# Enhanced Electrical Output in an Electrostatic Generator Using Charged Water

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**ABSTRACT:** Electrostatic charging of water, particularly at the water—hydrophobic interface, continues to perplex researchers despite centuries of work. Recent advancements in energy harvesting, materials synthesis, and sensing employing electrohydrodynamic processes have generated renewed interest in the electrostatic charging of water. This work aims to understand the charging of water from an energy-harvesting perspective. We used a single-electrode electrostatic generator initially to demonstrate enhancement of the electric output with the addition of water. Through several control measurements, we established that the enhancement was a result of the electrostatic charging of water. The role of electrode wettability and pH on the electric output was correlated with the output voltage. The system was extended to a



double-electrode electrostatic generator (DE-EG) to expand the applicability of the technique and increase the output. Using the DE-EG, we demonstrated the influence of an electric field on the charging of water. The electricity thus produced was used to power multiple light-emitting diodes. Furthermore, the technique was employed to treat wastewater containing a dye using a 3D-printed linear actuator. The insights presented are useful in enhancing the performance of water-based EGs and could help to better understand various electrohydrodynamic processes.

**KEYWORDS:** triboelectricity, energy harvesting, triboelectric generator, water charging, streaming electrification

# INTRODUCTION

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The Kelvin water dropper<sup>1</sup> and Leyden jar<sup>2</sup> are a few examples of early electrostatic generators (EGs) wherein water was used to store electric charge and produce electricity.<sup>3</sup> In such systems, the charging of water is driven by an external field, which pushes the charge into the water through electrostatic induction. Unlike induced charging, in contact charging, which is a more prevalent form of charging two surfaces when brought in contact and separated, develops an electrostatic charge. Much like solids, liquids in contact with other materials also develop static charge. Streaming or flow electrification refers to electrostatic charging at a liquid-solid interface because of flow.<sup>4</sup> It can further be extended to an air-liquid<sup>5</sup> interface, as in the case of aerosols, or a liquid-liquid interface, as in the case of emulsions.<sup>6</sup> The phenomenon has been known for many decades<sup>7,8</sup> and is still a topic of active investigation.<sup>9,10</sup> For example, the flow of hydrocarbons in petroleum pipelines causes accumulation of charge, leading to electric discharges causing explosion.<sup>8,11</sup> Though the streaming electrification of hydrocarbons has been known and studied, the contact electrification of water became prominent only after the advent of the semiconductor chip industry. Previously, electrostatic charging with water was considered

highly unlikely owing to its million-fold higher conductivity compared to hydrocarbons. $^{8}$ 

Electrostatic charging at the water—hydrophobic interface has been a subject of discussion for a long time. Studies on electrostatic charging at the water—hydrophobic interface have shown that water gets positively charged,<sup>10,12</sup> and the hydrophobic surface (generally, a polymer) gets negatively charged.<sup>7,13</sup> Burgo et al. studied charging of water when passed through tubes of different types of materials: glass, polymers, and metals. In the study, water always acquired a positive charge irrespective of the materials it was in contact with, except for the case where it was flown through air, where it acquired negative charge.<sup>10</sup> A number of charging mechanisms based on experimental and theoretical findings have been put forward. Most of these mechanisms are based on ion(s) adsorption at the solid—liquid interface, though they differ in the types of ions and mechanism of adsorption. The charging

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Figure 1. Illustration showing (a) tapping of the PTFE beaker containing water, (b) photograph of the setup—top: PTFE beaker with an electrode attached on the granite slab, middle: back of the beaker, and bottom: powering an LED using the SE-EG, (c) changes made to the EG—volume of water, pH, electrode wettability, and contacting surface, and (d) schematic of charge measurement setup with the Faraday cup, and materials used for its construction are listed on the right.

