

Triboelectric nanogenerators and self-powered sensors for smart farming

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SUMMARY

The primary goal of this project was to design a triboelectric nanogenerator (TENG) device that could function as a viable green energy source for smart farming. The TENG was designed to harvest energy from the wind through the triboelectric mechanism from movements assisted by magnets. We hypothesized that the larger displacements and faster switching of the triboelectric polar pairs for the TENG device would optimize the device's electrical output efficiency thus generating higher voltage output. Then, we tested the TENG under different moving displacements and frequencies, from which we found the electrical output was most dependent on the frequencies. Using the optimal configuration discovered from the tests, we integrated the TENG atop a plant-mimic structure that swings in the wind, thereby converting the wind energy into electricity to power a humidity sensor. This compact yet environmentally friendly energy harvesting device has promise as an alternative power source for smart farming sensors.

INTRODUCTION

Smart farming is a new method in modern agriculture that relies on robots and sensing technology to control and manage all farming procedures through computer-assisted data analysis and decision making (1,2). Smart farming is expected to substantially reduce cost and human power, while increasing efficiency and maximizing farming production. Typically, smart farming consists of three key components: sensing, data collection and analysis, and autonomous farm management (3). The sensing components collect data from the farmland and send this information to a computer system where the data will be analyzed and used to make decisions on farm management (3). Thus, the farm can be managed remotely and autonomously (3). Sprinklers, fertilizers, and other essential farming systems can all be accessed and controlled from a centralized system, which decides the optimal farming conditions by systematically analyzing the data collected through the smart farming framework (4). As an important part of future agriculture, smart farming can substantially improve workforce efficiency, reduce human-related errors, effectively use natural resources, maximize land production, and eventually impact the sustainability of the environment and human society (5).

One of the key challenges that these smart farming systems still face is efficiently powering the smart farming network. Different from other application sites – such as offices and or roads, where you can easily run wires through walls or previously created infrastructure – running electrical wires across the farm field is typically not an option. Currently,

major smart farming companies are using solar panels as the power source for sensors. However, solar panels have their limitations as well. For example, for low-growing crops, solar panels could obstruct the growth space of the crops and block their sunlight, whereas tall crops may block the sunlight to the solar panel (6,7). Furthermore, solar panels are not cost-efficient, due to building and maintenance costs incurred when a large number of sensors is needed (6,7). This may introduce a high economic barrier to the implementation of smart farm systems, particularly in many agricultural-based countries that are still in the developing stage (6,7).

Driven by these challenges, we proposed a small energy harvesting device based on the triboelectric nanogenerator (TENG) technique. The TENG technology is an emerging solution for self-powering small electronics by scavenging mechanical energy from the ambient environment (8,9). It is particularly suitable for smart farming applications due to its high energy conversion efficiency, low cost, and great scaling potential (10,11). A typical TENG consists of two different materials: one attracts positive charges (protons), and the other attracts negative charges (electrons) (12). When the materials touch, there is a trading of positive and negative charges. Then, when the materials are separated, the positive and negative charges are unbalanced, which creates an electric potential and a current flow if they are connected to an external load. Because of its simple mechanics and lack of complex parts, a TENG can be made from low-cost and easy-to-access materials, such as fibers, plastic films, metal sheets, and animal furs (13). The TENG device as a whole can also be designed in different configurations that specifically fit the farms among various plants and do not obstruct or disrupt their growth.

In this work, we designed a magnetically supported circular device that can move omnidirectionally and produce electricity in response to small winds or air circulations that can be commonly found in any farmland (14). Our main hypothesis was that the larger displacements and faster switching of the triboelectric polar pairs for the TENG device would generate higher voltage output. To test this hypothesis, we designed the device prototype with different electrode dimensions and measured their output under a variety of simulated wind conditions in terms of direction and speed. From these experiments, we discovered the optimal output conditions for the devices that were assembled with larger number of electrodes paired with moderate movement. Using this device configuration, the self-powering capability was demonstrated using a humidity sensor, an essential data set for smart farming. We believe this development may provide a cost-effective and generally adaptive solution as a future power source for smart farming sensors.

RESULTS

TENG device development

In our design, a sliding TENG was developed with a simple sliding mode in a circular shape so that it could respond to motion along any direction (**Figure 1A**). The sliding disk consisted of several concentric circular rings with the same width (d) and spacing (t), where t was always set two times wider than the diameter (**Figure 1B, left**). The overall diameter of the sliding disk was kept the same at 40 cm. Therefore, the larger the ring d , the smaller the number of rings placed on the sliding disk. In our experiment, we tested how ring d impacted the electrical output of the device. The d values tested were 1 mm, 2 mm, and 4 mm. The surface of each ring was covered with a layer of copper tape acting as the charge inducing surface. The rings on the sliding disks were meant to slide across the charge generating electrode pairs fabricated on the base of the TENG to generate electricity.

