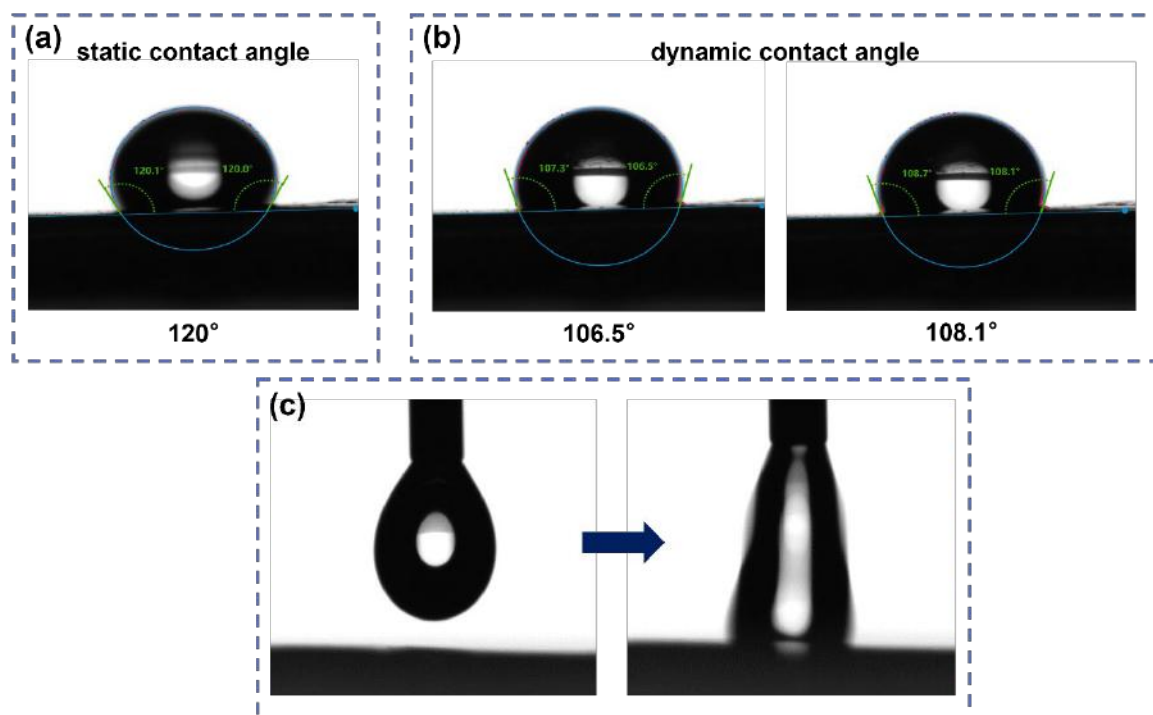


Fig.S4 CA of the FEP surface. (a) SCA. (b) Dynamic contact angle: ACA and RCA. (c) The interaction between solution and FEP tube.

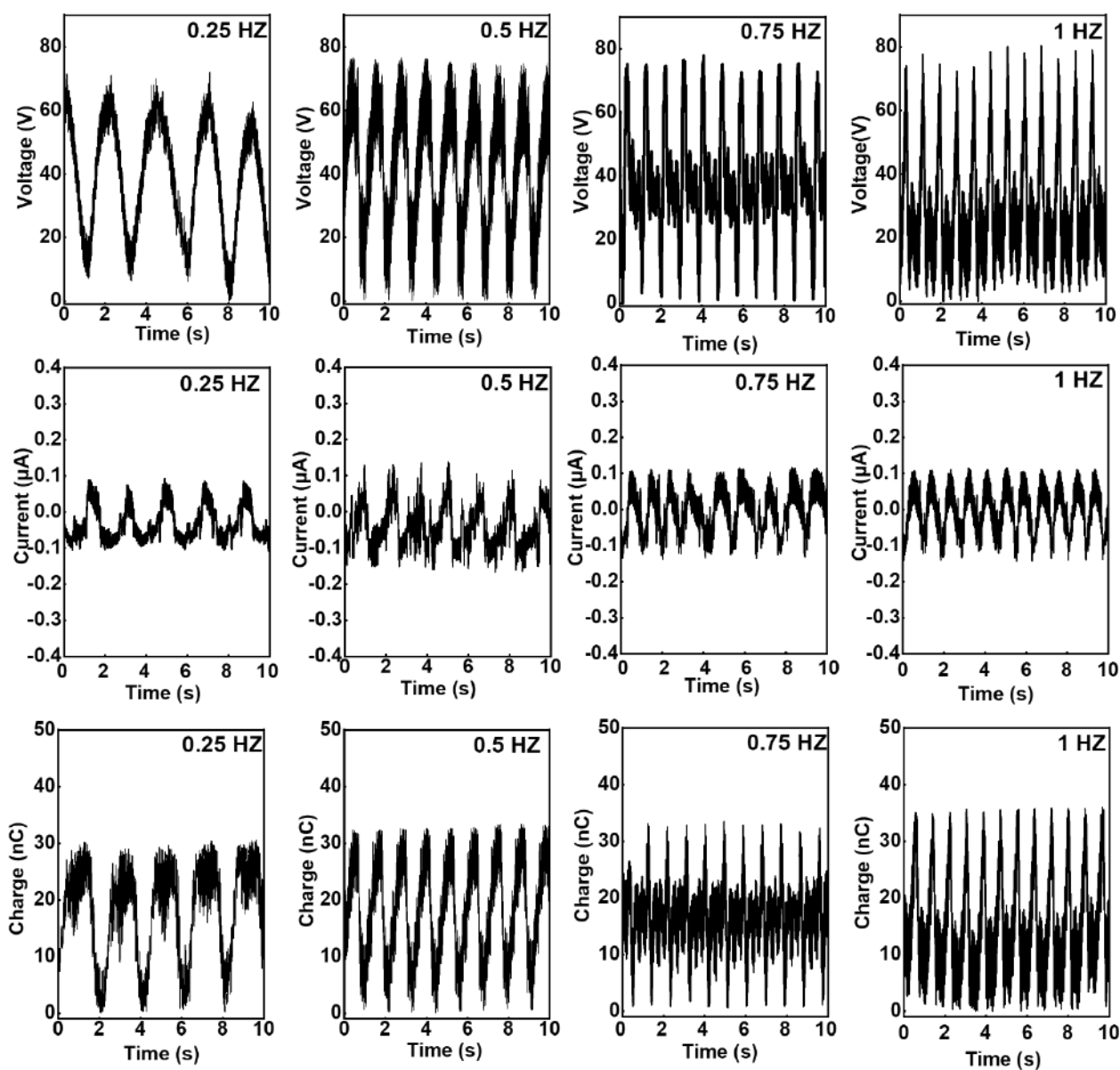


Fig.S5 The short-circuit current (I_{sc}), amount of transferred charge (Q), and the measured open-circuit voltage (U_{oc}) tested under different horizontal motion frequencies.

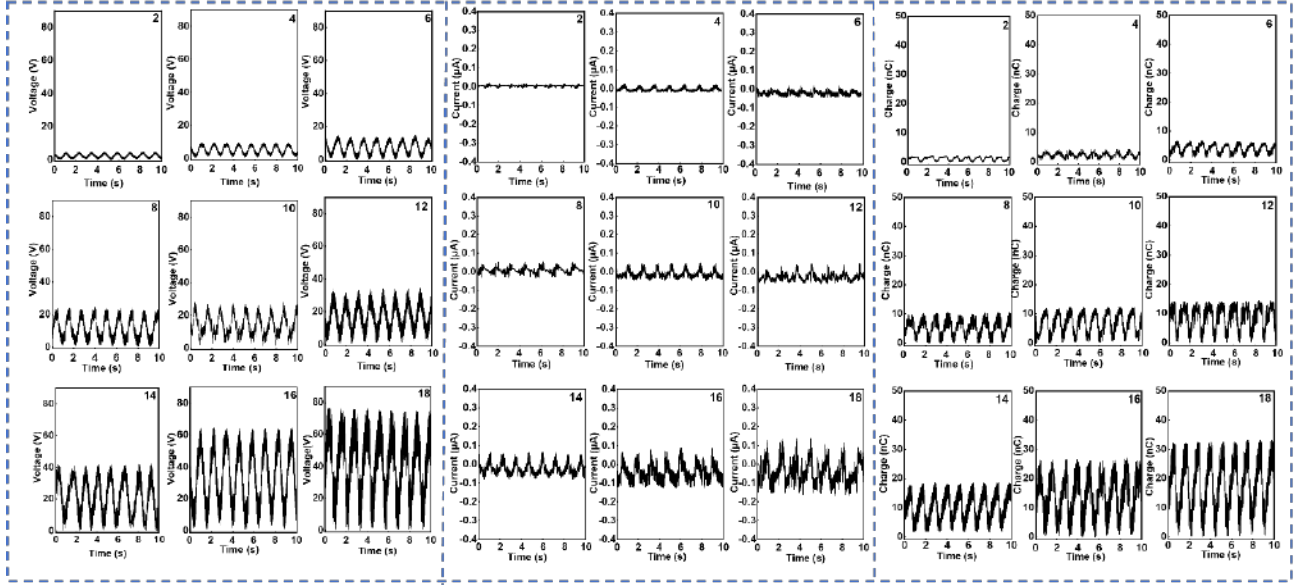


Fig.S6 The I_{sc} , Q , and U_{oc} were tested under different numbers of TENG units (from 2 to 18).

