

# Raindrop-modulated wind-driven rotational dynamics for enhanced triboelectric energy harvesting

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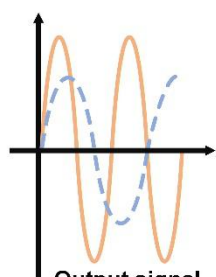
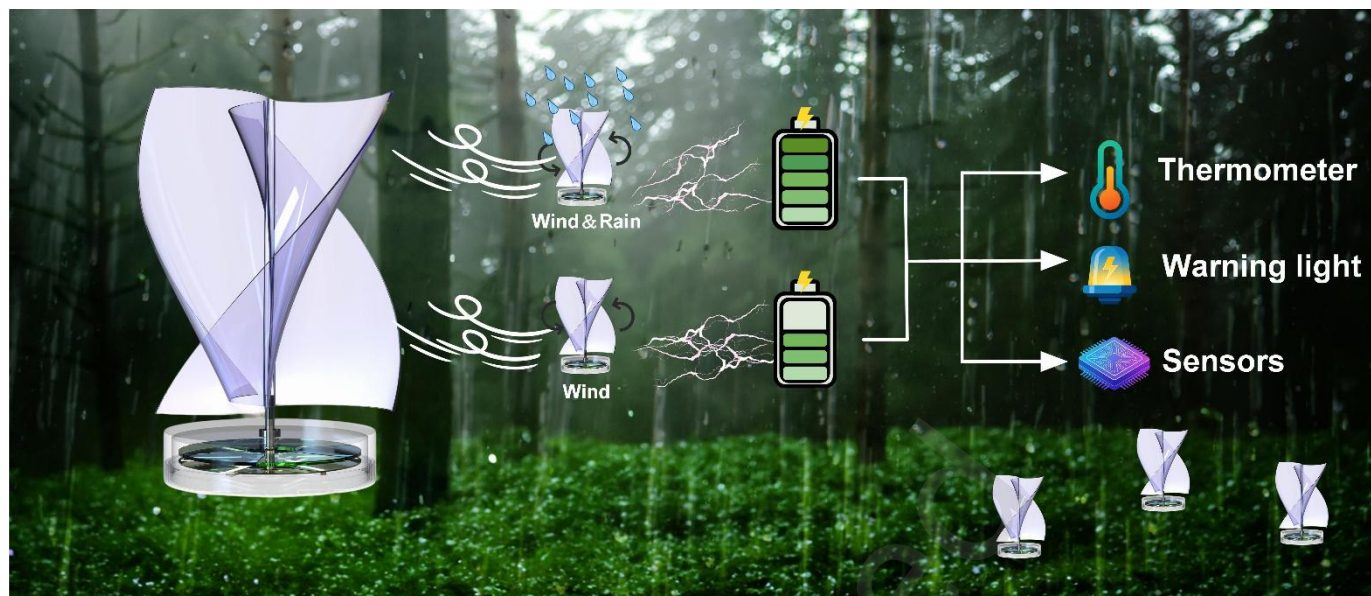
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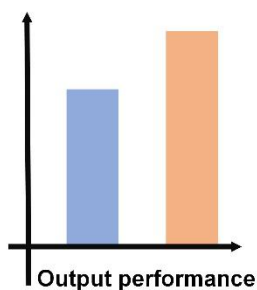
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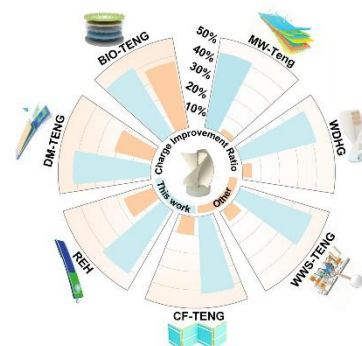
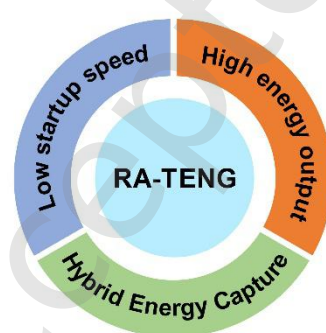
Output signal

Wind + Rain



Output performance

Only wind



To address the urgent need for wildfire warning and ecological monitoring in forest environments, as well as the power supply challenges caused by low wind speeds and frequent rainfall, this work reports a novel raindrop-assisted aerodynamically activated triboelectric nanogenerator for harvesting low-speed wind energy in the wild.

# Raindrop-modulated wind-driven rotational dynamics for enhanced triboelectric energy harvesting

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**ABSTRACT:** Triboelectric nanogenerators (TENGs) are highly effective for harvesting low-frequency and stochastic environmental energy. However, realistic outdoor conditions involve multiple coexisting stimuli. The resulting environmental perturbations disrupt rotor motion, which compromises the efficiency and stability of triboelectric charge transfer. Here, we report a raindrop-assisted aerodynamically activated triboelectric nanogenerator (RA-TENG) that leverages wind-rain coupling to enhance mechanical driving rather than treating rainfall as a detrimental factor. In this system, raindrop-induced momentum transfer actively modulates the rotational dynamics of the turbine, leading to a reduced activation threshold and improved rotational continuity. As a result, the frequency and stability of the device operation are significantly enhanced, thus reinforcing charge excitation and increasing charge transfer. The RA-TENG exhibits a low start-up wind speed of 3 m/s under wind-only conditions, which can be further reduced to 1.9 m/s under wind-rain excitation. At a wind speed of 6 m/s, the transferred charge of the device under combined wind-rain excitation is increased by 42% compared with that under single wind driving. This work establishes a mechanical-electrical coupling strategy and providing a general framework for converting environmental perturbations into constructive driving forces.

**KEYWORDS:** triboelectric nanogenerator; ternary dielectric triboelectrification; wind energy; raindrop energy; wind-rain synergistic

## 1 Introduction

Triboelectric nanogenerators (TENGs) enable efficient conversion of low-frequency[1–3], low-intensity[4–6], and stochastic mechanical stimuli into electrical output[7–9], making them particularly suitable for harvesting weak and irregular environmental energy, such as gentle breeze[10–12], raindrop impact[13–15], and random mechanical perturbations[16–19]. Their structural simplicity and compatibility with self-powered systems further highlight their potential for distributed energy applications[20, 21]. However, in realistic outdoor environments, energy sources rarely exist in isolation[22]. Instead, wind, rainfall, and humidity coexist and interact, introducing coupled environmental perturbations that significantly affect the mechanical driving process of TENGs. While wind serves as the primary driving force, raindrop impact and moisture can disrupt rotor motion, induce fluctuations in rotational dynamics, and compromise the stability of the power output[23–25]. These effects lead to reduced operational stability, increased start-up thresholds, and compromised energy conversion efficiency. Consequently, an intrinsic paradox arises: environmental complexity simultaneously provides abundant mechanical energy while perturbing the dynamic conditions required for efficient and stable

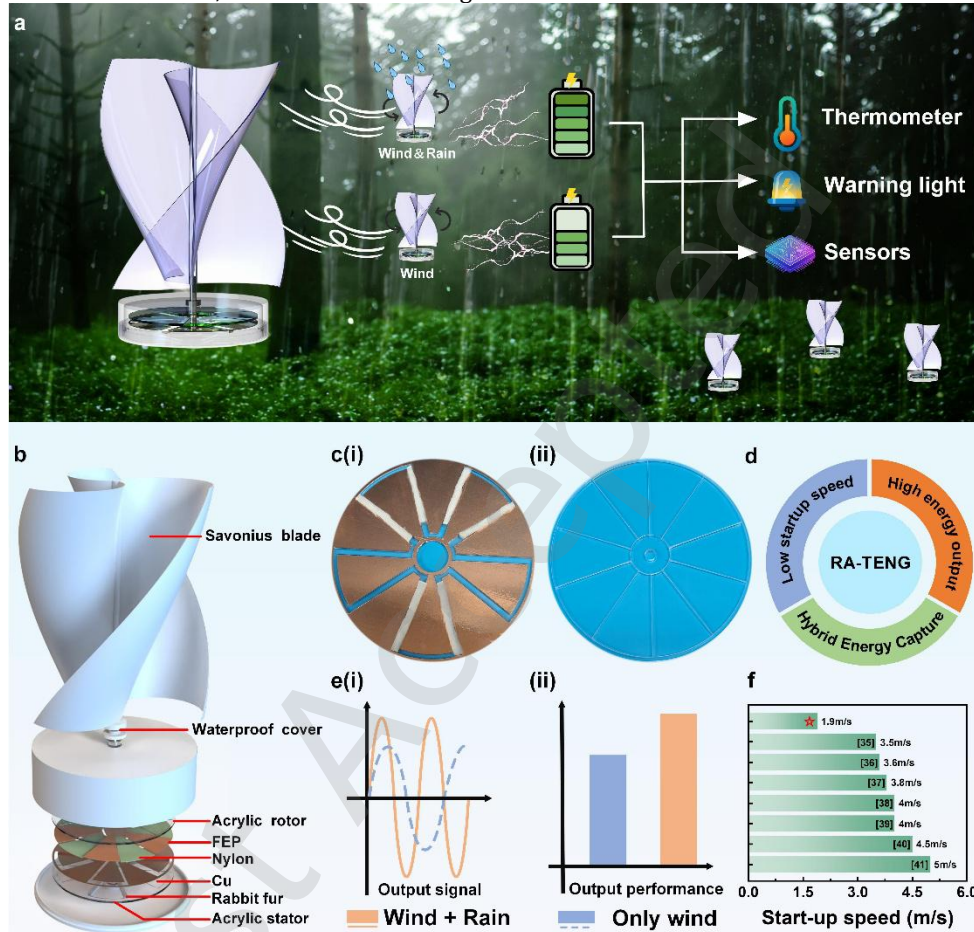
electrification. This unresolved contradiction fundamentally limits the practical deployment of TENG technologies in realistic environments.