The base had a pair of interdigitated concentric circular electrodes made from a thin layer of gold (**Figure 1B, right**). The width of electrodes (d') was made exactly the same as that of the charge-inducing rings on the sliding disk, while the spacing between electrodes (t') was the same as the electrode width. The overall diameter of the electrode pair was the same as that of the sliding disk. This geometric relationship allowed all the charge inducing rings to always be at the same position corresponding to the interdigitated electrode pairs. A pair of central (4mm wide) buses connecting the two sets of electrodes on each side were designed as the output leads that were connected to an external circuit. All of the gold electrodes were covered by a polytetrafluoroethylene (PTFE) tape – a triboelectric negative material that induced negative charges when interfacing with copper.

This specific TENG worked when the sliding disk moved over the base surface along any direction due to the central symmetric pattern (15, 16). When the copper surface contacted the PTFE, positive and negative charges could be induced on the copper and PTFE surfaces, respectively (**Figure 1C**). The

electrical current was generated upon the periodic sliding of copper charge-inducing electrodes across the PTFE tape, which induced a potential difference between the pair of charge-generating electrodes. At the initial stage, when the copper electrode was aligned with electrode A, electrode A tended to attract negative charges from electrode B to screen all the positive charges sensed from copper. This process induced a net current flow from electrode A to electrode B. This was followed by the intermediate stage, where there was no potential difference between two electrodes due to the same overlapped areas between copper and these two electrodes, yielding zero net current. As the copper moved to the B electrode side, a higher potential in electrode B was induced, which drove current flow from electrode B to electrode A. Repeating this process produced alternating current (AC) signals between the pair of interdigitated electrodes.

Device optimization for wind energy harvesting in the farm

Magnetic interaction was introduced to enhance the lateral movements of the sliding disk (**Figure S1**). The electric power generation performance was first tested by fixing the device to an actuator, which provided linear movements at a controlled frequency and extrusion distance (**Supplementary video S1**). Voltage output was measured from a typical 2 mm-electrode device when it was driven at a frequency of 1 Hz for 1 cm displacement (**Figure 2A**). Each section of voltage peaks represented one set of forward and back movements. All the voltage sections showed very close peak values of $\sim \pm 5$ V, suggesting that the TENG was producing a consistent electrical output. Voltage intensity started at ~ 0.5 V and reached the maximum of ~ 5 V when the actuator reached the maximum displacement. This was the point when the overlapping areas between the charge inducing rings and the interdigitated electrode maximized. As the actuator moved back to its original position, the overlapped area decreased, and so did the voltage output. When the displacement