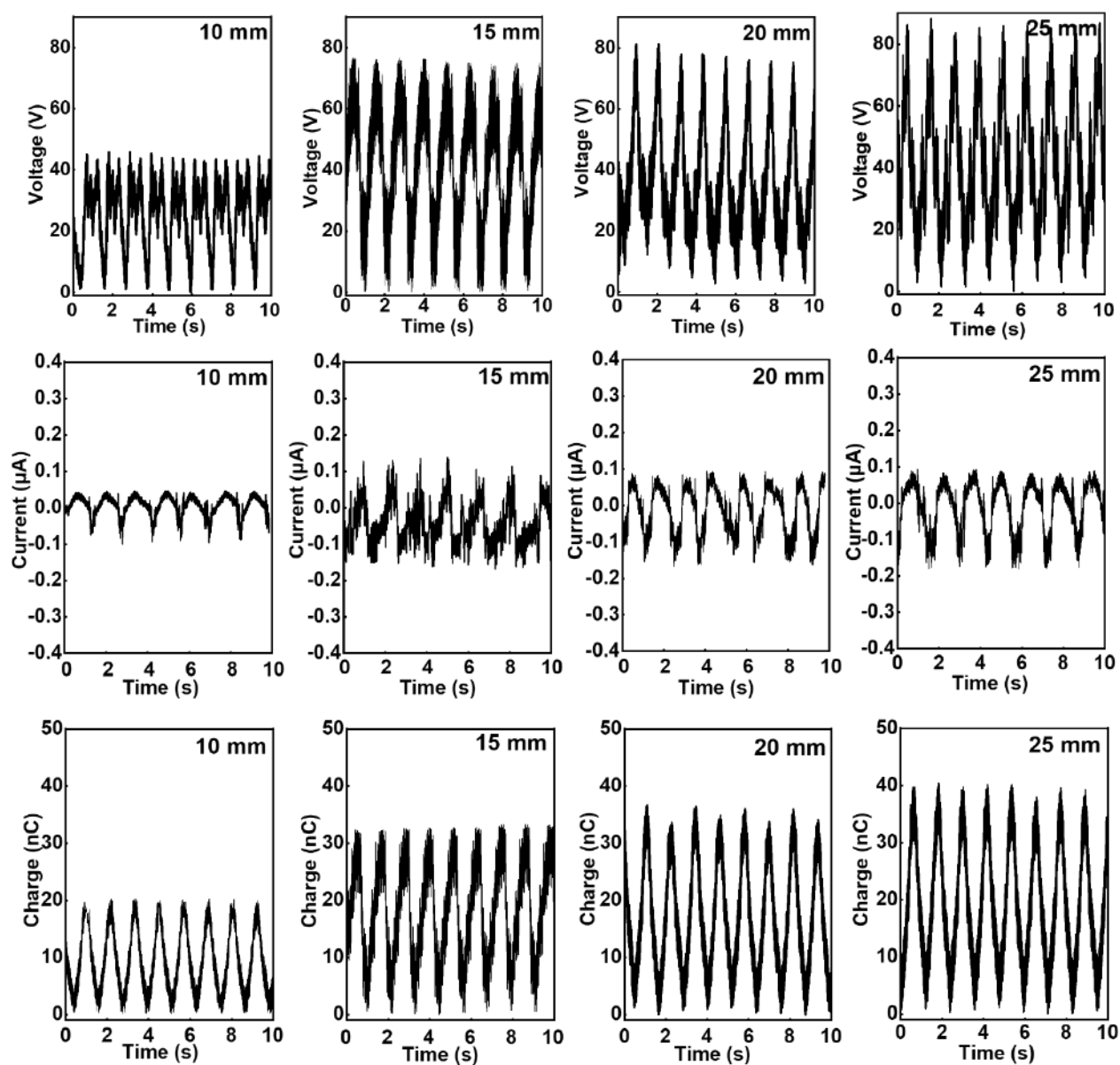


Fig.S7 The I_{sc} , Q , and U_{oc} were tested under different widths of the Cu electrode (10, 15, 20, and 25 mm).

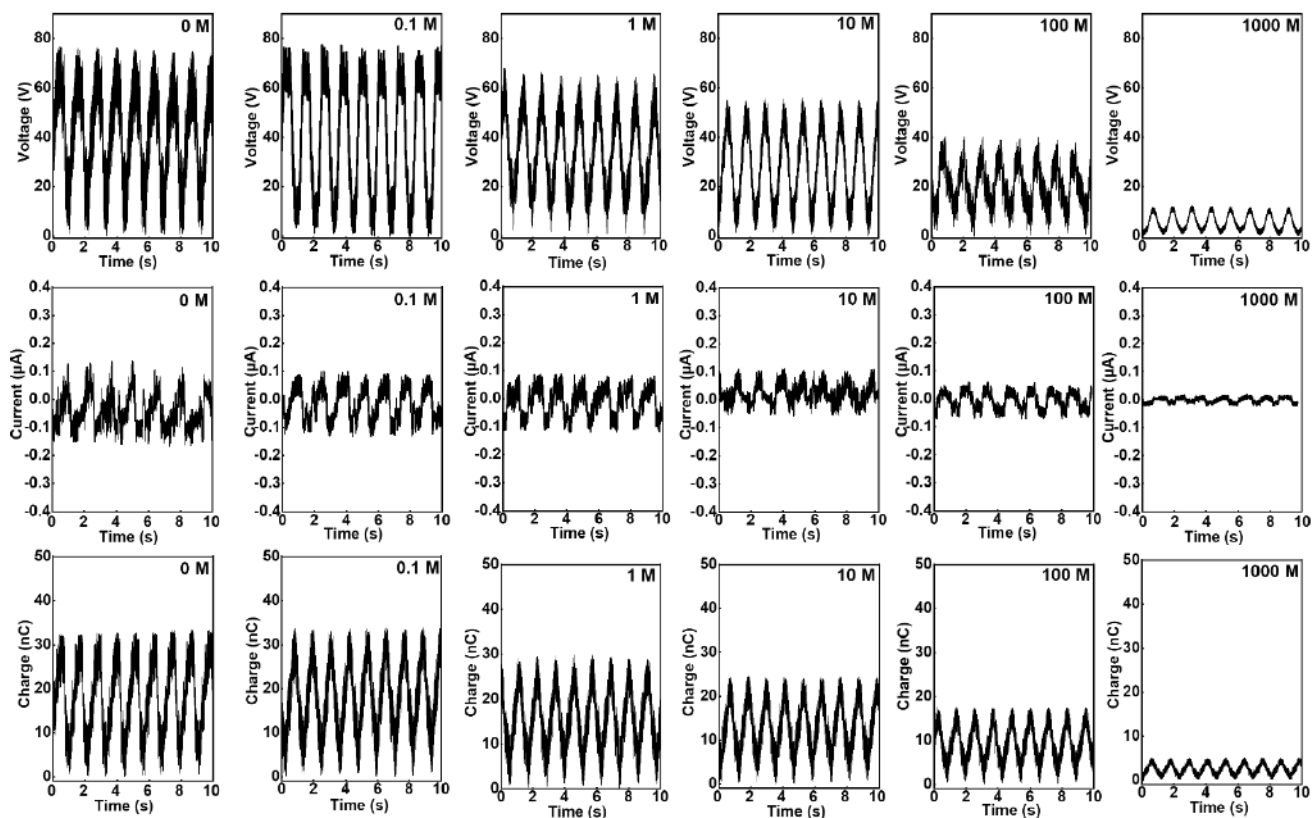


Fig.S8 The I_{sc} , Q , and U_{oc} were tested under different ionic strengths (0, 0.1, 1, 10, 100, and 1000 mM).

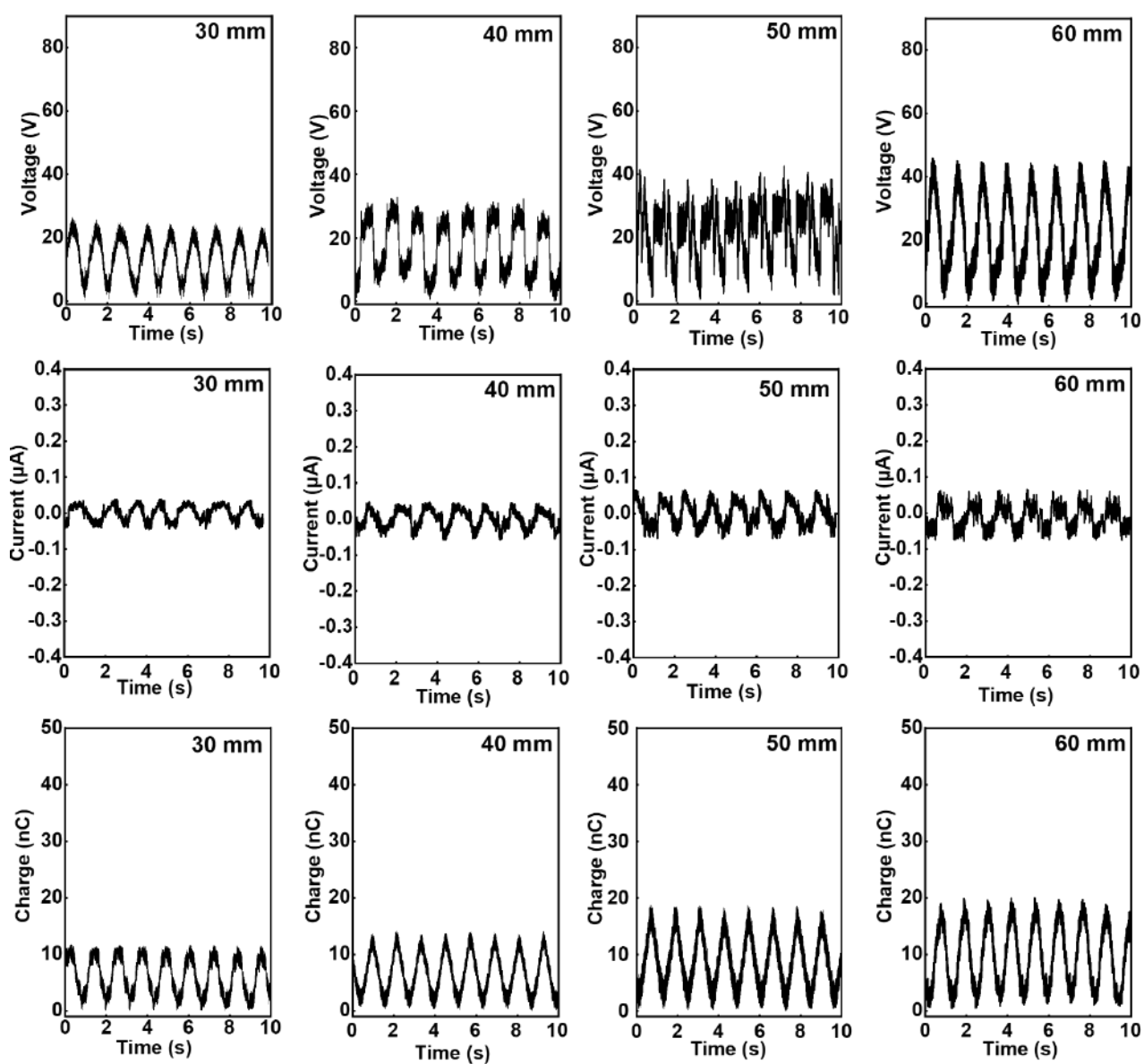


Fig.S9 The I_{sc} , Q , and U_{oc} were tested under different lengths of the FEP tube (30, 40, 50, and 60 mm).