To address these challenges, extensive efforts have been devoted to improving the performance of TENGs under realistic conditions. Wind-driven systems have been optimized through structural and aerodynamic design to enhance energy capture efficiency and reduce start-up thresholds[26–28]. Although wind-driven designs achieve high energy harvesting efficiency under isolated conditions, their rotational dynamics are still prone to destabilization when multiple environmental stimuli coexist. Surface engineering strategies, including hydrophobic modification and encapsulation, have been employed to improve operational stability in humid environments[29, 30], yet they primarily focus on mitigating external disturbances rather than utilizing them. In addition, hybrid systems that integrate multiple energy sources, such as wind, vibration, and water, have been developed to increase overall energy output[31–34]. However, such hybrid systems typically rely on the simple superposition of multiple energy inputs, without considering the intrinsic interactions between different environmental stimuli. As a result, environmental factors such as wind and rainfall continue to introduce dynamic perturbations to the mechanical motion of TENG systems, leading to unstable rotation behavior and limited

energy conversion efficiency. More importantly, existing strategies fail to define the role of environmental disturbances in TENG operation and cannot fully exploit the intrinsic coupling effect among multiple stimuli. In practice, wind and rain rarely occur in isolation in forested environments such as tropical rainforests and mountain forests, but instead co-occur as concurrent perturbations. This wind-rain coupling phenomenon is not only widespread but also long-lasting, containing abundant harvestable energy. As such, fully utilizing this coupling effect is of great practical significance for providing continuous and stable power supply to distributed sensors, and other monitoring

devices deployed under harsh weather conditions. Therefore, it is necessary to develop a new coupling-based design strategy that can actively harness environmental perturbations to enhance energy conversion performance.

Here, we present a raindrop-assisted aerodynamically activated triboelectric nanogenerator (RA-TENG) that establishes an intrinsically coupled energy conversion mechanism between wind flow and raindrop impact. Distinct from conventional approaches that treat rainfall as a detrimental factor, this system exploits raindrop-induced momentum transfer to actively



**Figure 1** Design concept and working principle of RA-TENG. (a) The model and design philosophy of RA-TENG. (b) Exploded View of the RA-TENG. (c) Structural photographs of the stator(i) and rotor(ii). (d) Multi-dimensional performance advantages of the RA-TENG. (e) Schematic diagram of the wind-rain synergistic performance. (f) Comparison of start-up wind speeds for wind power generation units.

modulate the rotational dynamics of the turbine under coupled environmental stimuli. This mechanically mediated coupling enhances rotational continuity and increases angular velocity, thereby lowering the start-up threshold and stabilizing the rotation process that governs charge generation. As a result, the frequency and effectiveness of contact electrification are significantly improved, leading to a 42% enhancement in transferred charge under wind-rain conditions compared with wind-only operation. The RA-TENG exhibits a reduced start-up wind speed of 1.9 m/s under wind-rain excitation. In this framework, raindrop impact functions not merely as an auxiliary energy input, but as a dynamic regulator that reshapes the mechanical driving process and synchronizes environmental stimuli with electrification behavior. This design moves beyond conventional additive hybridization and establishes a multi-stimulus coupling paradigm, in which environmental perturbations are harnessed to enhance, rather than disrupt,

energy conversion. This work provides a generalizable strategy for regulating contact electrification through mechanical dynamics, offering new insights into transforming environmental complexity into constructive driving forces for robust and sustainable energy harvesting in realistic conditions.

## 2 Results and discussion

### 2.1 Structural Design and Operation Principle

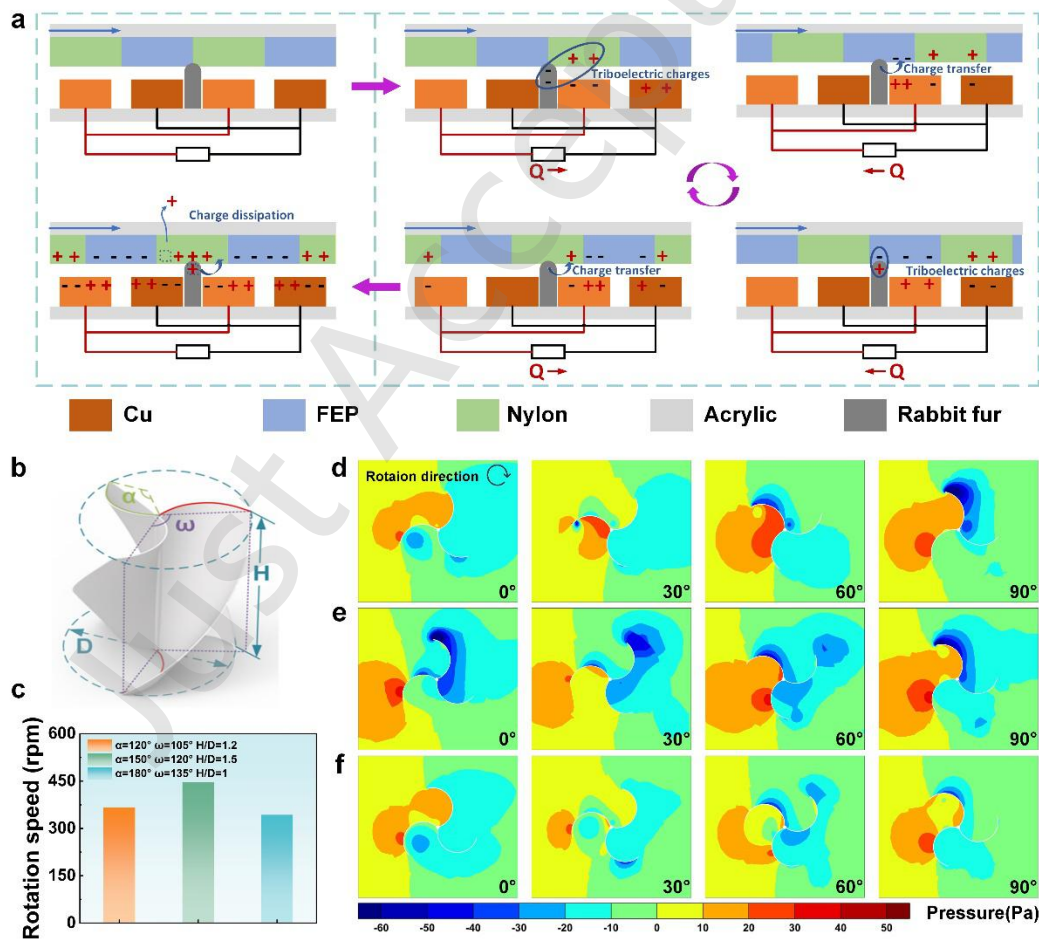
In forest environments, the rapid development of distributed sensing nodes for microclimate monitoring, wildfire early warning, and ecological infrastructure status tracking has created an urgent demand for sustainable and maintenance-free power supplies. Among various environmental energy sources, wind flow and rainfall are two ubiquitous mechanical inputs that frequently coexist under realistic outdoor conditions, particularly in forest rainy weather. Their low-frequency, stochastic, and irregular