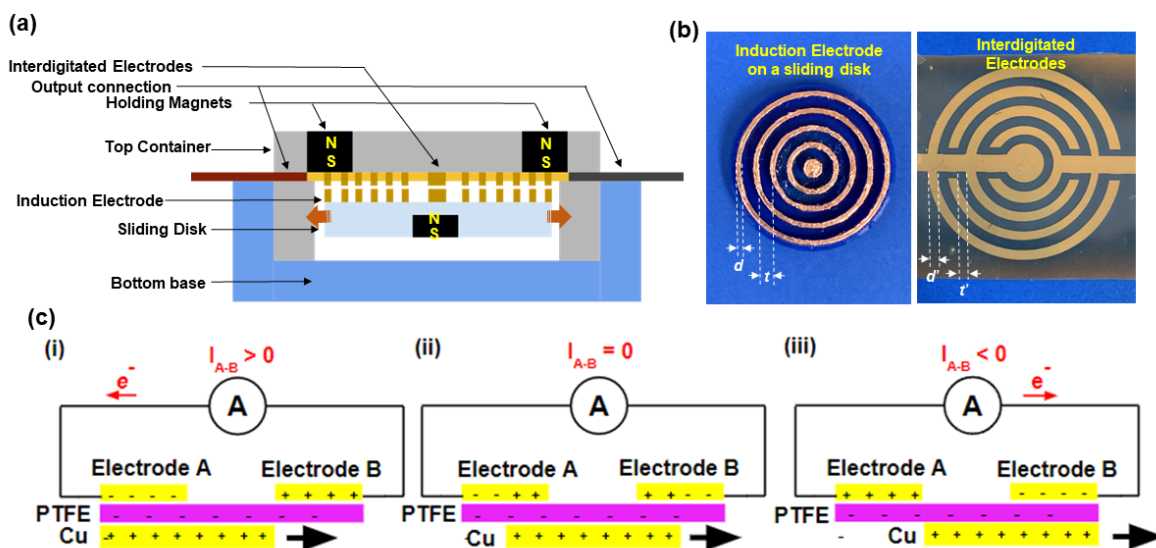


Figure 1. Omnidirectional sliding TENG device design. a) Schematic structure of the sliding TENG device. b) Photos of the interdigitated electrode film (left) and the induction electrode on the sliding mass (right). c) Mechanism showing how the electricity is generated between the interdigitated electrodes when the induction electrode moves across them. $I_{AB} > 0$, $= 0$, < 0 suggest the electric current flows from electrode A to B, no electric current, and the electric current flows from electrode B to A.

increased to 2 cm at the same frequency (**Figure 2B**), it was obvious that each voltage envelope became wider, while the peak voltage remained at the same ~5V.

We then tested the voltage output from two additional frequencies (2Hz and 4Hz) with a displacement of 1 cm (**Figure 2C-D**). As the frequency increased to 2 Hz, the output increased slightly while still remaining somewhat regular (**Figure 2C-D**). The faster swings by the actuator drove faster movements of the sliding disks inside the device. Therefore, the negatively and positively charged materials separated and contacted at faster rates, resulting in higher voltage output. When the frequency or movement speed rose too high, the output voltage became less regular, leading to generally lower power generation (**Figure 2D**). This was because the magnets that were supposed to hold the sliding disk at the center region of the base were not strong enough to overcome the inertia due to fast movements. Thus, the sliding disk hit and bounced against the wall, resulting in irregular motions and off from the overlapping with the interdigitated electrodes on the base.

The overall trends of voltage output in correlation with frequency were plotted together for illustration and comparison (**Figure 3A**). We then examined how voltage output was impacted by altering displacement amplitudes. We tested three amplitudes (1 cm, 2 cm, and 4 cm) at 1 Hz. The increase in displacement caused a steadier rise in voltage generated than an increase in frequency, as shown by the black line in (**Figure 3B**). Instead of showing an optimal peak value, the displacement displayed a plateau-like trend. This was because the movement of the sliding disk was induced by inertia, where only the acceleration and deceleration parts would impact its movement. As the displacement increased, the moving speed would reach a constant speed, at which the sliding disk would not be subject to any additional driving force for further movement. Therefore, the electrical output plateaued when the displacement got too high, in this case, at 4cm of displacement.

Using the same sets of displacements and frequencies, the voltage output from other electrode configurations, i.e., 2 mm and 4 mm ring widths, were also measured (**Figures S3 and S4**). To summarize and compare all the output relationships, the average peak-to-peak voltages from all three configurations were plotted as a function of frequency and displacement (**Figure 3A and 3B**, respectively). All three electrode configurations exhibited the same trends: for frequency, the average voltage outputs showed a peak value at 2 Hz; for displacement, the average voltage outputs plateaued as the displacement increased beyond 2 cm. The 1mm ring thickness outperformed the 2mm and 4mm ring designs in both the frequency and the displacement tests. This was due to the small ring thickness, which allowed more rings to be fabricated on the sliding disk as well as the electrodes. Under the same displacement, a larger number of charge-inducing rings would be scanned through by the sliding disk, and their contact-separation time became shorter. Therefore, more voltage peaks with higher peak intensity could be obtained. This subsequently showed that the area of the rings did not contribute as significantly to the output as the number of rings, even though the larger contact area was expected to generate a larger amount of charges. Since the 1mm ring design showed the best performance, it was used in all subsequent experiments.

The energy generation capability of the omnidirectional swing TENG was demonstrated by charging capacitors using the actuator to shake the container. In this demonstration, the device was agitated using the actuator at a fixed displacement of 2 cm. The two leads of the device were connected through a bridge circuit to a capacitor, and the voltage from the capacitor was monitored continuously. First, a 1 μF capacitor was charged at two different frequencies, where the 2 Hz actuation offered the fastest charging rate, which was almost twice as much as that from 4 Hz (**Figure 3C**). While a larger number of electric pulses could provide higher electrical power, the irregular output from the 4 Hz