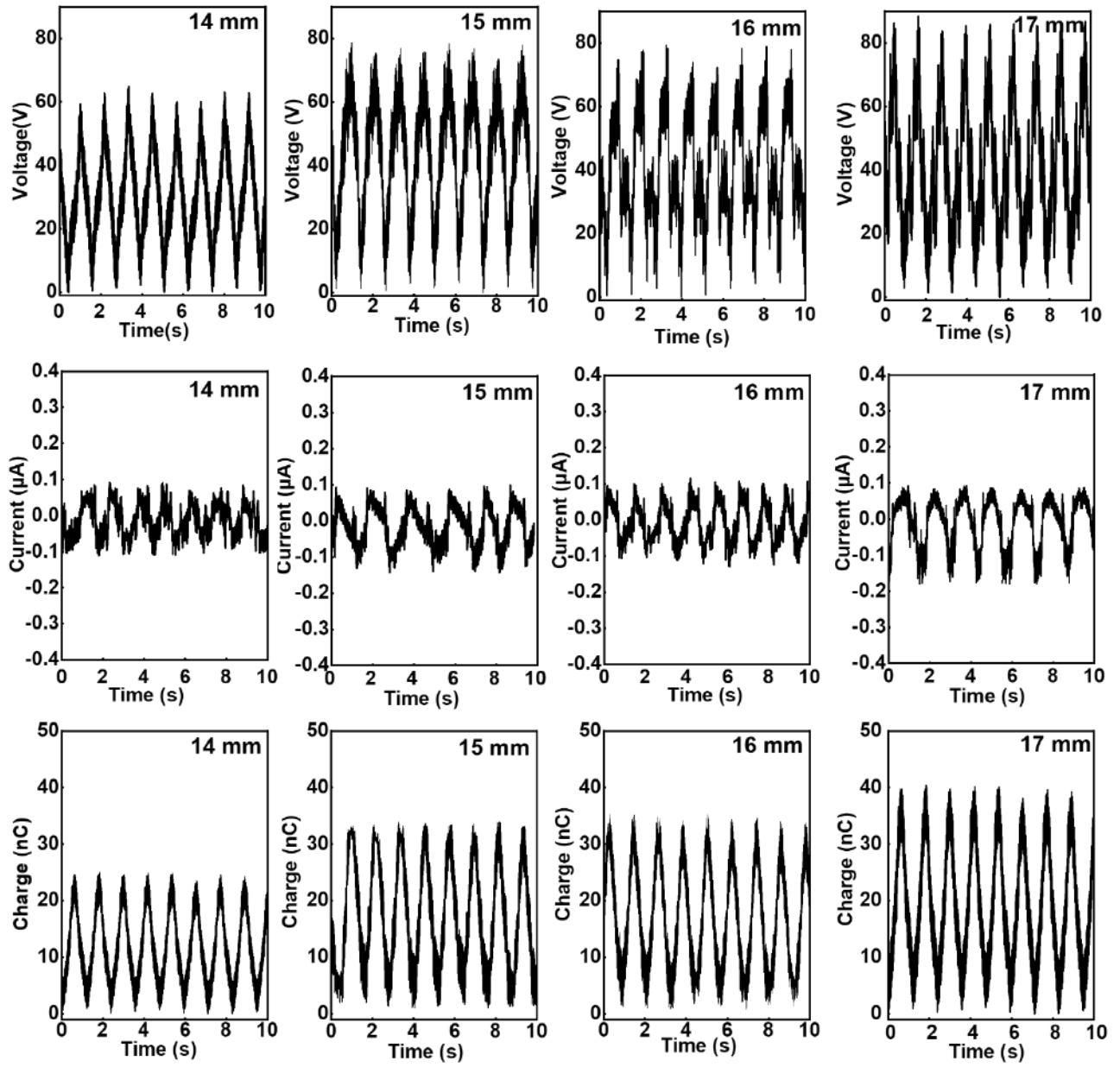


Fig.S10 The I_{sc} , Q , and U_{oc} were tested under different diameters of the FEP tube (14, 15, 16, and 17 mm).

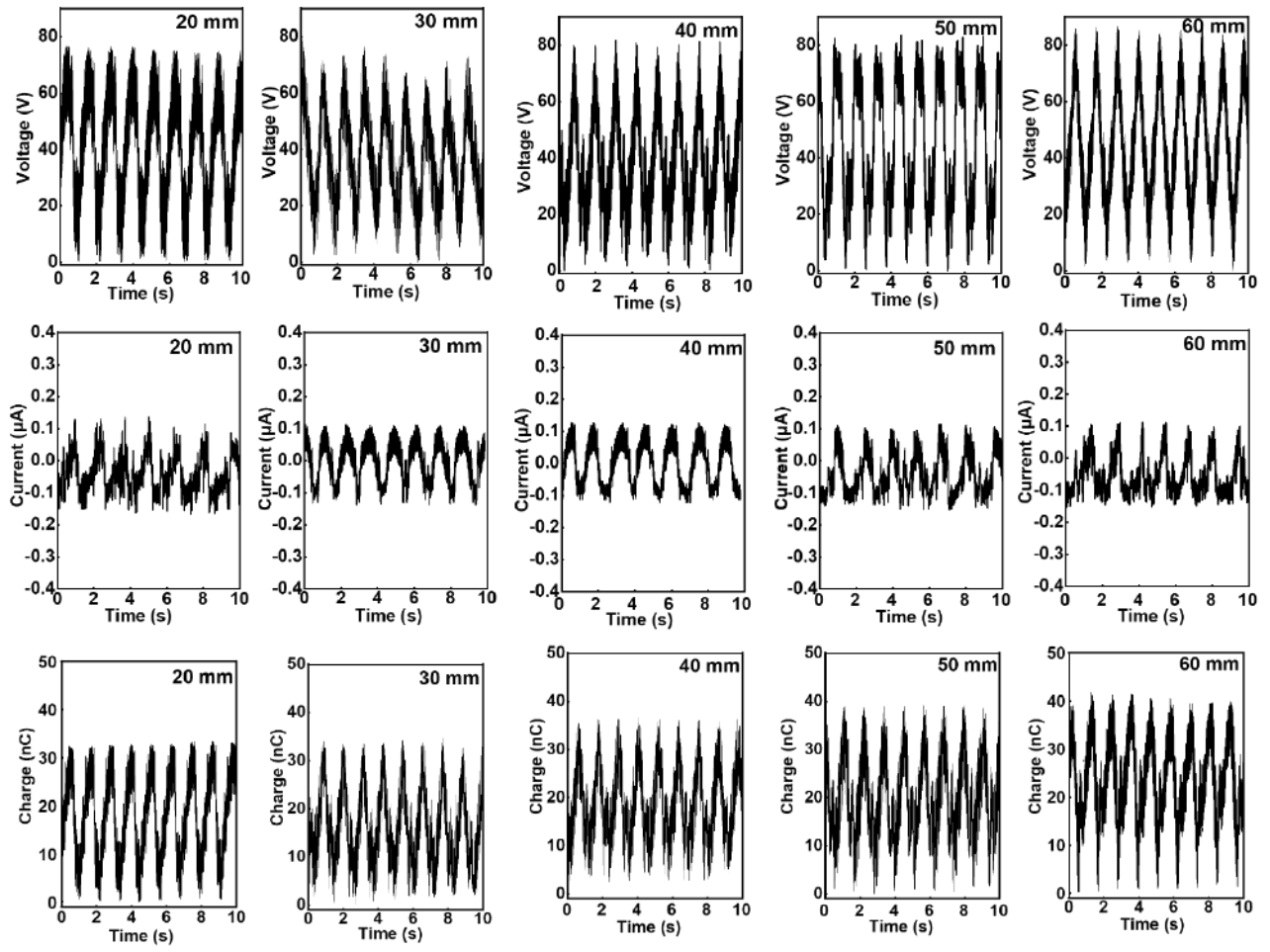


Fig.S11 The I_{sc} , Q , and U_{oc} were tested under different elongation lengths of the linear motor actuator (20, 30, 40, 50, and 60 mm).