characteristics make them highly suitable for triboelectric nanogenerators (TENGs), yet they are typically harvested independently in conventional designs. To more effectively utilize these naturally coupled environmental inputs, we propose a wind-rain synergistic strategy that exploits the interaction between wind flow and raindrop impact to enhance the mechanical driving dynamics of TENG systems (Fig. 1(a)). The RA-TENG consists of two primary components: a twisted Savonius rotor and a triboelectric nanogenerator unit (Fig. 1(b)). The upper section employs twisted Savonius blades that retain the low start-up wind speed and omnidirectional adaptability of conventional designs, enabling effective operation under complex forest scenario. More importantly, the twisted blade geometry converts raindrop-induced momentum into additional rotational driving force, allowing wind flow and raindrop impact to jointly regulate the rotor dynamics. This coupling mechanism enhances rotational continuity and increases angular velocity, thereby improving the mechanical conditions for subsequent electrification. The lower section comprises a fully encapsulated triboelectric generation unit housed in polylactic acid (PLA), including stator and rotor components. The stator consists of interdigitated electrodes mounted and three pairs of slender rabbit fur on an acrylic

plate (Fig. 1(c-i)), while the rotor is fabricated from a laser-cut acrylic substrate with alternately patterned FEP and Nylon films (Fig. 1(c-ii)). Flexible rabbit fur is introduced as an intermediate contact medium between the stator and rotor, forming a soft-contact interface that minimizes mechanical resistance while maintaining effective contact electrification. This design not only lowers the start-up threshold but also ensures stable rotation behavior under fluctuating conditions (Fig. 1(d)). As shown in Fig. 1(e), the RA-TENG exhibits enhanced electrical output under combined wind-rain excitation compared with rainfall-only conditions. Furthermore, comparison with previously reported wind-driven TENG systems demonstrates the superior start-up performance of the proposed design in complex environments (Fig. 1(f)) [35–41].

## 2.2 TENG theory and CFD analysis

To achieve the design objective of a low friction coefficient, the RA-TENG adopts a ternary dielectric triboelectrification mode characterized by a hybrid soft-contact and non-contact coupling. This configuration maintains electrification efficiency while significantly mitigating mechanical friction. The working principle is illustrated in Fig. 2(a). Wind energy and raindrop



**Figure 2** Design and Simulation of Twisted Savonius Blade. (a) Working principles of the TENG. (b) Key geometric parameters of twisted Savonius blade. (c) The rotation speed of different blades at 5m/s wind speed. (d-f) Pressure distribution cloud diagrams of blade cross-section.

potential energy captured by the blades are mechanically transmitted through the drive shaft to rotate the rotor, which triggers contact electrification between the rabbit fur and the Nylon film. Due to the higher electronegativity of the rabbit fur compared to the Nylon film, interfacial charge separation occurs at their contact interface, achieving an initial polarization of positive and negative charges. As the

rotor continues to rotate, after contacting with Nylon, the rabbit fur subsequently comes into contact with the more electronegative FEP film. During this process, electrons migrate from the rabbit fur to the FEP surface, while the frictional interaction further accumulates interfacial charges, enhancing the polarization effect. When the rotor moves to the next set of Nylon films, this electron transfer and charge

accumulation cycle continues, providing a continuous electron supply to the FEP film. Simultaneously, the Nylon film becomes enriched with positive charges through its interaction with the rabbit fur, forming a stable positive charge zone. Based on the principle of electrostatic induction, free charges on the electrode surfaces redistribute through the external load to balance the potential difference, thereby generating an induced current in the external circuit. The continuous mechanical rotation of the rotor, combined with the interdigitated electrode structure of the stator, enables periodic inductive coupling between the electrodes and the friction layers, ensuring that the RA-TENG delivers a continuous and stable AC output.

The twisted Savonius blade increases the frontal area of a single blade through an optimal twist angle, enabling more efficient conversion of ambient wind energy into mechanical energy. At the same time, the twisted blade surface effectively captures the kinetic energy of falling raindrops, enabling the coupled collection of wind energy and the potential energy of raindrops under rainy conditions. The geometric configuration of twisted Savonius blades is determined by three core parameters: angle of rotation ( $\omega$ ), aspect ratio ( $H/D$ ), and blade curvature ( $\alpha$ ) (Fig. 2(b)). We assume that rain falls uniformly on the twisted Savonius blade and denote the total impact force exerted by the rain on the entire blade as the macroscopic quantity  $F_v$ . The detailed derivation of the impact force  $F_v$  exerted by raindrops on the entire blade can be found in Note S1.

An infinitesimal element on the twisted blade is selected for analysis. Owing to the torsion of the blade, this element can be equivalent to an inclined plane, whose angle with the horizontal plane is  $\theta$ .

Since the twisted blade is uniformly twisted, the angle between the inclined plane of the infinitesimal element and the horizontal plane is a fixed value. The force analysis of a raindrop falling on the surface of the infinitesimal element is shown in Fig. S1. Defining the vertical force  $dF_v$  acting on a unit area of the horizontal projection of the infinitesimal element, we have Eq. (1):

$$dF_v = \frac{F_v}{A_1} dA \quad \text{Eq. (1)}$$

Where,  $A_1$  is the horizontal projected area of the twisted Savonius blade, and  $dA$  is the projected area of an infinitesimal element on the horizontal plane. The horizontal driving force  $dF_n$  received by this infinitesimal element on the inclined plane is then calculated as Eq. (2):

$$dF_n = \frac{1}{2} dF_v \sin(2\theta) \quad \text{Eq. (2)}$$

Therefore, the element torque  $dT$  generated by this element face is Eq. (3):

$$dT = \frac{1}{2} r \sin(2\theta) dF_v \quad \text{Eq. (3)}$$

Here,  $r$  is the distance from the center of the element to the vertical axis of rotation. To calculate the total torque  $T_{\text{total}}$  acting on the entire blade, we need to perform a double integral over the entire horizontal projected area  $A_1$  and we can finally obtain Eq. (4):

$$T_{\text{total}} = \iint_{A_1} \frac{F_v}{2A_1} r \sin(2\theta) dA \quad \text{Eq. (4)}$$

Furthermore, we calculated the optimal incident angle of the raindrops (Note S2). The results indicate that the blades can obtain the maximum torque when the relative angle between the raindrops and the twisted blade surface is 90 degrees.

Computational Fluid Dynamics (CFD) numerical simulation methods were employed to further investigate three geometric variants of twisted Savonius blades. The parameters for the three turbine models are as follows: Blade 1:  $\alpha = 135^\circ$ ,  $\omega = 180^\circ$ ,  $H/D = 1$ ; Blade 2:  $\omega = 120^\circ$ ,  $\alpha = 180^\circ$ ,  $H/D = 1.2$ ; blade 3:  $\omega = 135^\circ$ ,  $\alpha = 150^\circ$ ,  $H/D = 1.5$ . Assuming a uniform flow field with an inlet velocity of 5 m/s blowing from left to right and a blade damping of 5 mN·m, the mesh configurations for the three blade types are shown in Figs. S2 and S3. Fig. 2(c) illustrates the rotational speeds of the three blades under these conditions. We can determine that Blade 2 achieves the highest rotational speed under these conditions, reaching up to 446 rpm/min. Additionally, Figs. 2(d-f) display the pressure distribution contour maps at the rated wind speed for three specifications of Savonius wind turbines at four phase angles ( $0^\circ$ ,  $30^\circ$ ,  $60^\circ$ ,  $90^\circ$ ). The maximum and minimum pressure values are represented in red and blue, respectively. We can observe that the pressure at the channel inlet is relatively uniform. However, on the upstream side, the asymmetric geometry of the fan blades creates distinct high-pressure zones on the windward side and low-pressure zones on the leeward side within the flow field. This pressure differential across the blade surface induces rotation. All three blades demonstrated excellent aerodynamic stability throughout the entire rotation cycle, with surface pressure differences consistently maintained within a stable range. Blade 2 exhibited a darker color and the largest coverage area in the low-pressure zone on its leeward side, indicating a greater pressure difference  $\Delta P$  (Fig. 2(e)) and superior aerodynamic performance. This result aligns with the simulation findings in Fig. 2(c), further validating the accuracy of the simulation outcomes.