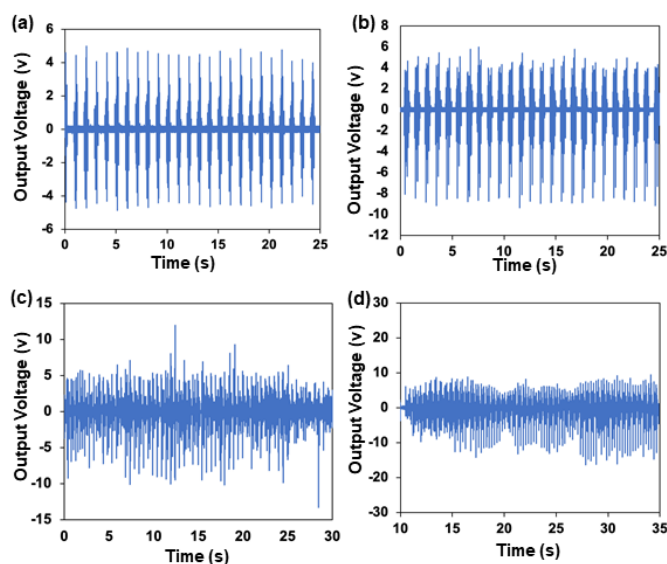


Figure 2. Voltage output from the TENG with a typical 2-mm electrode driven by the actuator at different movement conditions. a) Driven at 1 Hz with 1 cm displacement. b) Driven at 1 Hz with 2 cm displacement. c) Driven at 2 Hz with 1 cm displacement. d) Driven at 4 Hz with 1 cm displacement.

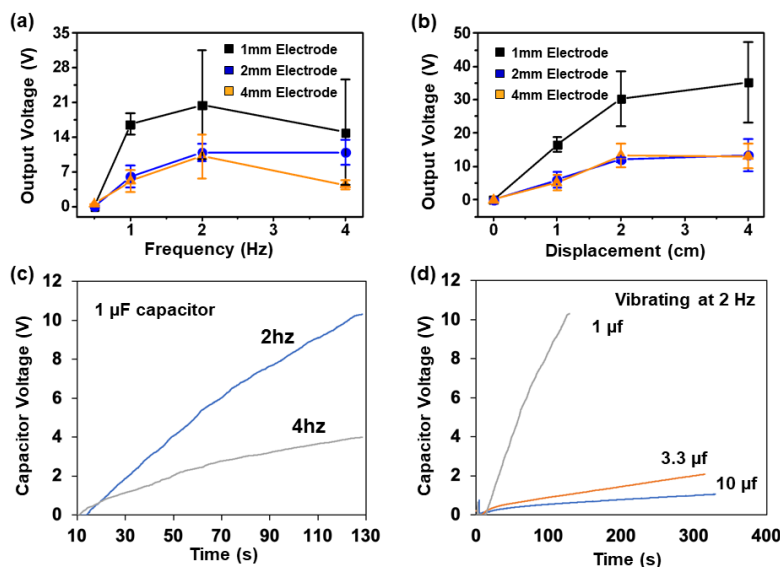


Figure 3. Electric output from the sliding TENG. Output voltage (mean $\pm$ SD, $n=5$ per point) from the TENG using different a) frequencies and b) displacements. c) Capacitor voltage over time shaking at different displacements. d) Capacitor voltage over time shaking at different frequencies.

substantially jeopardized the energy generation capability. The 2 Hz actuation was then selected to charge capacitors with different capacitances (Figure 3D). As expected, the higher the capacitance, the slower charging rates were obtained, primarily due to the leakage from the capacitor and charging circuit (17). Nevertheless, the steady increase in capacitor voltage suggests that the TENG model is a practical method of electrical energy generation for potential applications to smart farming.

Self-powering capability demonstration

The TENG was then fit into a plant-mimicking system meant to be placed in a farm field and respond to wind or other motions (Figure 4A). To simulate the effectiveness of this device in the real world, the pole was affixed to the ground, and pressurized air was released through a wide nozzle to simulate wind flow. The TENG head swung violently under the continuous wind blow in a circular pattern (Supplementary video S2), most likely as a result of the asymmetric distribution of the leaves. The output voltage was monitored from the electrical wires. The output was less regular compared to those obtained with the actuator because the swinging motion combined with the wind moved the device in a less organized fashion compared to what a pre-configured actuator does (Figure 4B). Most voltage peaks ranged between 1-3 V, with only a few exceptionally high peaks possibly due to instantaneous charge release. The consistent level of output voltage suggested that this device could be used to power a small electronic device through a power regulatory circuit. Driven by the wind flow, the electricity output of the TENG was still able to charge a 1 μ F capacitor through a bridge circuit for charge regulation. To demonstrate its practical application potential, a capacitor powered by the TENG was connected to power a humidity sensor, an essential type of environmental data for farming. Simply based on the electricity stored in the capacitor, the humidity sensor was able to function normally for ~15

seconds (Supplementary video S3). In that time frame, the humidity sensor gave an accurate measurement of the air's humidity (Figure 4C). This was an acceptable result, as the time it took to charge the capacitor to the operation level was much shorter than the time it would need in the real world to report the humidity data. The 15 seconds was also more than enough time to produce an accurate measurement and transfer it to a centralized data processing system.