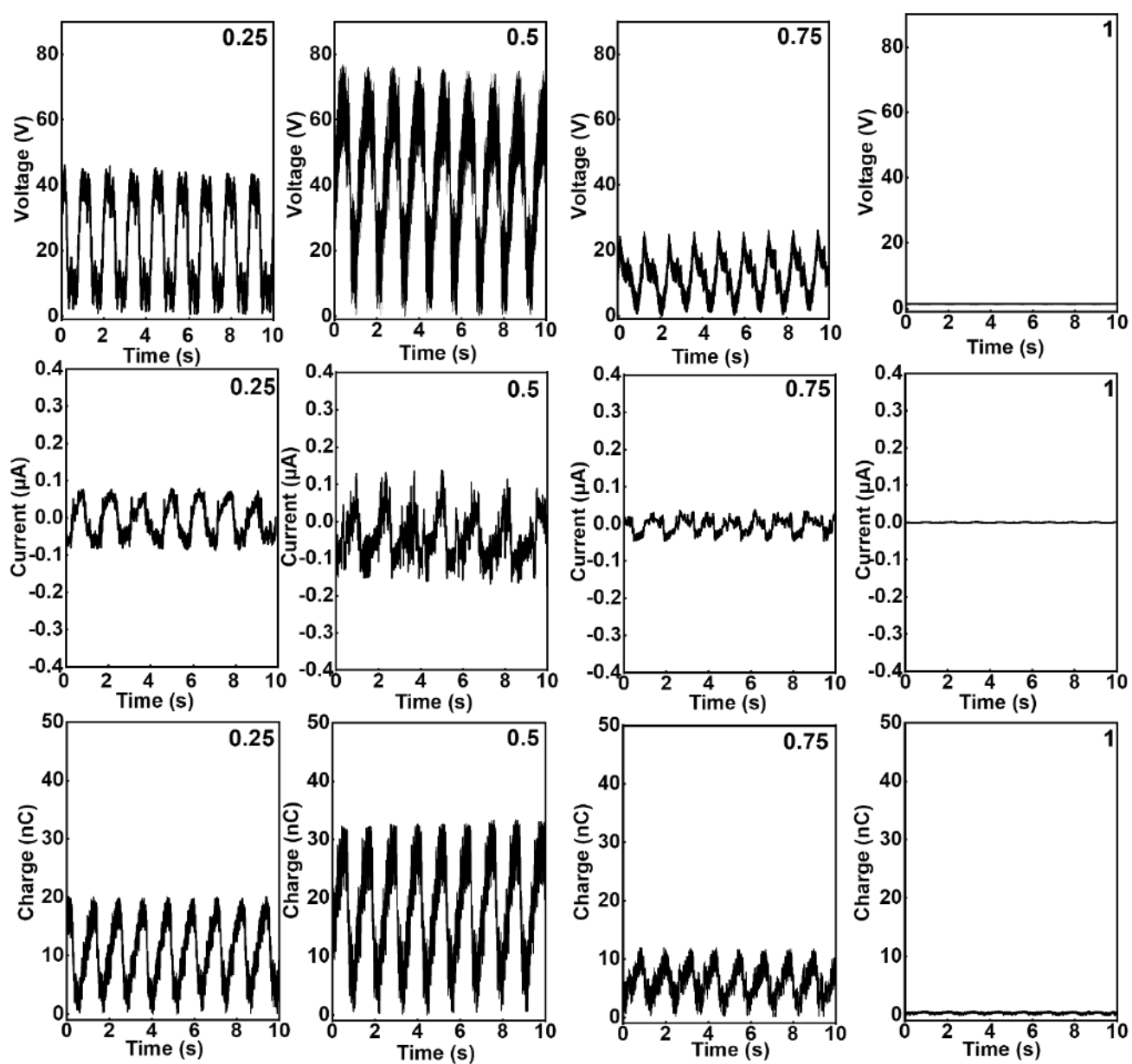


Fig.S12 The I_{sc} , Q , and U_{oc} were tested under different salt solution volumes (25%, 50%, 75%, and 100%).

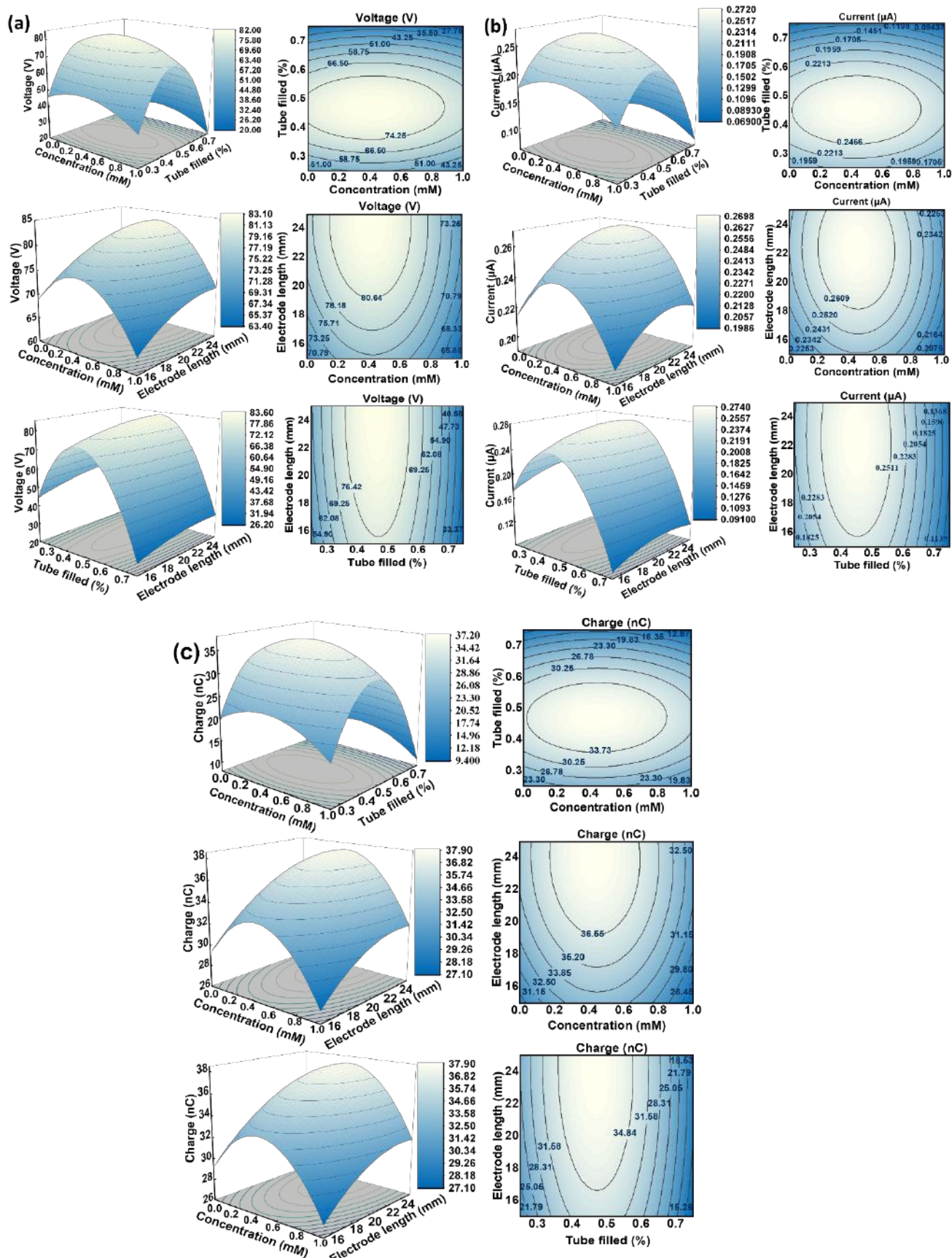


Fig.S13 Response surface and contour plots of C-TENG (voltage (a), current (b), and charge (c)).

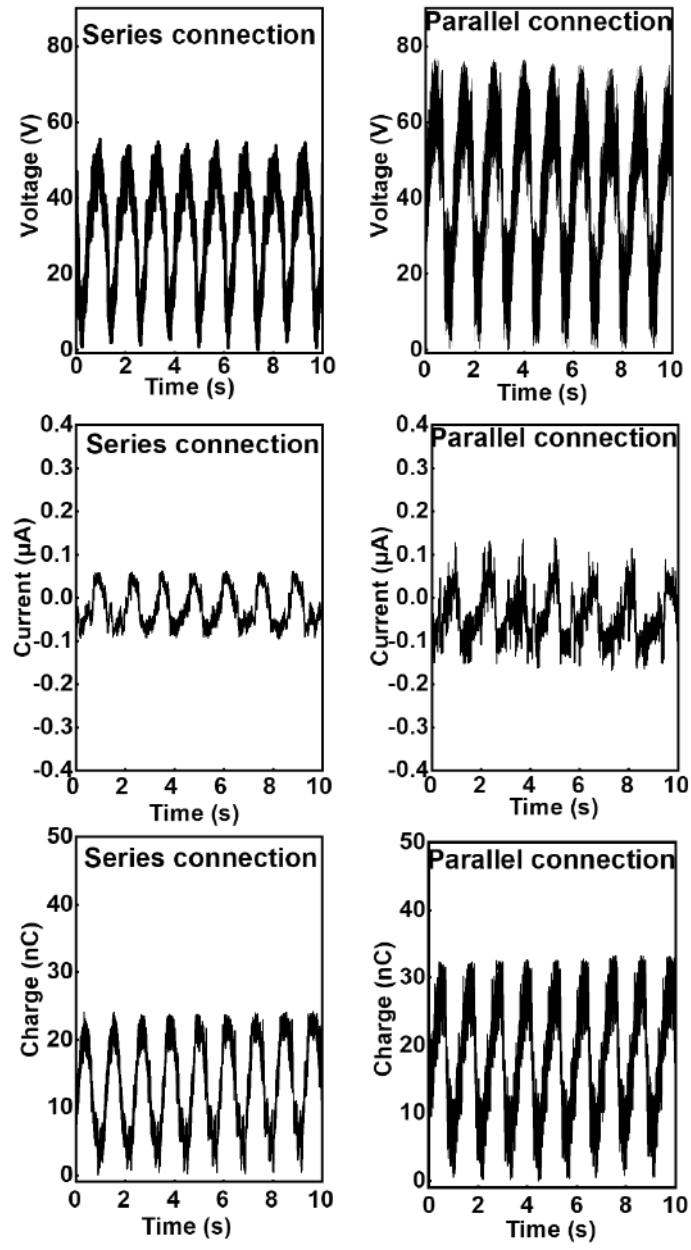


Fig.S14 The I_{sc} , Q , and U_{oc} were tested under series and parallel modes of C-TENG.

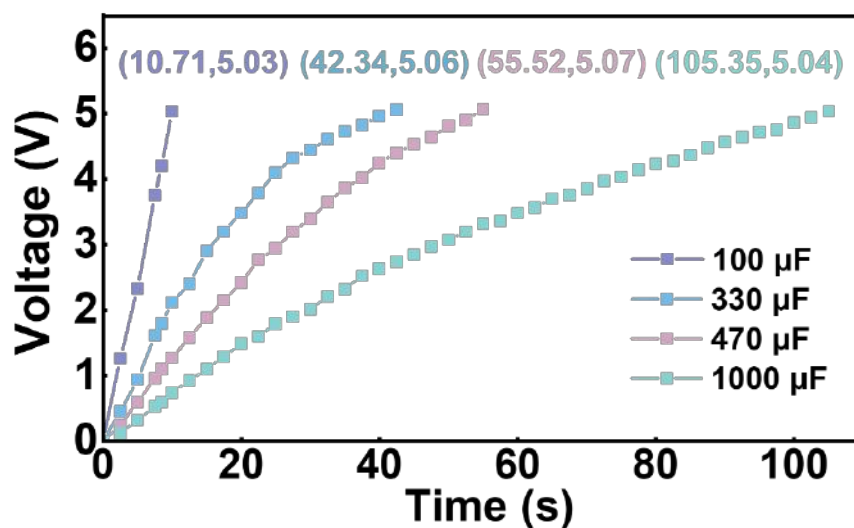


Fig.S15 Charging curves of various capacitors by the C-TENG.