at the water-hydrophobic interface is attributed to the formation of a double layer, leading to adsorption of OHions at the hydrophobic surface. This excess of OH<sup>-</sup> ions on a hydrophobic surface makes it negatively charged and leaves the water with an excess of H<sup>+</sup> ions, making it positively charged.<sup>5,7</sup> Kudin and Car modeled in detail the behavior of hydroxide and hydronium ions at the water-hydrophobic interface.<sup>9</sup> They observed that the hydronium ion clusters tend to occupy surface and subsurface regions, whereas the hydroxide ions prefer the surface layer. This preferential occupation of hydroxide ions could explain the negative charge acquired by hydrophobic polymeric surfaces like polytetrafluoroethylene (PTFE) in contact with water. Some claim that the observed electrophoretic mobility may not arise from the adsorption of ions but because of the anisotropic distribution of water molecules at the water-hydrophobic interface. The water droplets in oils have positively charged H atom sticking toward the oil.<sup>6</sup> Others attribute the charging to concoctions of ions present in the water, prominently the presence of carbonate  $(CO_3^{2-})$  and bicarbonate  $(HCO_3^{-})$  anions from dissolution of atmospheric CO2.<sup>14</sup> The presence of H<sup>+</sup> and OH<sup>-</sup> ions could not alone account for the calculated negative charge measured through interfacial tension or the zeta-potential at the

hydrophobic surface.<sup>14,15</sup> The charging of water droplets has also been observed to change physicochemical properties such as surface tension.<sup>16</sup> Furthermore, recent studies have pointed out a correlation between the charging of droplets and viscosity, which is a surface tension-dependent quantity. This implies that charging is dependent on surface tension, but at the same time these parameters are altered by charging.<sup>17</sup>

The advent of the triboelectric (nano)generator (TG/ TENG) has generated a renewed interest in the electrostatic charging of water.<sup>18-21</sup> Two types of liquid-solid-based TG exist. One is droplet-based, which utilizes continuous impingement of droplets on hydrophobic surfaces; such systems are useful for energy harvesting from rainwater.<sup>22,23</sup> The other is continuous flow-based, in which water is continuously pumped through an open tubular structure; such systems are useful for energy harvesting from running water bodies such as rivers, seas, or flow through pipes.<sup>24</sup> In both categories, water is passed on a hydrophobic surface, which causes triboelectric charging at the water-hydrophobic interface. The hydrophobic surface becomes negatively charged, and water becomes positively charged. Such liquid-solid-based TGs have several advantages over the solid-solid type in conventional TGs, such as reduced friction, better contact, and



Figure 2. (a) Output voltage of the SE-EG at different volumes of water, and the inset shows the zoomed-in view of the voltage profile at 0 mL, (b) current with sequential addition of water in steps of 10 mL, (c) charge of water when tapped on the granite slab, (d,e) working mechanism of the SE-EG without and with water, respectively.

efficient heat transfer. The solid–solid type TG suffers from heating due to continuous rubbing and poor heat transfer of insulators, while the water-based TG has better heat dissipation.<sup>24</sup>

Previous studies have discussed using water as a component in TGs/TENGs. However, the enhancement caused by the addition of water and the factors affecting it have hardly been discussed. These setups require water to start with and therefore lack distinction between those with and without the application of water. Furthermore, since the water-based TG operates under wet conditions, it becomes imperative to understand the effect of wetting properties of the electrode on the output performance.

In this article, we looked at the enhancement in the electric output (both voltage and current) by adding water and its subsequent charging in a PTFE beaker. We started with a simple setup that can harvest mechanical energy to produce electricity. As we progressively added water, a jump in the electric output was observed. By focusing on the energy harvesting aspect of charged water, we studied the effect of electrode wettability and pH on the output voltage. Furthermore, the effect of the electric field on the charging of water and its effect on output voltage have been studied. Additionally, through powering multiple light-emitting diodes (LEDs) with the setup, we have demonstrated the capacity of the process to drive low-power devices. The technique was further expanded for the treatment of dye-containing water by using a 3D-printed linear actuator (LA).

### MATERIALS AND METHODS

**Materials.** Methylene blue (MB) was purchased from SRL. Sodium hydroxide (NaOH) pellets, sodium chloride (NaCl), and hydrochloric acid (HCl), were purchased from Rankem. An Al tape was purchased from the local market. A 200 mL PTFE beaker was purchased from a local market. The beaker has an outer diameter of 6.8 cm, height of 8.8 cm, thickness of 0.24 cm, and a weight of 127 g. All measurements were performed in a temperature range of  $23 \pm 1.5$  °C and humidity range of  $51 \pm 2\%$  RH. The humidity was controlled using a OriginO60 Dehumidifier. The tapping force was calculated using an Arduino powered force sensing resistor sensor. However, the electrostatically charged PTFE beaker surface interfered with force measurement, making the accurate force measurement difficult.