DISCUSSION

In this work, we created an omnidirectional TENG based on a circular design of a sliding mode mechanism. This omnidirectional design combined with a magnetic ring configuration was chosen to allow for efficient mechanical energy collection, aiming at achieving high electrical energy output.

Our overarching hypothesis for this project was that the larger displacements and faster frequencies of switching of the triboelectric polar pairs for the TENG device could generate higher voltage output than smaller displacements and slower frequencies. Driven by this hypothesis, various electrode ring widths were used in the TENG device, and their outputs were tested at different oscillating frequencies and displacements. It was discovered that a higher number of electrode rings is preferable for higher output, but the electrode surface area appeared less relevant to the electric output. This is consistent with our hypothesis because increasing the number of electrodes increased the switching rate between the positive and negative triboelectric electrodes. Increasing the electrode surface area can increase the amount of electric charge but slow down the switching rate, thereby yielding a nearly zero net impact on the electric output. The output was also found to be more sensitive to the oscillating frequency but less sensitive to the displacement amplitude. The relatively large output variations at different frequencies are consistent with our hypothesis because higher frequencies yielded higher switching rates. However, it was surprising to see that the

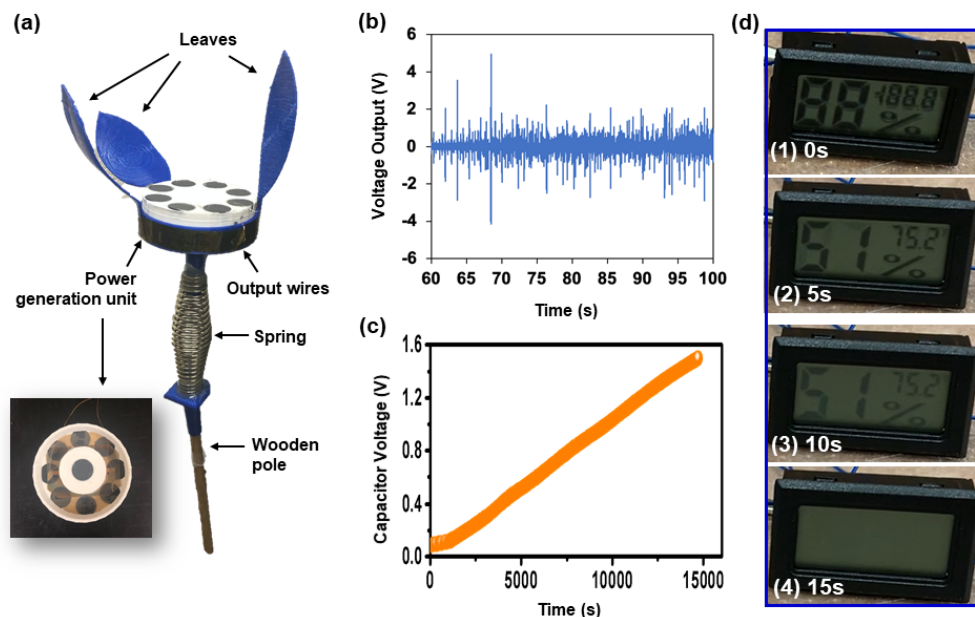


Figure 4. Device and capacitor voltage charging from the TENG. a) Labeled diagram of the entire device including the TENG. b) The voltage output from the TENG over time. c) The voltage inside the capacitor over time. d) The charge in the capacitor being used to power another device that lasts a bit under 15 seconds.

output plateaued as the displacement amplitude increased. We think it may be related to the limited internal space inside TENG, as the internal moving piece could always hit the wall at large overall displacement. Based on our initial results, we used a plant-mimicking design to host the omnidirectional TENG, and its electricity generation capability was tested under simulated wind blows. Through a regulation system, the generated electricity was able to power a humidity sensor, demonstrating the self-powered operation for collecting critical environmental data. One of the major advantages of this device is the potential low cost as it is fabricated mainly from easily accessible and cost-effective materials. The device framework and a majority of the supporting structure were made of polylactic acid (PLA) filament, which can also be replaced by other types of plastic materials. The primary cost in our development came from the technology needed to fabricate the functional components of the TENG device for electricity generation. We used copper tape as well as gold sputtering to fabricate the charge induction and collecting electrodes. However, given the electrode size and dimension, we expect this electrode fabrication can be replaced by a standard printed circuit board (PCB) manufacturing process when moving to large-scale production. Apart from this, another relatively high-cost component was the magnets. Based on this material and fabrication analysis, we expect the cost of our energy harvesting device to be comparable to a regular portable speaker (around \$20 USD), which comprises a similar combination of materials.