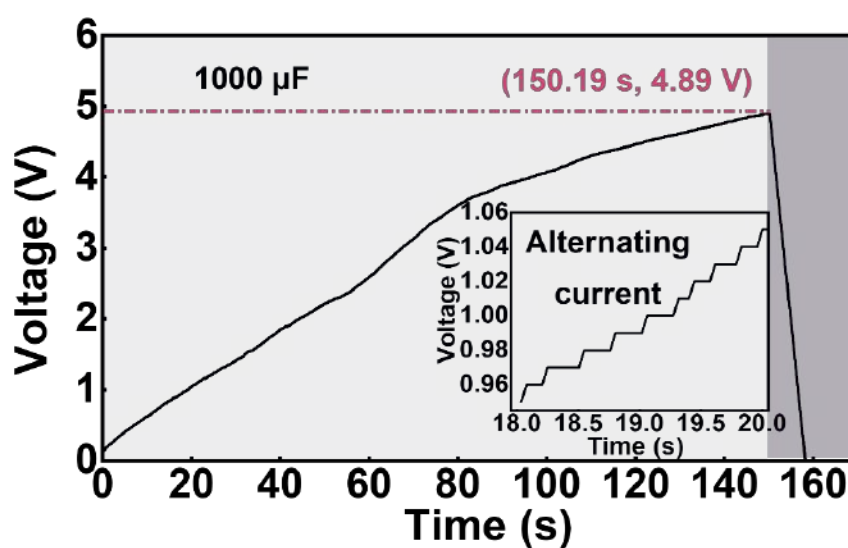


Fig.S16 Capacitance charge curve of 1000 μF . (In the experiment, we first charged the 1000 μF capacitor to 4.89 V through the C-TENG, then disconnected the C-TENG power supply connection and connected the MCDI. After 8.4 s, the power in the capacitor was exhausted).

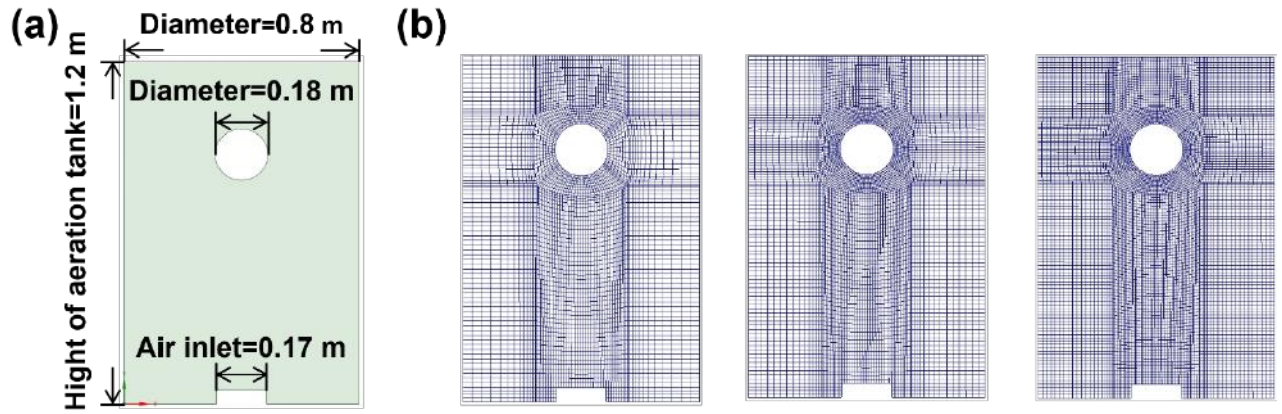


Fig.S17 CFD simulation results of the aeration tank. (a) The aeration tank geometry and size. (b) Three levels of non-uniform structured grids (coarse, medium, and fine).

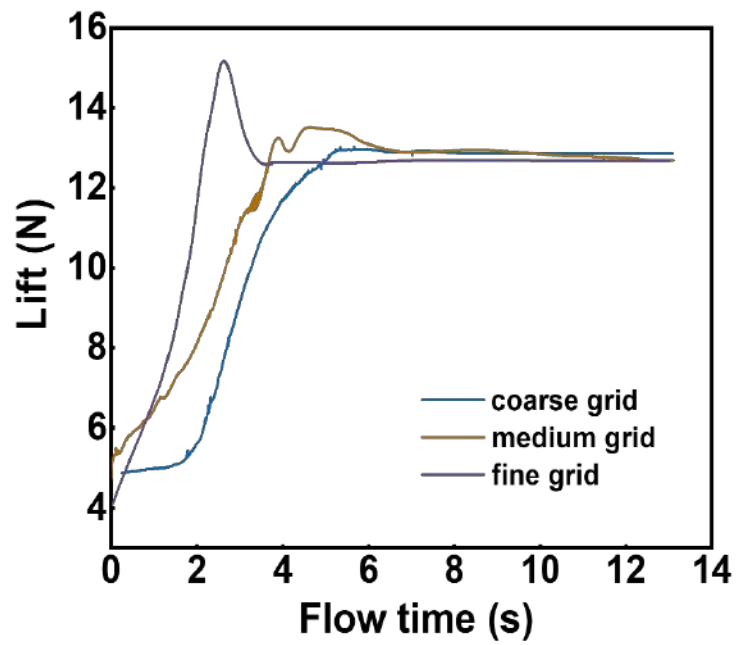


Fig.S18 The gas-liquid two-phase flow generated the kinetic energy under quasi-steady state conditions for three grid resolutions.

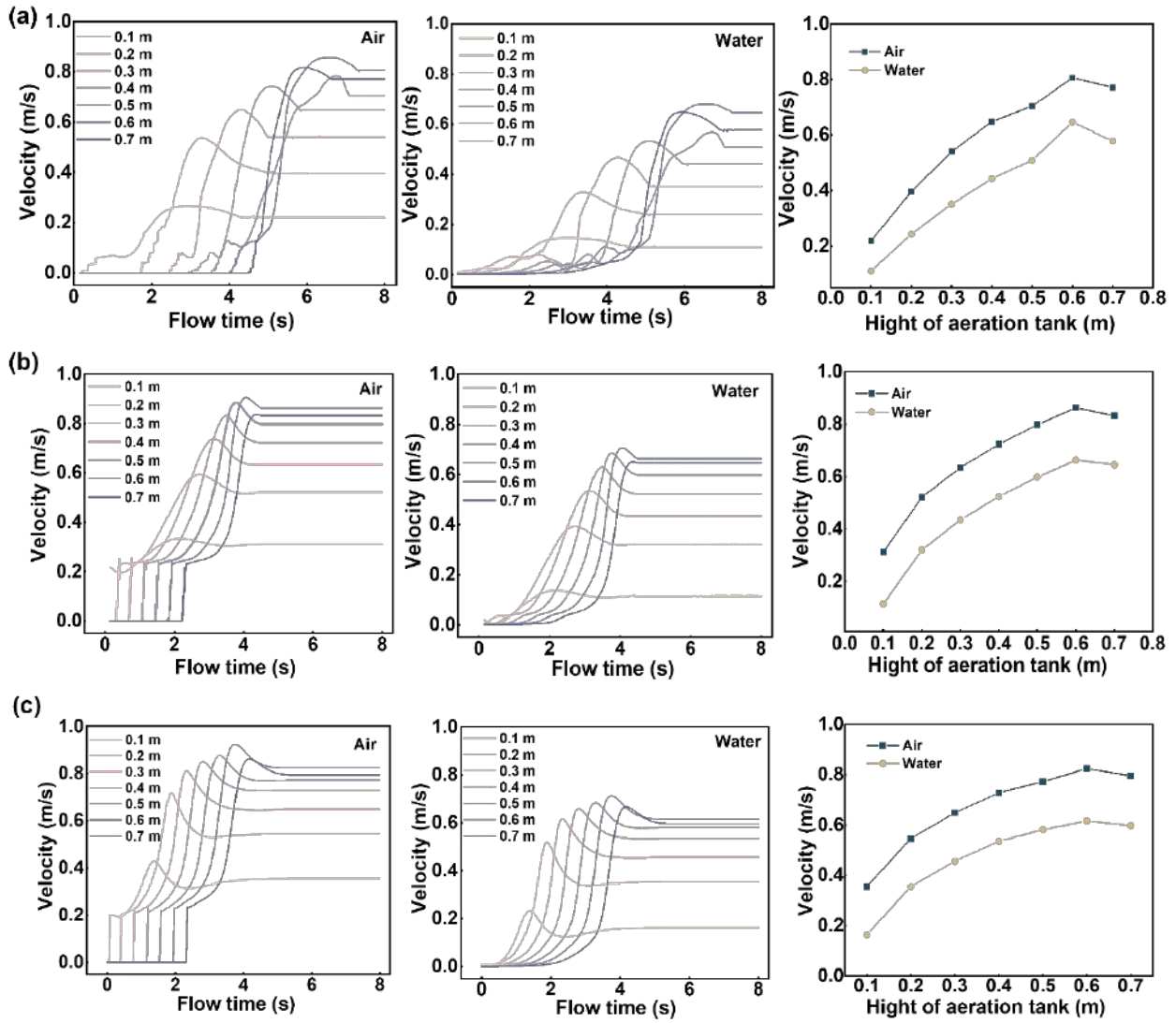


Fig.S19 The variations in gas and liquid phase velocity vectors for both instantaneous and time-averaged flows, across coarse (a), medium (b), and fine grid (c) resolutions.