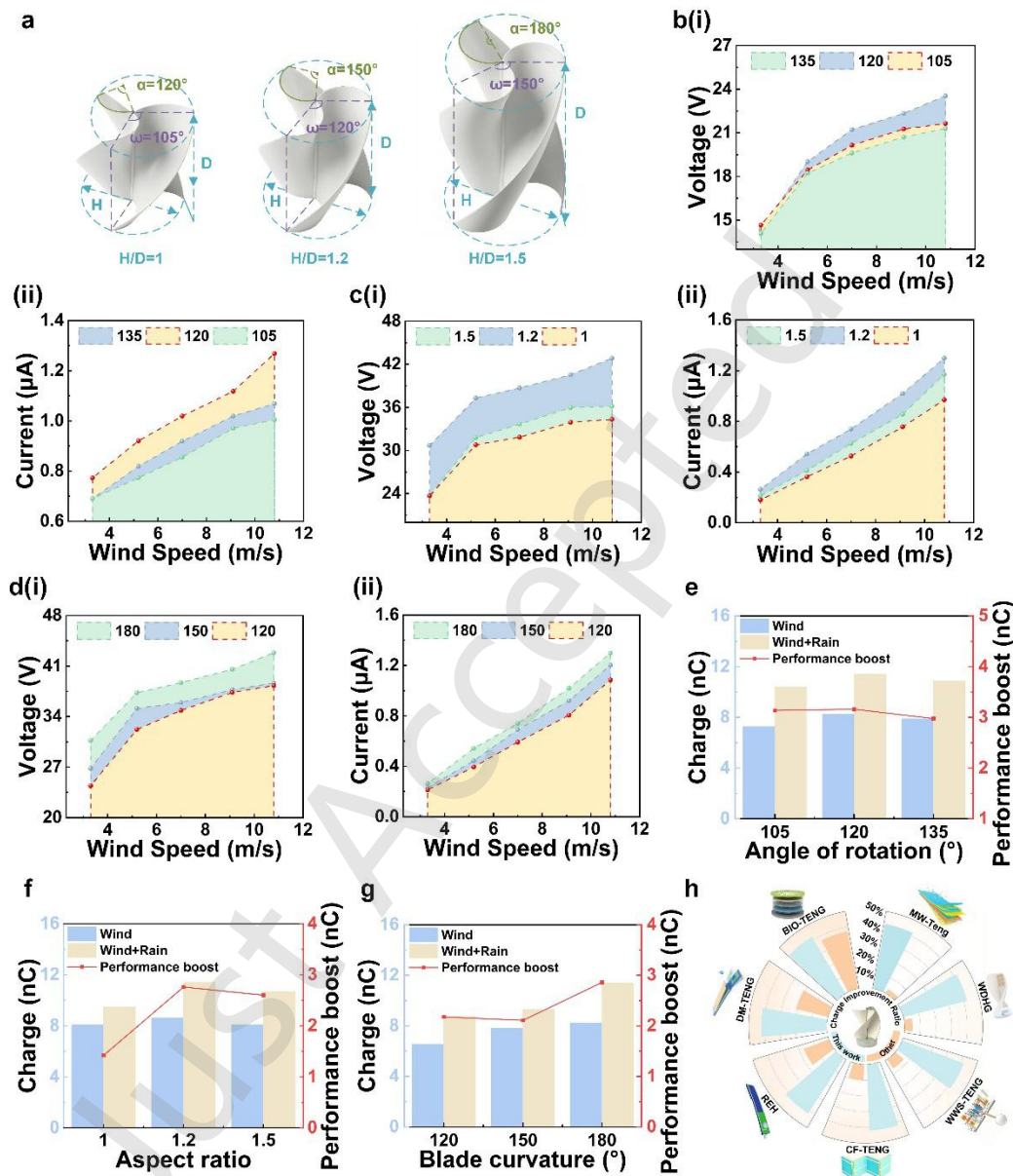
### 2.3 Performance optimization

To validate the reliability of computational fluid dynamics simulations and investigate the impact of twisted Savonius blades on generator output under wind rain synergistic conditions, this study systematically tested the electrical output performance of twisted blades with different specifications using a RA-TENG under pure wind and combined wind-rain environments (Fig. 3).

The specific models of blades with parameters for the three types are shown in Fig. 3(a). The initial wind speed was set to 3.3 m/s. By comparing samples of twisted Savonius blades with different geometric parameters, it is observed that despite variations in basic blade parameters, the peak signal output of the RA-TENG in each group is positively correlated with wind speed. That is, the higher the wind speed, the greater the power output of the RA-TENG. The results indicate that at a wind speed of 3.3 m/s, the angle of rotation of the blades has a negligible effect on generator output. However, as wind speed gradually increases, the output performance differences among the three configurations become increasingly pronounced. At a wind speed of 10.8 m/s, the blade with a  $120^\circ$  angle of rotation delivers optimal output performance, achieving an

8% and 10% increase in voltage output compared to the 105° and 135° respectively (Fig. 3(b-i)), and current outputs that are 18% and 26% higher than those of the other two models, respectively (Fig. 3(b-ii)). Under different aspect ratios and blade curvature, the aspect ratio of 1.2 shows the optimal output performance (Fig. 3(c)), and the blade curvature of 180° exhibits the best output performance (Fig.

3(d)). Moreover, short-circuit charge transfer in RA-TENG devices with Savonius blades of different specifications was evaluated. Experimental results indicate that the evolution pattern of short-circuit charge transfer exhibits a high degree of consistency with the growth trends of voltage and current (Fig. S4).



**Figure 3** Comparative study of TENG output characteristics for different Savonius blade designs. (a) 3D structural models of blades with varying specifications. (b) Comparison of TENG outputs under different angles of rotation. (c) Comparison of TENG outputs under Aspect ratio. (d) Comparison of TENG outputs under Blade curvature. (e) Comparison of TENG outputs with various angles of rotation under wind-rain conditions. (f) Comparison of TENG outputs with various aspect ratio under wind-rain conditions. (g) Comparison of TENG outputs with various blade curvature under wind-rain conditions. (h) Comparison of the percentage enhancement in transferred charge of the hybridized TENG.

Finally, under a constant wind speed of 6 m/s, simulated rainfall excitation was introduced to test the output performance of the RA-TENG under complex wind-rain coupling conditions. Experimental data show that the charge transfer quantities at rotation angles of 105°, 120°, and 135° increased by 42%, 38%, and 37% respectively, compared to pure wind conditions, reaching 10.4 nC, 11.4 nC, and 10.8 nC (Fig. 3(e)). We can conclude that even under combined wind-rain conditions, the 120° angle of rotation delivers the highest output. This is because when raindrops fall vertically at a certain terminal velocity and strike the surface of a blade,

the direction of their motion is forced to change. According to the theorem of momentum and Newton's third law, the raindrops are subjected to a normal force exerted by the blade surface, and in turn exert an equal and opposite reaction force on the blade, thereby increasing the rotational speed of the blade and enhancing the charge transfer quantity. Furthermore, under combined wind-rain conditions, the blade with aspect ratio of 1.2 achieved a charge transfer of 11.4 nC (Fig. 3(f)), representing a 32% increase. The blade with a 180° blade curvature achieved a charge transfer of 11.4 nC (Fig. 3(g)), representing an

increase of 34%. Open-circuit voltage and short-circuit current of the TENG under various wind speeds in combined wind-rain conditions for different blade models can be found in Fig. S5. The results indicate that the patterns of variation in its output open-circuit voltage and short-circuit current are identical to those of the maximum blade parameters shown in Figs. 3(e-g). The results further validate that the optimized Savonius blade configuration, which demonstrates outstanding performance in single wind field conditions, also exhibits exceptional energy capture capability under complex combined wind and rain conditions. This consistent performance demonstrates that the optimized geometry possesses strong environmental adaptability and gain stability under multi-physics excitation. In addition, we compared the improvement ratios of transferred charge density for various hybrid triboelectric nanogenerator devices reported in recent literature (Fig. 3(h)) [42–48]. The results demonstrate that although these devices exhibit a certain enhancement in overall charge transfer after hybrid integration, their improvement magnitudes are lower than that of the RA-TENG developed in this work. More importantly, most existing hybrid devices rely merely on simple structural superposition or unit assembly to increase transferred charge, which usually requires additional device modules to achieve performance gains. In contrast, the proposed RA-TENG in this study enables a remarkable improvement in charge transfer without introducing extra components, relying solely on its rational structural design, thus showing distinct advantages in both performance enhancement mechanism and integration superiority.