Although our device is a very cost-effective and easily scalable energy source, there are also a few challenges that need to be addressed in further research. The first challenge is the relatively low energy output. It took our device 20 minutes to charge a capacitor to a sufficient level for operating a humidity sensor. This is adequate for sensing humidity information; however, for smart farming, there are many more functions

that the smart farming systems also need to perform, such as sensing the pH of the soil, detecting infection in plants, and processing and transmitting collected data. These functions require much more power than what we demonstrated using the humidity sensor. Improving the output power should, therefore, be the primary task in future development. Based on the device structure and application conditions, we believe that optimizing the strength and configuration of the magnets could allow for smoother movements and lower frictions, thereby achieving a higher energy conversion efficiency and longer device lifetime. In addition, our current design only has one contacting layer for electricity generation. It is possible to introduce several more triboelectric layers within the same volume to multiply the output.

Another challenge is the environmental influences on the device's performance. Because the TENG output is directly related to the amount of charge induced on the surface, humidity may change the amount of charge generated by the TENG (18). It is necessary to study how the TENG output is related to the humidity so that we can better quantify its electricity generation ability. Apart from this, water from rain or snow may infiltrate into the device and cause damage. Just like many other outdoor electronics, our device may need to be completely sealed to prevent rainwater or other liquids from damaging the TENG.

Furthermore, the sliding TENG mechanism requires that the sliding layer constantly moves against the electrode layer. This may introduce considerable wear to the electricity generating components of the device and pose significant challenges to its lifetime. This issue is a general limitation that affects almost all TENG devices because of their contact electrification mechanism (19). Our device used an upside-down configuration to lower the friction impacts. This could be further optimized by adjusting the strength and arrangement of the magnets to allow for swifter and more controlled

movements. Furthermore, we may introduce a lubricant to the surface to minimize friction and associated wear.

Despite these challenges, our development provides preliminary support showing the feasibility of achieving an effective, eco-friendly, and cost-efficient solution of power supply for implementing sensors and sensor networks in a large farmland, which is essential for smart farming.

MATERIALS AND METHODS

Fabrication of omnidirectional TENG

The omnidirectional TENG follows the design of a sliding model TENG with a circular shape (15, 16). The TENG base was fabricated by a UltiMaker S3 3D printer. The UltiMaker 2.85mm polylactic acid (PLA) filaments were used as the printing material. The printing models were designed and drawn using Blender (18) and subsequently finalized to form a printable file using the Ultimaker Cura 3D printing software (19). The base had a circular shape with a radius of the ring width. On the back side, a recessed circular space with a 45 mm diameter was created at the center to fit a magnet inside. The front side of the base had several concentric protruding rings with equal ring width and spacing. The center of the base was a circle with a diameter based on the rings. Based on the design, the number of rings was made to the max to fit each ring width. The rings varied in widths of 1 mm, 2 mm, and 4 mm, with the spaces between the rings equal to the width, respectively. To enable electric current induction, copper tape (0.1 mm in thickness, purchased from Amazon.com) was applied to completely cover the front surfaces of all the rings and the center circle. The chargecollecting electrodes were a pair of interdigitated concentric electrodes that were made with the same width and spacing as those of the charge inducing electrodes. This interdigitated electrode design was drawn using Microsoft PowerPoint. Its inverse pattern (the electrode area was left blank) was printed on a transparent polyester (PET) film by a commercial inkjet printer. The patterned PET film was then used for e-beam deposition of 10 nm Cr and 100 nm Au. After deposition, the film was washed with acetone to remove the inks, and the interdigitated electrodes were left on the PET film. The PET film with fabricated interdigitated electrodes was glued to the sliding disk. A PTFE tape (50µm, CS Hyde Company) was applied to completely cover the PET film with the interdigitated electrodes serving as the triboelectric charge generating layer. The electricity was measured or collected from this pair of electrodes (see Device Characterization subsection).