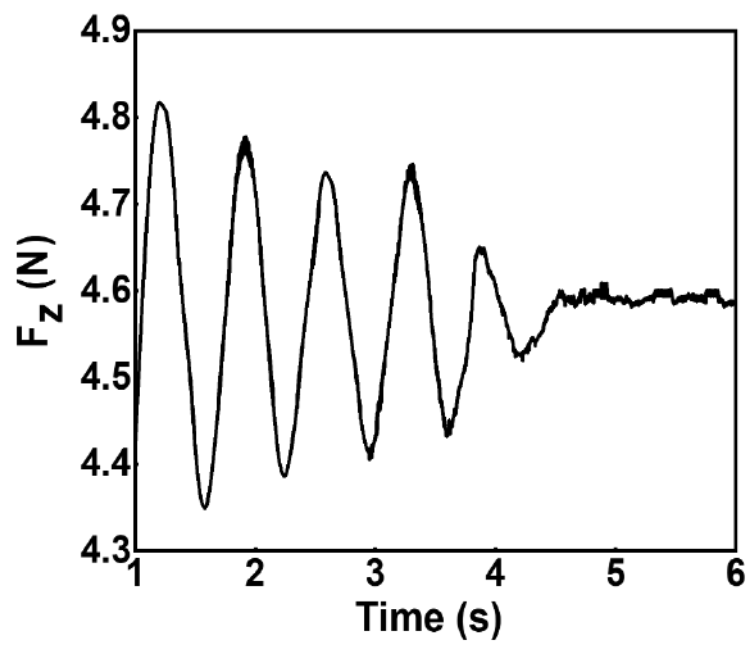


Fig.S20 Numerical data of the vertical wave force acting on the C-TENG.



Fig.S21 C-TENG's motion form in the aeration tank.

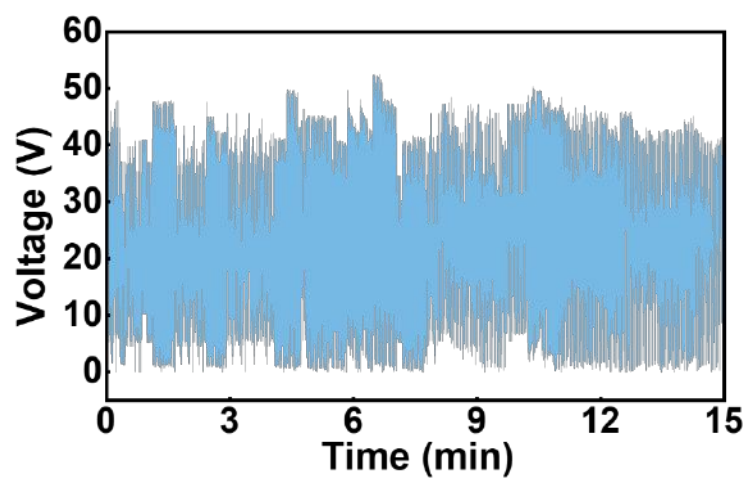


Fig.S22 Continuous voltage output of the C-TENG in a pilot-scale aeration tank.

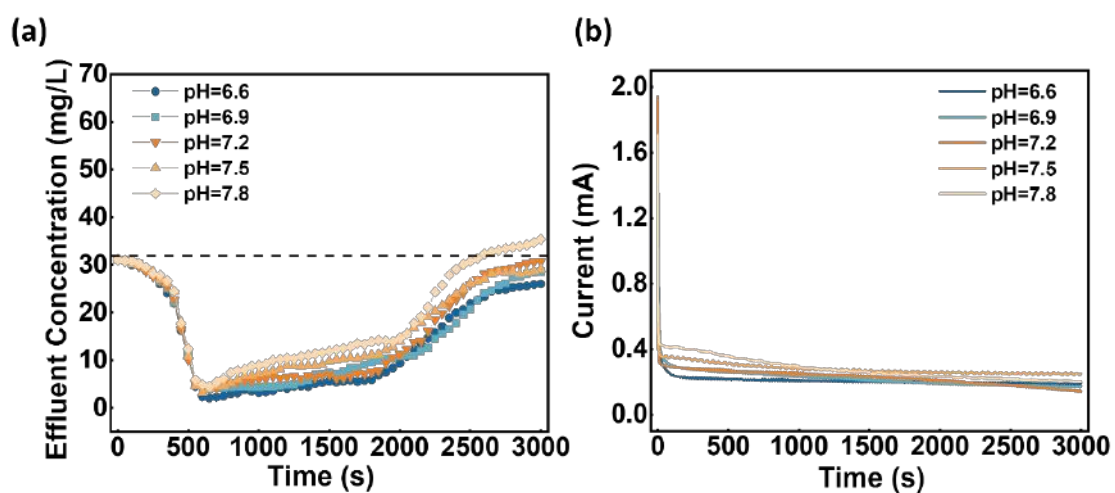


Fig.S23 In C-TENG//MCDI system. (a) Conductivity variations diagram. (b) Current variation diagram for different pH levels.

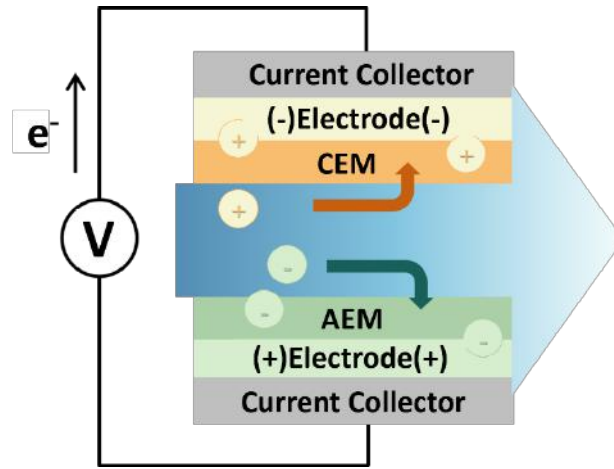


Fig.S24 Ionic adsorption mechanism of MCDI.

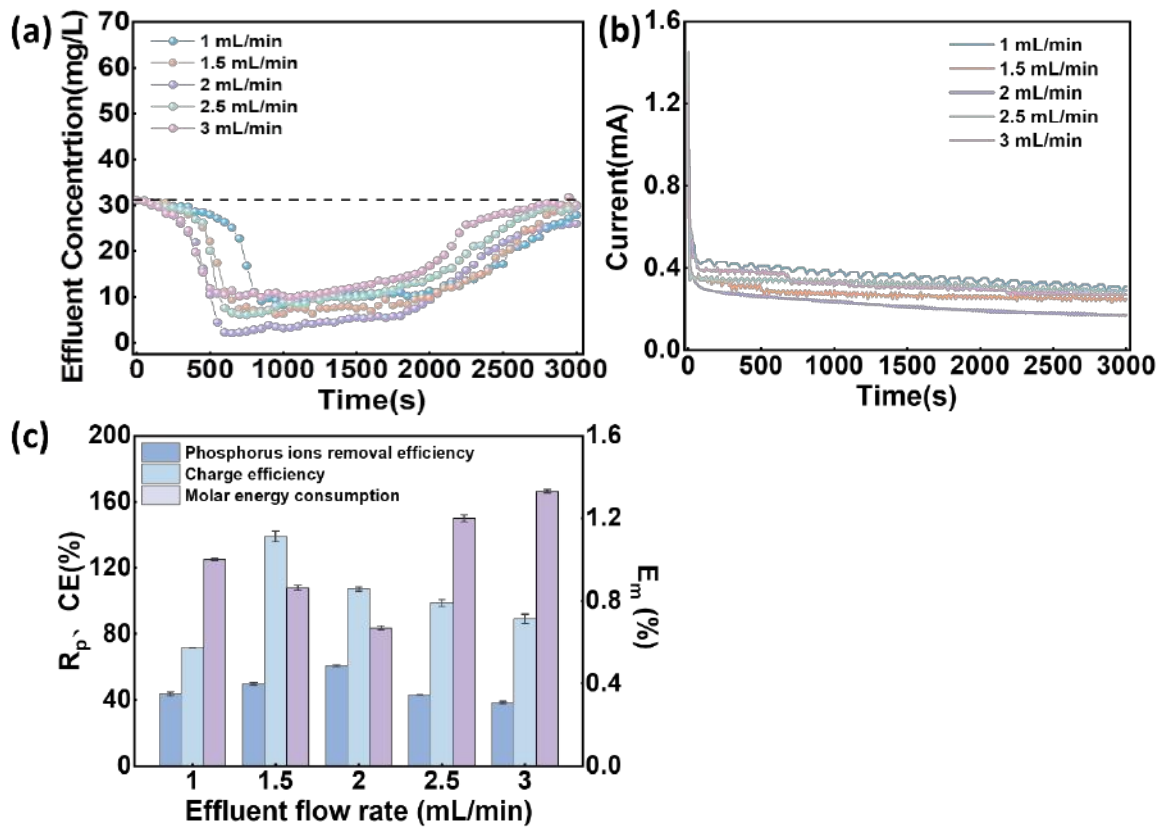


Fig.S25 In C-TENG//MCDI system, (a) Conductivity variations diagram, (b) Current variation diagram, (c) R_p , CE , and E_m of different flow rate (1-3 mL/min).

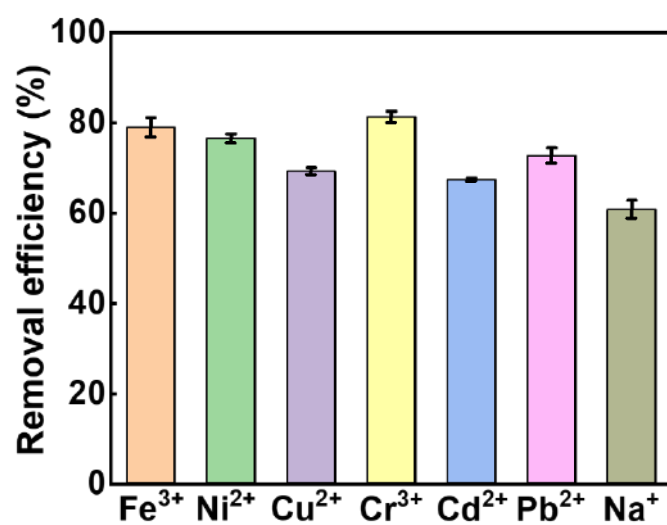


Fig.S26 The removal efficiencies of heavy metal ions.