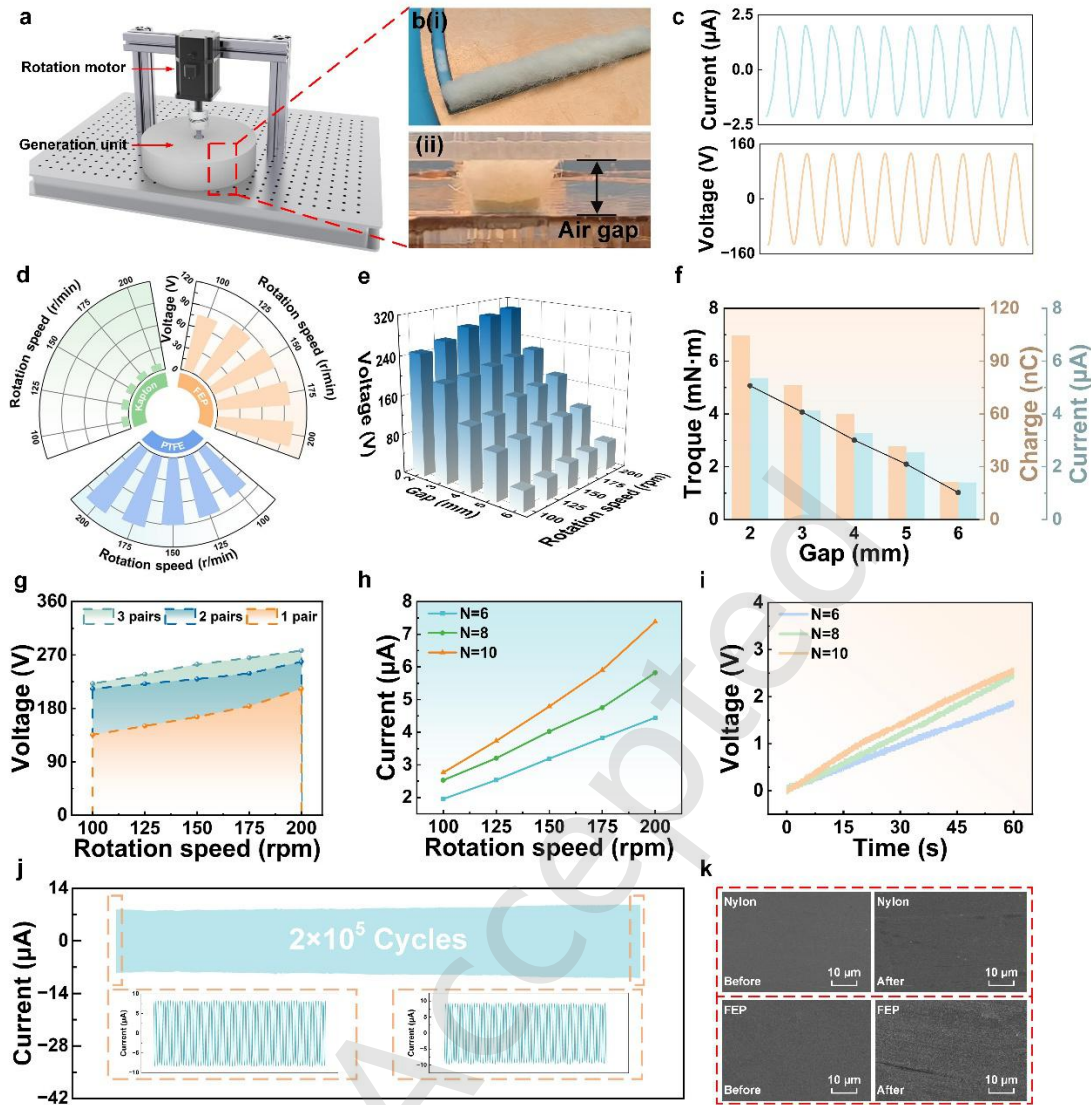
#### 2.4 Optimization of the RA-TENG generation unit

To optimize the power generation unit of RA-TENG, a test platform driven by a rotating motor was constructed (Fig. 4(a)). This platform rotates the rotor to evaluate the impact of the following factors on the unit's performance: the material composition of the power generation unit, the gap between the stator and rotor, the number of rabbit fur, and the number of grid cells. Fig. 4(b) shows a detailed close-up of the RA-TENG power generation unit. The soft rabbit fur makes soft contact with the rotor, and a gap is formed between the stator and the rotor. Fig. 4(c) illustrates the comprehensive electrical output characteristic curves of the TENG power generation unit, clearly revealing the current and voltage response behaviors under external mechanical excitation.

First, we investigated the material combinations for the rotor. Nylon was selected as the fixed electropositive material, followed by several common electronegative materials paired with nylon for the rotor: Kapton, PTFE, and PTFE. The open-circuit voltage (Fig. 4(d)) and of the three electronegative materials' TENG were measured at different rotational speeds. Experimental results indicate that the electrical output characteristics of the nylon/FEP composite outperform those of nylon/Kapton and nylon/PTFE. This advantage is primarily attributed to FEP's exceptionally high electron affinity and outstanding surface tribological properties. During rotational friction, FEP exhibits a more

pronounced electronegativity difference compared to Kapton, enabling it to induce a higher density of interfacial charge transfer. PTFE possesses a higher theoretical electronegativity than FEP, but experimental results indicate that FEP exhibits higher electrical energy conversion efficiency in ternary dielectric systems. Analysis indicates that PTFE's excessively low friction resistance limits effective charge excitation at the friction interface, whereas FEP's moderate tribological properties ensure more complete charge transfer under rotational conditions. Subsequently, we investigated the effect of the stator-rotor gap on the output of the power generation unit. Setting the gap between the stator and rotor to 2–6 mm, we tested the open-circuit voltage at different rotational speeds (Fig. 4(e)). Result indicate that optimal output performance is achieved when the gap between the stator and rotor is 2 mm. This occurs because electric field strength  $E$  is inversely proportional to the distance  $d$ . Within the ternary dielectric layer, surface charges generated by friction induce a potential difference between electrodes. As the gap decreases, the equivalent capacitance between electrodes increases. Consequently, for the same charge quantity, the induced vertical electric field strength significantly intensifies, driving more electrons to flow rapidly within the circuit. However, optimizing the stator-rotor gap requires balancing generator output power with mechanical losses. Experimental observations indicate that while smaller gaps enhance output, they also increase interfacial friction forces (Fig. 4(f)). Nevertheless, since ternary dielectric triboelectric nanogenerators employ indirect contact, their inherent mechanical resistance remains relatively low. Consequently, a 2 mm gap was selected as the optimal assembly clearance between the stator and rotor. The number of rabbit fur used for indirect contact also affects the generator output (Fig. 4(g)). Experimental results demonstrate that at constant rotational speed, both the open-circuit voltage of the TENG exhibit a steady increase as the number of rabbit fur electrodes increases from one pair to three pairs. This is attributed to the enhanced charge excitation frequency per rotational cycle achieved by increasing the number of rabbit fur strands, enabling efficient charge compensation and significantly boosting the surface charge density at the friction interface.

The number of electrode grids is also a key parameter for regulating the electrical output of TENG. The output characteristics of the power generation unit were compared at different rotational speeds when the grid count was 6, 8, and 10, respectively (Fig. 4(h)). Experimental results show that at a constant rotational speed of 200 rpm, increasing the grid number from 6 to 10 elevated the short-circuit current from 4.4  $\mu\text{A}$  to 7.4  $\mu\text{A}$ . This indicates that increasing the number of grids effectively enhances the charge transfer frequency per unit time. Furthermore, comparative charging tests on a 200  $\mu\text{F}$  capacitor (Fig. 4(i)) confirmed that the 10-grid configuration exhibited the optimal charging rate at 200 rpm, raising the capacitor voltage to 3.1 V in just 60 s that significantly outperforming configurations with fewer grids. Additionally, we systematically investigated the influence of various key parameters on the charge transfer amount,



**Figure 4** Performance optimization of the power generation unit. (a) Schematic of the experimental test platform. (b) Enlarged details of the RA-TENG power generation unit: (i) stator and rabbit fur (ii) gap between stator and rotor. (c) Electrical output characteristics of the TENG unit. (d) Influence of materials and rotational speeds on the open-circuit voltage. (e) Influence of gap distances and rotational speeds on the open-circuit voltage. (f) Influence of gap distance on torque, charge, and current. (g) Effects of rabbit fur number and rotating speed on open-circuit voltage. (h) Influence of grid numbers and rotational speeds on the open-circuit voltage and short-circuit current (i) Effect of grid number on capacitor charging performance of TENG. (j) Durability test. (k) SEM images of Nylon and FEP surfaces before and after durability testing.

short-circuit current and open-circuit voltage in TENG under different rotational speeds (Fig. S6). To evaluate the durability of the device, the TENG was driven by a motor to undergo  $2 \times 10^5$  rotational cycles (Fig. 4(j)). Scanning electron microscopy (SEM) characterization results reveal that after the durability test, the FEP surface exhibited a small number of scratches, while the Nylon surface showed even sparser scratch distribution (Fig. 4(k)). The minimal scratches observed on both film surfaces benefits from the hybrid soft-contact and non-contact coupling between the stator and rotor, which effectively reduces rigid friction loss and significantly improves the overall durability of the device. In addition, we also characterized rabbit-fur via SEM and obtained corresponding SEM images (Fig. S7). The results show that after  $2 \times 10^5$  rotational cycles tests, the surface of the rabbit fur fibers maintains a well-preserved micromorphology, with no fractures or splitting observed, and only slight debris residues on the surface.