Energy harvesting device integration

The container was fabricated by 3D-printing using PLA (see detail above). The container was connected to the top of a spring base, which was attached to a wooden stick, all affixed with epoxy. The device was placed that way so the TENG could be shaken as much as possible to produce the maximum current. In the device, there were two different parts that make the main device: the container and the base. The base was the part that contained most of the nanogenerator. The base itself was a cylindrical cup with a series of circular holes cut in the bottom in a circular pattern around the outside of the base to place magnets in a circular pattern around the center (**Figure S1**). Each magnet hole had an equal distance from the others. Another magnet with opposite polarity was inserted into the backside of the sliding disk. The magnetic

attractive force held the sliding disk against the interdigitated electrode layer. When the sliding disk moved closer to one side, the magnetic force became repulsive dominating, and the disk was pushed back toward the center. Thereby, the sliding disk could move/rebound freely along any direction with minimal friction. On the center of the base, there were the charge-collecting electrodes that were taped to the floor of the top cap. The top cap would then slide onto the bottom base, and the bottom base would connect the main TENG area to the rest of the full device. A shallow base was designed to hold the circular TENG inside and upside down. Thus, the magnets still held the sliding disk in contact with the charge generating electrodes and gravity largely reduced the friction, thus making the sliding disk more sensitive to movement. A spring was used to support the base and connect it to a rigid pole that raised the TENG head to higher elevations, which enhanced the swing rate and amplitudes. Artificial leaves were also added to catch the wind and enhance the swing motions. Two output wires were attached to the pole and released from the lower end to minimize the influences on the TENG head motion.

Device characterization

The electrical output was measured using a DMM6500 digital multimeter (Keithley, internal resistance of 1 MΩ). The data were recorded by the multimeter and then processed and plotted using Microsoft Excel. The TENG was first tested under linear motion implemented by a computer-controlled actuator. The actuator pushed and pulled the TENG at a series of designed frequencies (1, 2, and 4 Hz) and distances (1, 2, and 4 cm) to determine the motion-related electric outputs of all TENG devices. The completely assembled energy harvesting device was tested in a simulated windy environment mimicking the real application conditions. In this simulation, we used a wind blower against the leaves on the device, which spun the TENG, causing an electrical current.

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APPENDIX

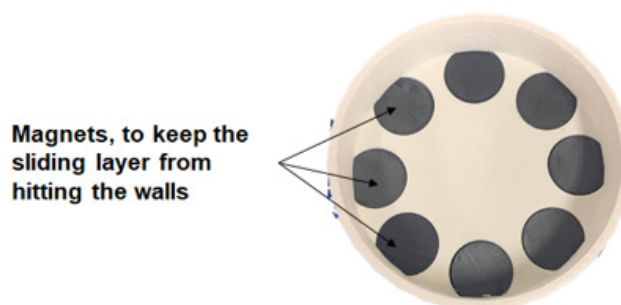


Figure S1. The top container that holds the electrode and the sliding layer. This picture is of that section without the electrode and sliding layer installed. The magnets are placed into previously created holes to prevent the sliding layer from hitting the walls and increasing efficiency. The center is where the electrode is placed, and there are two holes on opposite sides of the container wall to allow for wires to pass through.

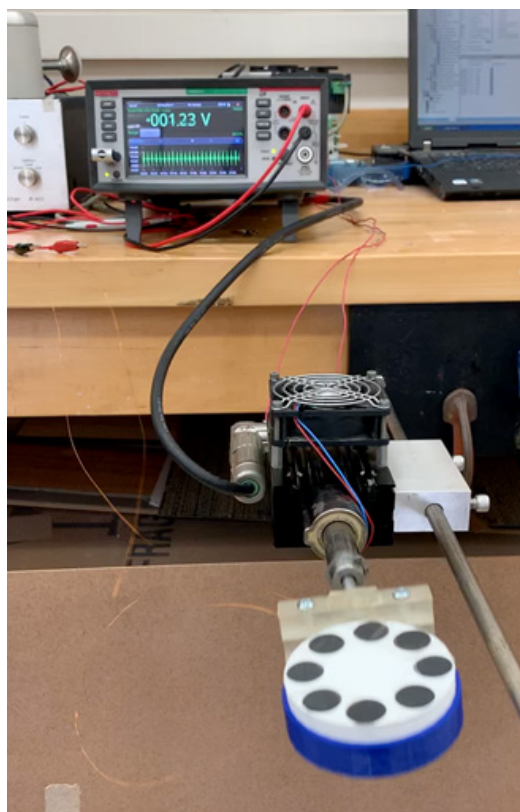


Figure S2. The setup used to test the voltage output from swinging the TENG, using an actuator. The actuator that moves the TENG and its container has two different configurable variables, its extrusion distance and its frequency of extrusion in Hz. The extrusion distance options are 1 cm, 2 cm or 4 cm, and the extrusion frequency options are 1 Hz, 2 Hz and 4 Hz. Both the extrusion distance and extrusion frequency configurations were tested with the other configuration being set as 1 cm or 1 Hz.