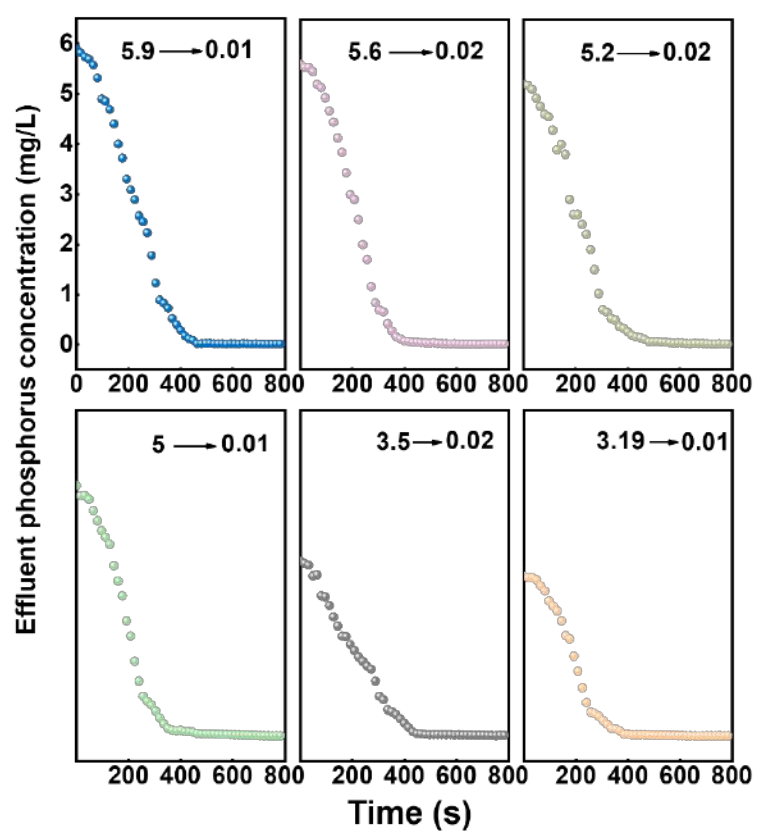


Fig.S27 Removal performance of the C-TENG//MCDI system under different phosphorus concentrations.

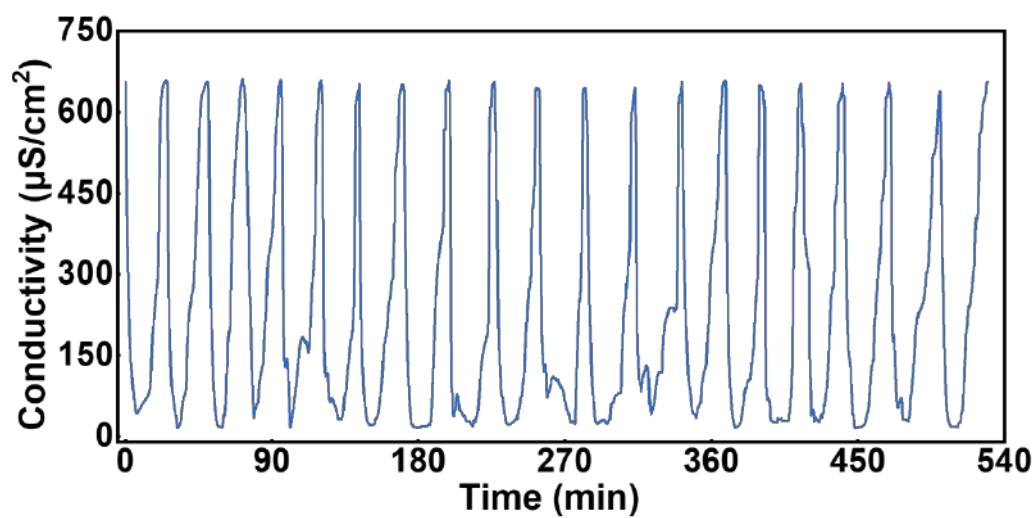


Fig.S28 Deionization-regeneration profiles of the C-TENG//MCDI system in a multi-metal ion solution.

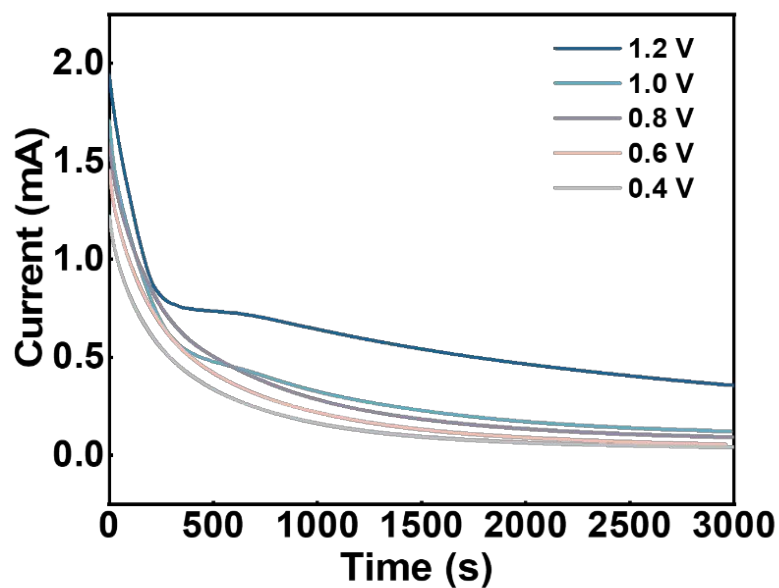


Fig.S29 The current change during the charge and discharge cycle.

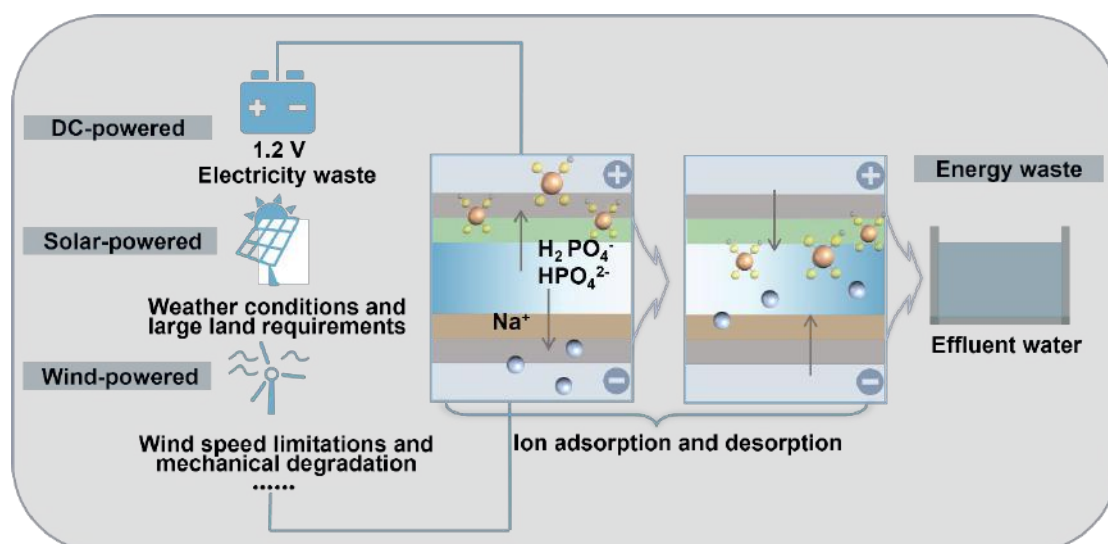


Fig.S30 Existing energy supply technologies and ion removal processes.