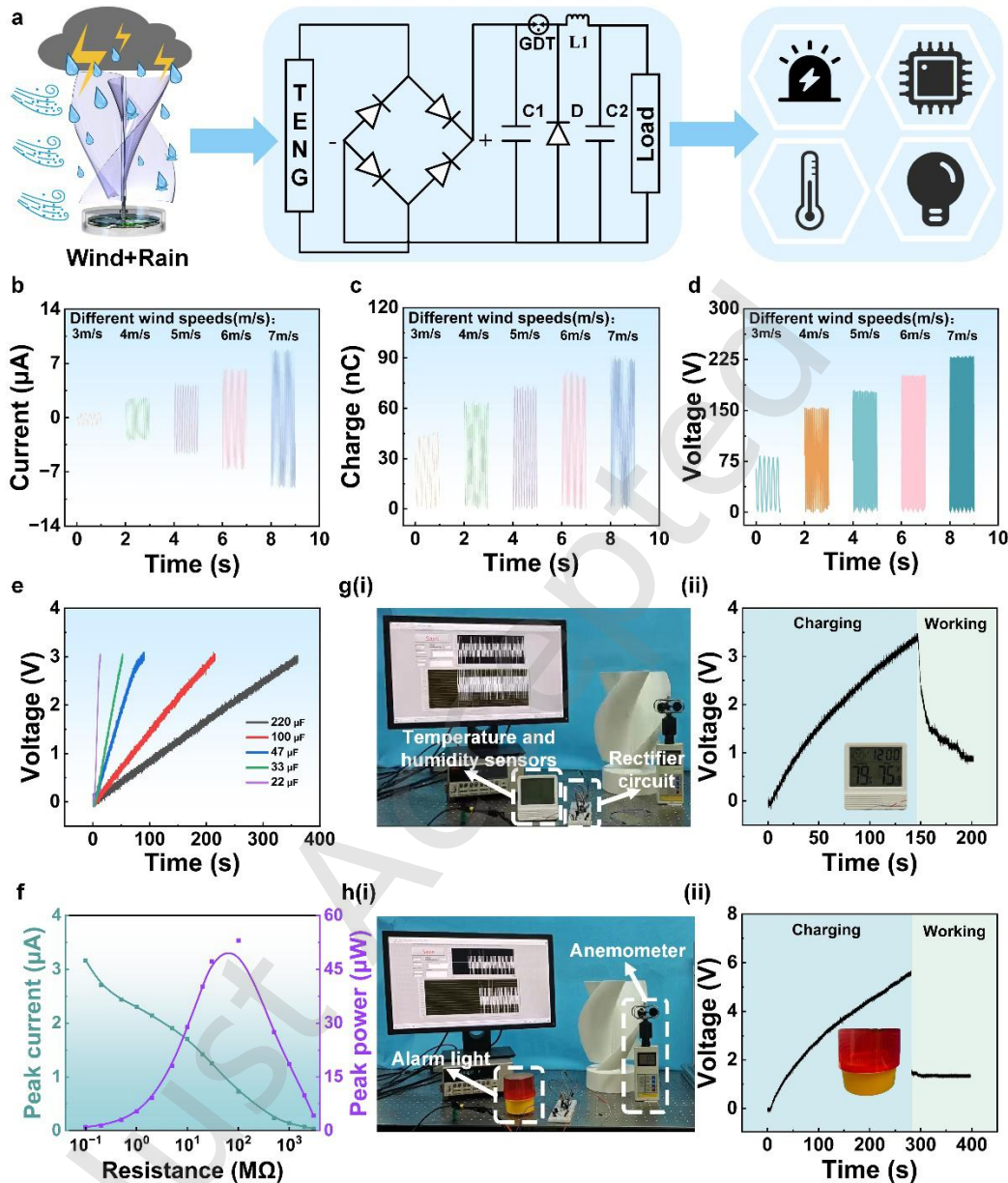
### 3 Application of the RA-TENG

Due to the inherent high-voltage and low-current output characteristics of triboelectric nanogenerators

(TENGs), efficient power management is essential to enable practical energy utilization. To address this, a power management circuit (PMC) based on a buck conversion architecture was constructed to regulate, store, and stabilize the electrical output of the RA-TENG, thereby improving its compatibility with real-world electronic systems. As illustrated in Fig. 5(a), the integration of the PMC enables stable and usable power delivery, demonstrating the feasibility of the RA-TENG as a practical energy source. The power management circuit for the TENG, which converts its high-voltage, pulsed AC output into stable DC power for the load. The TENG's output is first rectified by a full-wave bridge rectifier and smoothed by capacitor C1. When the voltage across C1 reaches the breakdown threshold of the Gas Discharge Tube (GDT), the GDT triggers, rapidly discharging C1 through inductor L1 to transfer energy to the output stage. Diode D provides a freewheeling path for L1, while capacitor C2 further filters the output voltage, ensuring a steady DC supply to the load. Figs. 5(b-d) present the electrical output performance of the optimized RA-TENG ( $\alpha = 120^\circ$ ,  $\omega = 180^\circ$ ,  $H/D = 1.2$ ). At a wind speed of 7 m/s, the device delivers an open-circuit voltage of 229 V, a short-

circuit current of  $8.9 \mu\text{A}$ , and a transferred charge of  $91 \text{ nC}$ , indicating effective energy conversion under typical operating conditions. The energy storage capability of the system was further evaluated through capacitor charging tests (Fig. 5(e)). The RA-TENG is capable of charging a  $220 \mu\text{F}$  capacitor to  $3 \text{ V}$  within  $360 \text{ s}$  at a wind speed of  $7 \text{ m/s}$ ,

demonstrating its ability to accumulate intermittent environmental energy and convert it into a stable electrical supply. In addition, the output power reaches a peak value of  $53 \mu\text{W}$  at an optimal load resistance of  $100 \text{ M}\Omega$  (Fig. 5(f)), confirming its suitability for powering low-power electronic devices.



**Figure 5** Applications of RA-TENG. (a) Schematic diagram of the application systems of wind-rain synergistic harvesting. (b-d) Output performance of RA-Teng at different wind speeds. (e) Capacitive charging performance of RA-Teng. (f) Instantaneous peak current and power-resistance relationship profiles for the RA-TENG at the wind speed of  $6 \text{ m/s}$ . (g) Application of the RA-TENG for powering a high-precision temperature/humidity sensor. (h) Application of the RA-TENG for powering warning lights.

To demonstrate its practical applicability, the RA-TENG was employed to power typical environmental monitoring components through the PMC (Figs. 5(g) and 5(h)). At a wind speed of  $4 \text{ m/s}$ , the system successfully charged capacitors to  $5.5 \text{ V}$  and  $3.4 \text{ V}$ , enabling continuous operation of a temperature-humidity sensor and an alarm indicator, respectively (Movies S1 and S2). These results verify the capability of the RA-TENG to provide sustained energy for distributed sensing nodes under realistic operating conditions. Furthermore, under wind-rain coupled conditions, the RA-TENG maintains effective rotational motion at a low wind speed of  $1.9 \text{ m/s}$  and is capable of simultaneously lighting 60 LEDs (Movie S3). This enhanced performance at low wind speeds highlights the advantage of

wind-rain coupling in improving the environmental adaptability of the system, particularly under fluctuating and multi-stimulus conditions. Beyond these demonstrations, the proposed RA-TENG shows strong potential as a sustainable energy solution for distributed sensing networks in complex outdoor environments.

In scenarios such as forest microclimate monitoring, wildfire early warning, and ecological environment monitoring, where long-term, maintenance-free operation is required, the ability to harness coexisting environmental stimuli provides a significant advantage over conventional single-source energy harvesters. More importantly, by transforming environmental perturbations into constructive mechanical driving forces, the RA-TENG establishes a new

paradigm for self-powered systems that leverage, rather than resist, environmental complexity. This concept also suggests opportunities for integrated energy-information systems, in which environmental dynamics not only drive energy generation but may also serve as implicit sensing inputs, enabling more adaptive and responsive self-powered platforms.