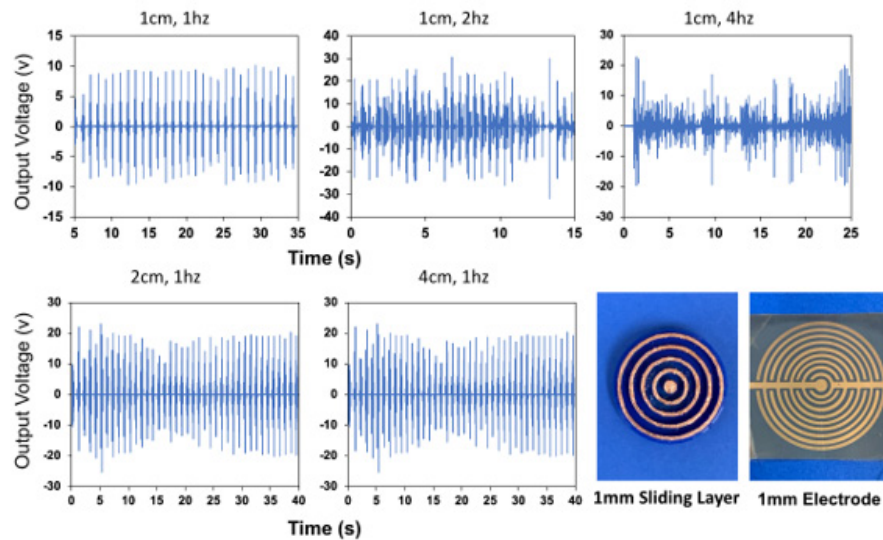


Figure S3. The voltage output data collected from the swinging TNEG, with the electrode & sliding layer both being 1 mm (shown in the photo in the bottom right). The testing conditions (extrusion distance and extrusion frequency) are marked on top of each graph.

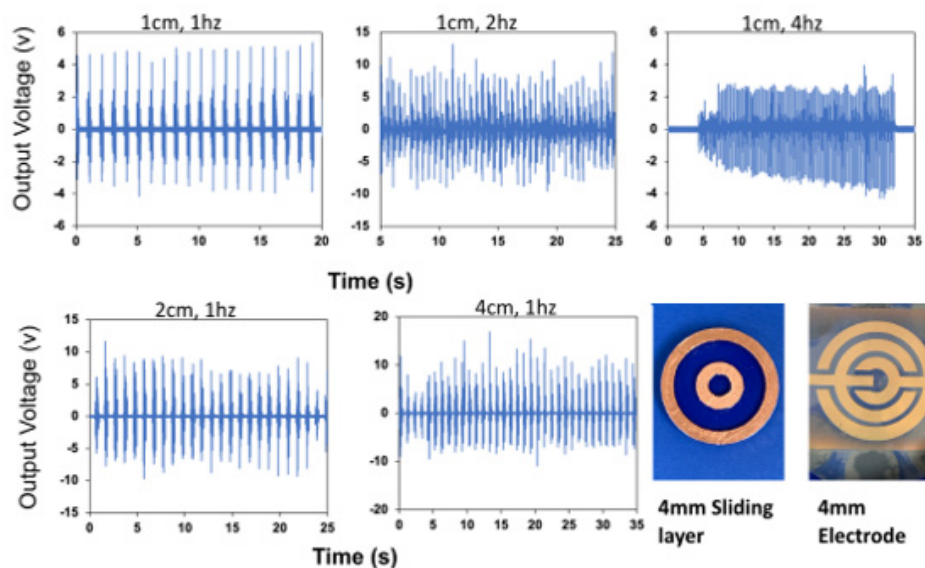


Figure S4. The voltage output data collected from the swinging TNEG, with the electrode & sliding layer both being 4 mm (shown in the photo in the bottom right). The testing conditions (extrusion distance and extrusion frequency) are marked on top of each graph.

Supplementary Video S1: The actuator pushing the TENG device (the top container and the bottom base with the TENG inside) to generate voltage, with the voltage generation being recorded.

<https://youtube.com/shorts/MgMiC700bcU>

Supplementary Video S2: The wind simulation setup where the whole device was blown by air flow. The voltage was used to charge a capacitor, and the voltage from the capacitor being recorded.

https://youtu.be/IsShss8L_Vs

Supplementary Video S3: The capacitor, previously charged by the device using the wind simulation setup, used to power a humidity sensor and giving an accurate reading of the humidity.

<https://youtu.be/QQWh4A6bBrM>