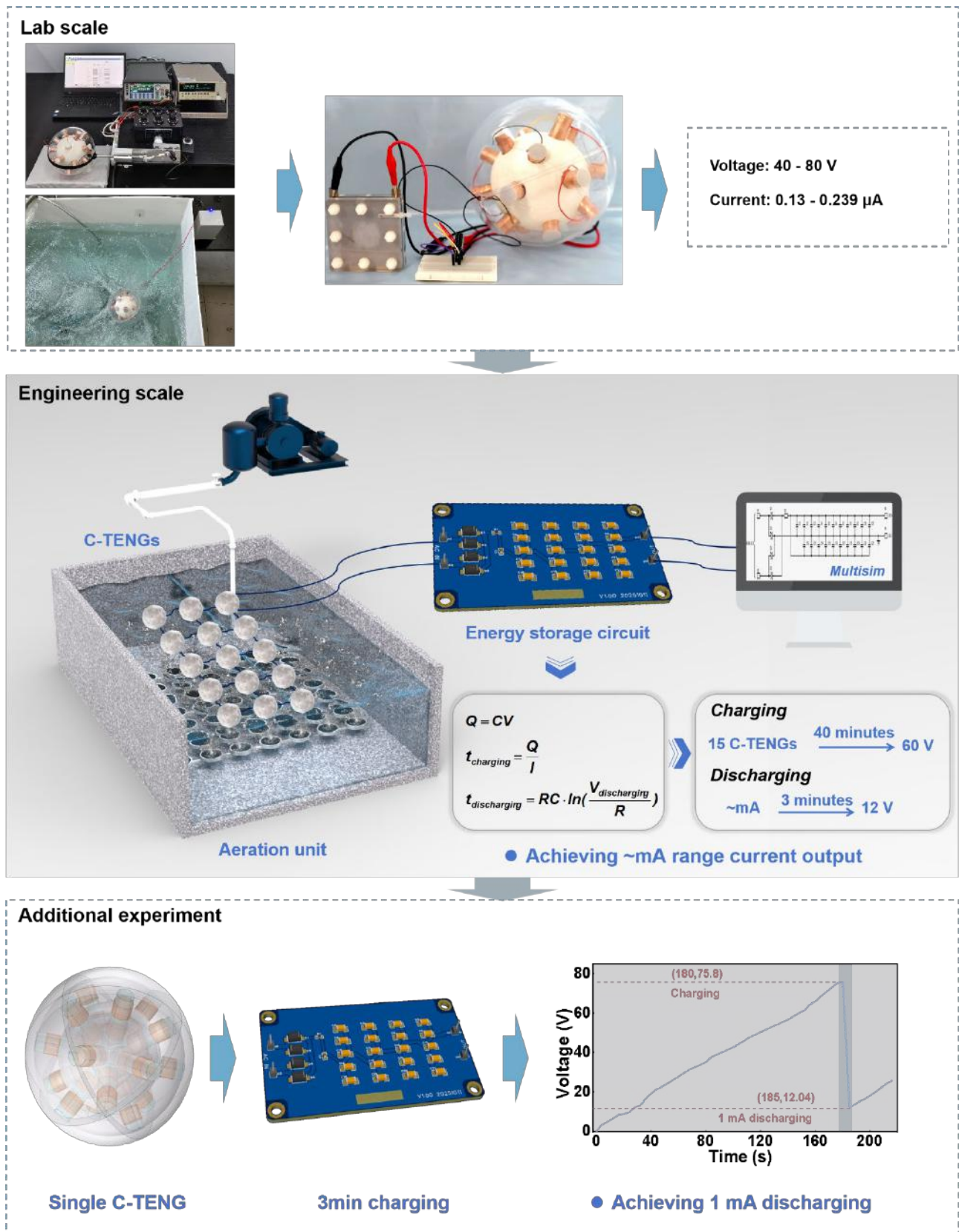


Fig.S31 Schematic diagram of performance output at the lab scale and engineering scale.

Table S1

Coding level of RSM factors.

Factor	Code	Coding level		
		-1	0	1
Salt solution concentration (mM)	A	0	0.5	1
Solution volume (%)	B	0.25	0.5	0.75
Electrode width (mm)	C	15	20	25

The model's required dependent variables and their corresponding response values were presented in Table S2. Experimental comparisons were conducted to assess the impact of various factors on electrical output performance. The electrical output properties (peak voltage, peak current, and transfer charge) of the constructed C-TENG exhibit significant variations under different mechanical structural conditions. By employing Design-Expert Software 8.0.6 to fit the experimental data presented in Table S2, a quadratic multinomial regression equation was derived to establish the relationship between salt solution concentration (A), solution volume (B), structural electrode width (C), and peak voltage (Y_1), transferred charge (Y_2), as well as peak current (Y_3).

$$Y_1 = -120.98066 + 29.91427 A + 607.03031 B + 4.64927 C + 4.19396 AB - 0.11557 AC - 0.60748 BC - 35.68733 A^2 - 636.31636 B^2 - 0.087937 C^2 \quad (R^2 = 0.9487)$$

$$Y_2 = -64.40252 + 17.82615 A + 267.67062 B + 2.99876 C + 1.57754 AB - 0.062429 AC - 0.35026 BC - 19.77432 A^2 - 277.97124 B^2 - 0.058191 C^2 \quad (R^2 = 0.9419)$$

$$Y_3 = -0.39375 + 0.12844 A + 1.63409 B + 0.024481 C + 0.017892 AB - 0.000605 AC - 0.000250554 BC - 0.14339 A^2 - 1.76770 B^2 - 0.000515562 C^2 \quad (R^2 = 0.9528).$$

Table S2

Analysis of response surfaces for peak voltage, peak current, and transfer charge based on experimental results.

No	Coding level			μA	nC	V
	A	B	C			
1	-1	-1	0	0.168987	19.2218	43.7546
2	1	-1	0	0.151121	17.2706	38.9193
3	-1	1	0	0.084756	11.4525	24.8879
4	1	1	0	0.075836	10.2901	22.1495
5	-1	0	-1	0.21406	29.0317	68.8644
6	1	0	-1	0.19428	26.0847	61.2542
7	-1	0	1	0.24428	35.1818	79.322
8	1	0	1	0.21845	31.6105	70.5562
9	0	-1	-1	0.178079	20.4522	46.3892
10	0	1	-1	0.0893167	12.1857	26.3875
11	0	-1	1	0.203214	24.7851	53.4337
12	0	1	1	0.101924	14.7673	30.3946
13	0	0	0	0.26832	37.003	82.6326
14	0	0	0	0.26158	36.703	80.5682
15	0	0	0	0.27925	36.9852	79.5656
16	0	0	0	0.26953	37.6356	81.0534
17	0	0	0	0.25384	36.051	81.7774

Table S3

Analysis findings of peak voltage variation.

Source	Sum of squares	df	Mean square	F Value	p-value Prob>f
Model	8241.50	9	915.72	203.74	<0.0001
<i>A</i>	71.70	1	71.70	15.95	0.0052
<i>B</i>	773.76	1	773.76	172.16	<0.0001
<i>C</i>	118.67	1	118.67	26.40	0.0013
<i>AB</i>	1.10	1	1.10	0.2446	0.6361
<i>AC</i>	0.3339	1	0.3339	0.0743	0.7931
<i>BC</i>	2.31	1	2.31	0.5132	0.4970
<i>A</i> ²	335.15	1	335.15	74.57	<0.0001
<i>B</i> ²	6659.52	1	6659.52	1481.69	<0.0001
<i>C</i> ²	20.35	1	20.35	4.53	0.0709
Residual	31.46	7	4.49		
Disfit	26.02	3	8.67	6.37	0.0528
Pure error	5.45	4	1.36		
Total deviation	8272.97	16			

Note: A significance level of $P < 0.001$ was considered as extremely significant, a significance level of $P < 0.01$ was regarded as highly significant, and a significance level of $P < 0.05$ was deemed as statistically significant.

Table S4

Results of reliability analysis for the regression equation.

Item	c.v.%	R-Squared	Adj R-Squared	Pred R-Squared	Adeq Precision
	3.71	0.9962	0.9913	0.9487	37.5129

Table S5

Parameter configuration for Multisim simulation.

Parameter	Value
Software	Multisim 14.0
Steady-state alternating current source (I_0)	1.0 μ A, 1 HZ
Internal impedance (R_0)	100 M Ω
Internal reactance (C_0)	10 nF
Range of load resistance (R_1)	10 k Ω -1 T Ω
Range of load Voltage (C_1)	10 pF-10 μ F

Table S6

Physical properties and operating conditions of the CFD modeling.

Parameters	Values	Units
Aeration tank conditions	Length	0.8
	Depth	0.8
	Aeration pan radius	0.085
	Aeration pan area	0.022698007
	Aeration capacity	0.00025
	Aeration flow rate	0.011014183
The physical parameters of the C-TENG	Quality	0.466
	Radius	0.09
	Volume	0.003053628
	Density	152.6053596
	Medium density	1000
Operating conditions	Temperature	25
	Density of air	1.225
	Density of water	998.2
	Bubble diameter	2
	Viscosity of air	1.7894×10^{-5}
	Viscosity of water	1.003×10^{-3}

Table S7

C-TENG motion parameters: angular velocity, force magnitude, and force orientation (at 3.6 s, 3.8 s, and 4.2 s).

	3.6 s	3.8 s	4.2 s
V_x (m/s)	-0.004129	-0.004985	-0.017487
V_y (m/s)	-0.040973	-0.055707	-0.149615
V_z (m/s)	0.047596	0.007971	-0.030204
$V_{\text{magnitude}}$ (m/s)	0.1602	0.165726	0.18647
F_x (N)	-0.00092	-0.00163	-0.0063
F_y (N)	-0.00916	-0.01823	-0.0446
F_z (N)	0.01064	0.00261	0.0168
F_w (N)	0.0024	0.002	0.0065
F_v (N)	0.0058	0.0054	0.0164
F_b (N)	2.405	2.530	2.716
F_s (N)	0.036	0.035	0.036
$F_{T(w+v+b+s)}$ (N)	2.4492	2.5724	2.7749
h (cm)	1	1	1
θ_f (°)	74.3	71.4	79.4
θ_c (°)	75	72	80

Table S8

The final outlet metal ion concentrations.

Ion types	C_0 (mg L ⁻¹)	C_t (mg L ⁻¹)	Removal efficiency (%)
Fe ³⁺	10	2.103	78.97
Ni ²⁺	10	2.345	76.55
Cu ²⁺	10	3.075	69.25
Cr ³⁺	10	1.873	81.27
Cd ²⁺	10	3.259	67.41
Pb ²⁺	10	2.729	72.71
Na ⁺	100	39.2	60.8

Table S9

Energy recovery efficiency of the MCDI system in the reference.

Hardness in/concentration	Applied voltage (V)	Flow rate (mL/min)	CDI type/electrode	Energy recovery	References
10 Mm, NaCl	1.2 V	2 mL/min	CDI cell with carbon powder	45%	Kang et al., 2016
10 Mm, NaCl	1.2 V	40 mL/min	CDI cell with activated carbon fiber	46.6%	Chen et al., 2018
9mM, NaCl	1.0-1.4 V	1-15 mL/min	CDI cell with konyl activated carbon cloth	30-45%	Han et al., 2015
10.27 mM, NaCl	2.4 V	1340 mL/min	CDI cell with activated carbon electrodes	47%	Jeon et al., 2022

Table S10

Descriptive information on the technical parameters and economic studies of the MCDI stack ([Chen et al., 2022](#)).

	Unit	Wastewater discharge	Remarks
Process parameters			
Electricity consumption for MCDI process	kWh/ m ³	0.680	
Product water flow rate	m ³ /day	0.036	
Volume-averaged desalination depth (ΔC)	mM	23.3	
Productivity (P)	L/h/m ²	3.750	
Cost components			
Capital cost			
MCDI module	\$/m ³	0.045	MCDI stacks of 10 working pairs
Balancing system	\$/m ³	0.150	Power electronics and power management
Indirect capital cost	\$/m ³	0.045	Research and development
Operation and maintenance cost			
Electricity	\$/m ³	0.049	Primary data based on electricity consumption
Chemical use	\$/m ³	0.133	Fouling cleaning solution of citric acid
Material replacement	\$/m ³	0.098	Electrodes and membrane replacement
Labor	\$/m ³	0.012	
LCOW	\$/m ³	0.53	

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