## 4 Conclusions

In summary, we have developed a raindrop-assisted aerodynamically activated triboelectric nanogenerator (RA-TENG) for efficient energy harvesting under realistic wind-rain environments. By introducing raindrop-induced momentum transfer, the system exploits the intrinsic interaction between wind flow and rainfall to actively regulate the rotational dynamics of the turbine. This coupling enhances rotational continuity, reduces the start-up threshold, and stabilizes the rotation process that governs charge generation, leading to significantly improved electrical output under coupled environmental conditions. Distinct from conventional strategies that mitigate environmental disturbances or independently harvest multiple energy sources, this work demonstrates that coexisting environmental stimuli can be harnessed to enhance mechanical driving. The performance improvement originates from modulation of mechanical dynamics rather than direct modification of interfacial charge processes, establishing a clear linkage between environmental coupling, rotor motion, and contact electrification. This study thus provides a general framework for regulating electrification via mechanical dynamics under multi-stimulus environments, enabling robust self-powered systems that leverage, rather than resist, environmental complexity. These findings advance the understanding of mechanically mediated electrification and highlight the potential for scalable deployment in distributed sensing networks.

## 5 Experimental section

### 5.1 Fabrication of the RA-TENG

The blades of the RA-TENG are fabricated using 3D printing with PLA material, measuring 230 mm in length and 276 mm in height. The TENG is connected to the blades via an 8 mm diameter, 600 mm long steel shaft. The TENG housing is also 3D printed from PLA material. Both the internal stator and rotor are laser-cut from 2 mm thick plates, with the disc having an outer diameter of 160 mm and an inner diameter of 45 mm. The stator surface features 10 grid structures etched to a depth of 1 mm, with 5 mm gaps between grids. Six pairs of rabbit fur strips, each 4 mm wide and 50 mm long, are affixed within these gaps. An 80  $\mu$ m thick copper foil electrode is affixed to the stator surface, while the rotor surface features an alternating pattern of 25  $\mu$ m thick nylon film and 30  $\mu$ m thick FEP film.

### 5.2 Experimental measurement

The rotary experimental platform consists of a Servo Motors and Servo Controllers. The performance parameters of the triboelectric nanogenerators were tested by a programmable electrometer (6514, Keithley, USA), and the data were recorded using a data acquisition system (USB-6211, National Instruments, USA). The data were processed and displayed using LabVIEW software.

## Data availability

All data needed to support the conclusions in the paper are

presented in the manuscript and/or the Electronic Supplementary Material. Additional data related to this paper may be requested from the corresponding author upon request.

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## Declaration of competing interest

All the contributing author(s) report(s) no conflict of interests in this work.

## Author contribution statement

Y.Y.C. : Conceptualization, Writing - review & editing, Supervision. H.Y. : Validation, Investigation, Writing - Original Draft. Z.X.L. : Investigation, Writing - Original Draft. Y.M.F. : Conceptualization, Writing - review & editing, Supervision. H.Y.L. : Resources, Writing - review & editing, Supervision. Y.C.B. : Investigation, Validation. G.S.J. : Investigation, Validation. S.C.G. : Investigation, Validation. Y.Y. : Writing - review & editing, Supervision, Writing - review & editing, Supervision. T.H.C. : Resources, Conceptualization, Writing - review & editing, Supervision. X.J.C. : Resources, Writing - review & editing, Supervision. All the authors have approved the final manuscript.

## Use of AI statement

None.

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## Electronic Supplementary Material

# Raindrop-modulated wind-driven rotational dynamics for enhanced triboelectric energy harvesting

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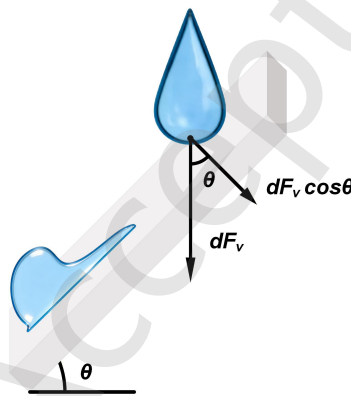


Figure S1. Force analysis of raindrop impact on blades.

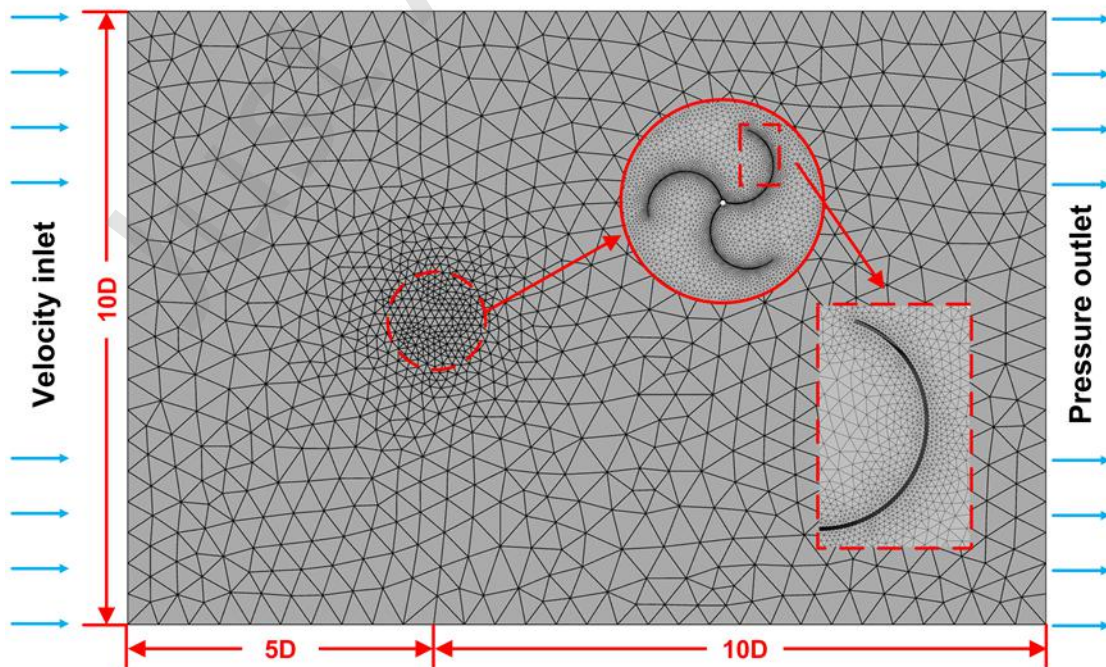


Figure S2. Mesh details (taking  $\alpha = 135^\circ$ ,  $\omega = 180^\circ$ ,  $H/D=1$  as an example, where  $D$  is the blade diameter).

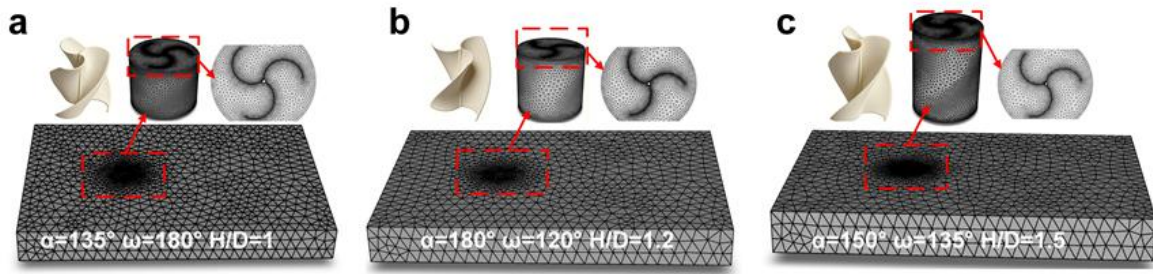


Figure S3. Detailed information on blade calculation domain and 3D mesh generation. (a)  $\alpha=135^\circ$   $\omega=180^\circ$   $H/D=1$ ; (b)  $\alpha=180^\circ$   $\omega=120^\circ$   $H/D=1.2$ ; (c)  $\alpha=150^\circ$   $\omega=135^\circ$   $H/D=1.5$ .

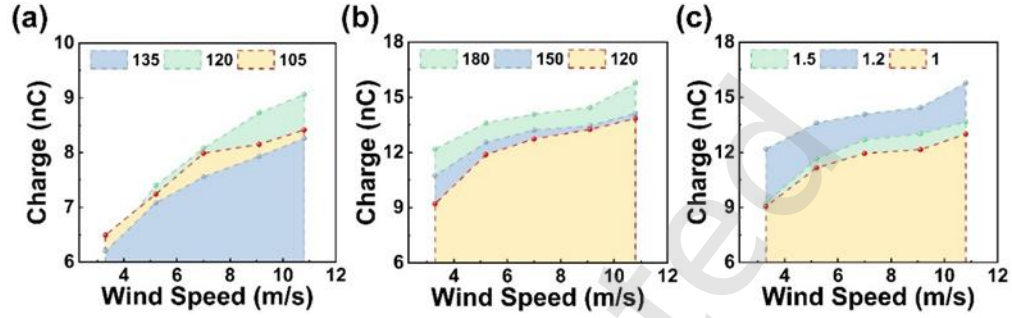


Figure S4. Transferred charge of different blade types at various wind speeds. (a) Angle of rotation. (b) Blade curvature. (c) Aspect ratio.