**Instrumentation.** The UV–vis spectra were recorded by using a PerkinElmer Lambda 365 UV–vis spectrophotometer. The electrodes' morphology was studied using a Thermo Scientific Verios G4 UC SEM. The contact angle was measured using a GBX Digidrop contact angle meter with a 10  $\mu$ L water droplet. The charge, current, and voltage measurements were performed by using a Keithley 6514 electrometer.

Design and Fabrication of the Faraday Cup. An in-house Faraday cup was designed and fabricated to accurately measure charges at the subnano Coulomb level. The design employed a twolevel grounding scheme to protect the system against the external electrostatic field. Mu-metal shielding was introduced to protect against the magnetic field. To avoid electric contact, PTFE was used as a separator between metals. For charge measurement, the test material was introduced into the Faraday cup. To obtain the charge reading, the Faraday cup was connected to an electrometer. For data acquisition, Keithley ExceLINX software, which is an Add-in to Microsoft Excel, was used. The electrometer, Keithley 6514, was interfaced with the computer using an IEEE-488 USB to GPIB interface, Keithley KUSB-488B.

**Linear Actuator.** To perform continuous tapping for a long duration for dye-degradation experiments, a 3D-printed LA was developed. The modeling of the LA was done in FreeCAD and printed in a Flashforge Dreamer 3D-printer. The linear rail was driven using a servo motor (SG90) and controlled using a microcontroller, Xiao SAMD21. The programming was done in the Arduino IDE.

**Preparation of the Electrode.** The fabrication of hydrophilic (philic-) and hydrophobic (phobic-) Al electrodes were done by

modifying a previously described<sup>25</sup> method for the preparation of philic- and phobic-Cu surfaces.

*Hydrophilic Aluminum.* To make philic-Al, the metal tapes were dipped in 1 M aq. sol. NaOH for 14-17 min. Before dipping, the tapes were cut to the right size, and the adhesive side was kept well protected by sealing the back side with Teflon tape.

*Hydrophobic Aluminum.* The NaOH-treated philic-Al tapes were submerged in a 6 mM ethanol solution of stearic acid for 2 min and then kept for drying. Once dried, the process was repeated twice for a superior hydrophobic coating.

#### RESULTS AND DISCUSSION

Figure 1 illustrates the overall design of the experimental setup. Inside a PTFE beaker, aluminum tape (length = 3.5 cm, width = 2.5 cm, thickness = 30  $\mu$ m) with conductive adhesive was stuck to the bottom. This Al tape acts as an electrode. While the electrode was pasting, a metal wire was attached to the tape on the adhesive side. For the measurement, a load was connected between the electrode and the ground, as shown in Figure 1a,b. When the beaker was tapped on a surface, here on a granite slab, the system acts like a single-electrode electrostatic (or a triboelectric) generator (SE-EG) and produces electricity. Since the bottom of the beaker had a ring-shaped protrusion (OD = 6.8 cm, ID = 4.8 cm) along its periphery, the actual contact area, ca. 18 cm<sup>2</sup>, was much smaller than the cross-sectional area of the beaker, as shown in Figure 1b. In order to characterize the system in detail, various parameters were varied systematically, as shown in Figure 1c. This includes measuring the output voltage with the change in volume of water added, pH of water, electrode wettability, and base material upon which the beaker was tapped. For the charge measurement, an in-house-developed Faraday cup was connected to the electrometer. Figure 1d shows a schematic of the charge measurement system. The power generation parameters (voltage and current) from the device are listed in Figure 2. Figure 2a,b shows the voltage and current profile when the beaker was tapped constantly on the granite slab. The inset in Figure 2a shows a zoomed-in view of the voltage waveform generated by the SE-EG at base voltage (0 mL). The beaker was tapped with a hand at a frequency of 3 Hz, as shown in Figure S1. The observed tapping height was 2.5-3cm and tapping force was 2.5-2.7 N. Interestingly, when water was added sequentially into the beaker, both the voltage and the current showed an increase by more than 3 times (Figure 2a,b). This increase in electric output by addition can be attributed to the contact charging of water with PTFE, as shown by us previously<sup>12</sup> and by others.<sup>26</sup> The system was observed to be current-limiting, as the output current remains unchanged when measured across resistors ranging from 100  $\Omega$  to 1 M $\Omega$ , while the voltage scales following Ohm's law with the increase in resistance. To uniformly compare different systems, we used 1 M $\Omega$  as a standard to measure the output voltage and current across all of the setups.