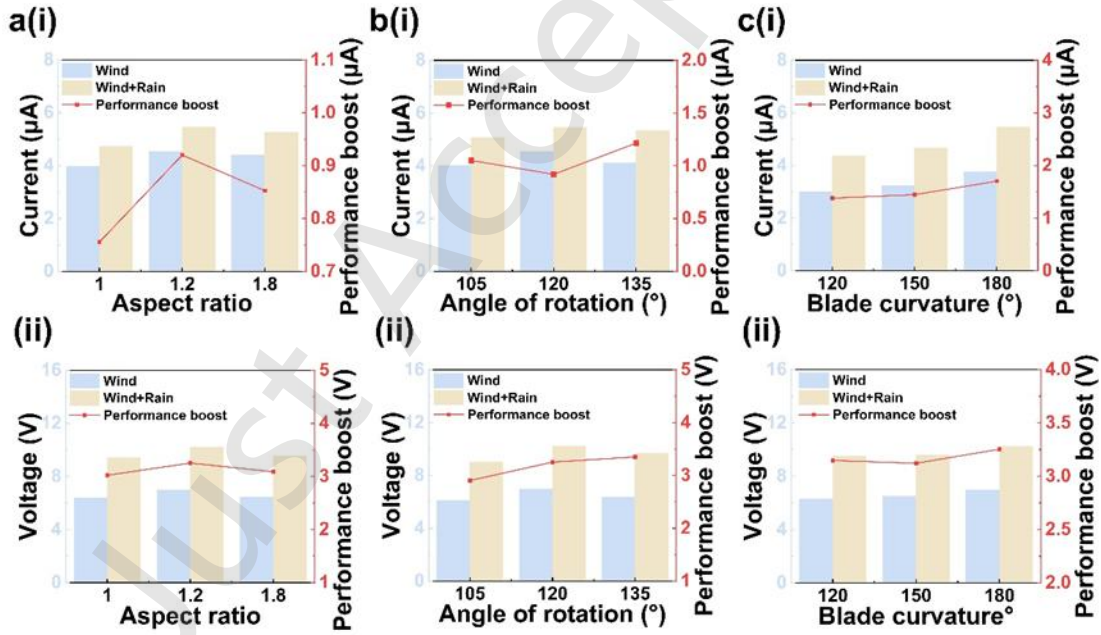


Figure S5. Output performance of different blade types in wind-rain synergistic environment. (a) Aspect ratio. (b) Angle of rotation. (c) Blade curvature.

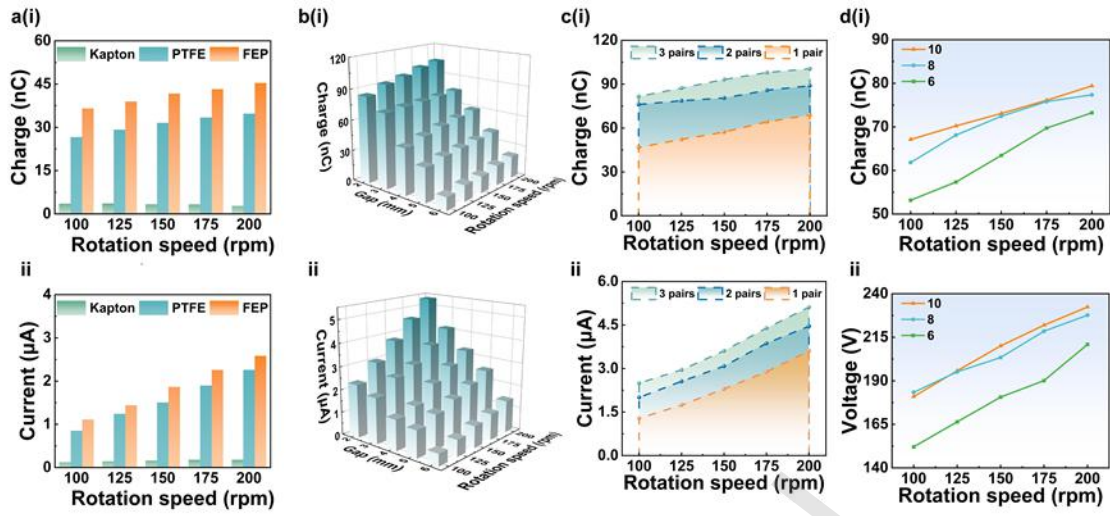


Figure S6. Transferred charge of TENG under various conditions. (a) Material. (b) Gap distance. (c) Rabbit fur pair count. (d) Grid number.

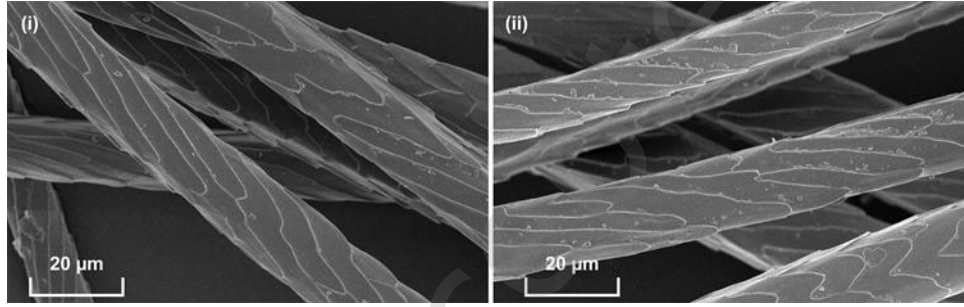


Figure S7. SEM images of rabbit fur surfaces before and after durability testing: (i) before the durability test, (ii) after the durability test.

#### Note S1.

The kinetic energy  $E$  of a raindrop during rainfall is given by Eq. 1:

$$E = \frac{1}{2}mv^2 \quad (1)$$

where  $v$  is the terminal velocity of the falling raindrop, and the mass  $m$  of the raindrop impinging on the leaf can be derived from the following Eq. 2:

$$m = \rho \cdot A_1 \cdot I \cdot \Delta t \quad (2)$$

where  $\rho$  is the density of water,  $I$  is the rainfall intensity, and  $\Delta t$  is the transient duration during which the vertical velocity of the raindrop decelerates to zero upon impacting the leaf. Substituting the obtained  $m$  into Eq.1 gives Eq. 3:

$$E = \frac{1}{2}mv^2 = \frac{1}{2}(\rho \cdot A_1 \cdot I \cdot \Delta t)v^2 \quad (3)$$

Subsequently, the total energy input per unit time is calculated as Eq. 4:

$$P = \frac{E}{\Delta t} = \frac{1}{2}\rho \cdot A_1 \cdot I \cdot v^2 \quad (4)$$

We define the average velocity of falling raindrops as  $v_0$ , where  $v_0=0.5v$ . Since the vertical velocity of the raindrops reduces to zero upon impact (neglecting rebound), the equivalent average relationship corresponding to the energy conversion process is given by Eq. 5:

$$P = F_v \cdot v_0 \quad (5)$$

Finally, substituting Eq. 4 into Eq. 5 yields the final formula for  $F_v$  for Eq. 6:

$$F_v = \rho \cdot A_1 \cdot I \cdot v \quad (6)$$

**Note S2.**

When the angle between the inclined plane and the horizontal plane is  $\theta$  and the angle between the external force  $F_v$  and the horizontal ground is  $\alpha$ , we can derive:

$$F_x = F_v \cos \alpha \quad \backslash * \text{MERGEFORMAT (7)}$$

$$F_y = F_v \sin \alpha \quad \backslash * \text{MERGEFORMAT (8)}$$

where  $F_x$  and  $F_y$  are the horizontal and vertical forces caused by the raindrop impact respectively. Subsequently, we can obtain the horizontal force  $F$  exerted by the raindrop on the blade:

$$F = F_v \cos \alpha + F_v \sin \alpha \cdot \tan \theta \quad \backslash * \text{MERGEFORMAT (9)}$$

Ultimately, it can be simplified to the following equation:

$$F = F_v \cdot \frac{\sin(\alpha + \theta)}{\cos \theta} \quad \backslash * \text{MERGEFORMAT (10)}$$

As indicated by Eq. 10,  $F$  reaches its maximum value when  $\alpha + \theta = 90^\circ$ . At this point, the incident angle of the raindrops is perpendicular to the twisted blade surface.