Figure 2c shows the charge measurement with normal water (pH 7) as a result of tapping on granite. Here, 20 mL of water was placed in a PTFE beaker and tapped for 15 s for contact charging. From this, 500  $\mu$ L of water was collected using a custom-made PTFE pipette and transferred to the Faraday cup connected to the electrometer. This was to keep the nature of the contacting materials the same throughout the measurement. The value obtained was scaled to obtain the charge per mL of the liquid. The measurement was continued with fresh 500  $\mu$ L, in steps.

Mechanism. The SE-EG without added water is essentially a typical TG in vertical contact-separation mode,<sup>27,28</sup> whose working mechanism is shown in Figure 2d. The repeated contact between PTFE and granite causes charging. The periodic tapping motion between two charged surfaces generates an oscillating electric field. This changing electric field induces a change in the electric potential at the electrode surface. This leads to the push and pull of the electrons across the load, causing a current,  $I_{\text{TB}}$ , to flow. The cycle consists of four distinct phases. During contact, Figure 2d(i), and separation, Figure 2d(iii), positions, the negatively charged PTFE surface reverses its direction and comes to a temporary halt. Hence, there is no change in the induced electric field on the electrode and, consequently, zero  $I_{TB}$ . As the PTFE surface ascends, Figure 2d(ii), it moves away from the positively charged base, reducing the pull on electrons and causing them to be pushed away from the electrode. This increases the induced charge and drives  $I_{\text{TB}}$  toward the electrode. Conversely, during descent, Figure 2d(iv), the PTFE surface approaches the positively charged base, decreasing the induced charge on the electrode. This causes the electrons to move toward the electrode and hence the current,  $I_{\text{TB}}$ , away from it.

The behavior is akin to how a charged object, when approaching a neutral gold leaf electroscope, induces a charge separation within the electroscope through electrostatic induction, causing its leaves to move apart. For instance, if a negatively charged object is near the electroscope, it repels the electrons. These electrons move away from the cap and accumulate on the gold leaves, making the cap positively charged and the leaves negatively charged. As a result, the leaves repel each other and spread apart. When the charged object is removed, the charge redistributes evenly throughout the electroscope, causing the leaves to collapse.<sup>2,29,30</sup> Interestingly, if an oppositely charged object (in this case, positively charged) is brought near the negatively charged electroscope, it attracts some of the excess electrons. This decreases the induced negative charge on the leaves, decreasing their repulsion and causing reduced separation between the gold leaves.

With water added, as shown in Figure 2e, the rapid oscillation of the beaker over a small distance in a short period of time causes the sloshing of water.<sup>31</sup> The combination of sloshing, as captured and explained in detail by Constantin et al.,<sup>31</sup> and charging of water at the water-hydrophobic interface, as discussed previously, leads to the observed enhancement in the electric output. When the positively charged water in the beaker is stationary, as shown in Figure 2e(i), the negatively charged PTFE surface pushes electrons away from the electrode, while both the positively charged water and the positively charged base pull electrons toward it. As a result, the induced charge on the electrode (or the number of electrons pushed away) is less than it would be without water being present. When the beaker accelerates upward, as depicted in Figure 2e(ii), the water moves away from the base due to the rapid acceleration. This upward movement of the positively charged water increases the induced charge on the electrode by reducing the pull on the electrons, allowing the negatively charged PTFE to push more electrons away. The outward electron movement creates an inward current flow toward the electrode, adding excess current  $(I_{\rm TW})$  to the base current  $(I_{\rm TB}$ , which occurs without water). During the beaker's downward descent, the water's inertia causes it to maintain its upward acceleration, lagging



Figure 3. (a) Cyclic testing showing the role of water addition on peak voltage, (b) effect of weight on voltage output, (c) differential voltage,  $V_{\text{diff}}$  at different pH for electrodes with different wettability, and (d) charge of water at different pH.

behind and eventually crashing against the beaker's base, forming a valley. This compression brings the positively charged water closer to the electrode, pulling electrons toward it and causing the current to flow away from the electrode, as shown in Figure 2e(iii). As the beaker reaches the top of its ascent and begins to reverse direction, it momentarily halts, resulting in no current flow, as illustrated in Figure 2e(iv). This cycle of movement creates a compound effect of water sloshing and charging within the PTFE beaker. The alternating current flows generated by these movements result in an enhanced electric output, demonstrating how mechanical motion can be converted into electrical energy through this triboelectric system.

Factors Affecting the Electric Output of the SE-EG. Cyclic Test and Effect of Weight. To test whether the increase in the output was indeed a result of the addition of water, we performed a cyclic test, in which we sequentially added water from 0 to 30 mL and then reduced it from 30 to 0 mL in steps of 10 mL and recorded the voltage in each step. The system traced back to almost the same values as shown in Figure 3a. The mean and standard deviation (error) for the peak voltages were calculated from the respective voltage output. At first, the peak values were obtained using the find peaks function in the SciPy library<sup>32</sup> in Python. For peak voltage calculation, all the peak values were recorded for 30 s period, from 70 to 100 s after the tapping began. This was to ensure the collection of the steady-state response of the system while avoiding any potential artifacts from the stopping process. Each measurement encompassed a total of 170 peak values, including both

the upper and the lower peaks of the voltage waveform. Following this, the mean value of the peak voltages was calculated to represent the average performance, while the standard deviation was computed to quantify the variability or error in the measurements. Each of the experiments was conducted at least twice to test the reproducibility of the result. In Appendix S1, we discuss in detail the calculation of the peak voltage. This cyclic test confirms that the addition of water is responsible for the observed enhancement in the electric output. It can also be argued that the jump in the output is due to the added weight of the liquid and not because of charging. To further strengthen our point that the observed increase in electric output was indeed because of the charging of the liquid, we tested the effect of weight on the output voltage. For this, three wooden blocks, each with a mass of 10-12 g and representing a mass of 10 mL of water, were placed in the beaker. Wood was chosen because of its antistatic nature. Since it does not get electrostatically charged,<sup>33</sup> it allows us to distinguish between the contributions of weight and electrostatic charging. We found that the addition of weight had only a minor effect, which was an order of magnitude smaller than that with water. As shown in Figure 3b, in the line plot of the output voltage for water and wood, the obtained voltage profile was almost flat, with only a slight increase with the addition of wooden weights. This further confirmed that weight alone has a very minimal effect on the output voltage, and the charging of liquids is important to account for the enhancement observed with water addition. In Figure S3, we show that a similar enhancement can be achieved with an electrode completely

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**Figure 4.** (a) Illustration of the DE-EG, (b) exploded view of the base, (c) output voltage of the DE-EG with subsequent addition of water, and the inset shows the zoomed-in view of the voltage profile at 0 mL, (d) bottom bar chart shows the differential voltage,  $V_{\text{diff}}$  for SE-EG (light blue **I**) and DE-EG (teal **I**) and, the floating top bar chart shows the difference between consecutive voltages,  $V_i - V_{i-1}$ , for i = 20 and 30 mL for SE-EG (yellow **I**) and DE-EG (coral **I**), (e) charge of water when tapped on granite and paper, and (f) powering of multiple LEDs using the DE-EG.

covered with Teflon tape. This is significant because when exposed to a harsh environment, the electrode may get damaged, which will degrade the performance of the EG.

Effect of Electrode Wettability and pH. The effect of electrode wetting on the voltage output was investigated by fabricating electrodes with three distinct wetting patterns. To characterize the wetting properties of the prepared electrodes, contact angles were recorded. The measured values for philic-Al, untreated-Al, and phobic-Al electrodes were 37, 74, and 142°, respectively, as shown in Figure S4. The morphologies of the modified electrodes were captured by using FESEM at various magnifications. The FESEM images, Figure S5, showed a patchy-layered structure with grooves at deeper levels. Only one face of the electrode was modified, while the other side, which sticks to the Teflon beaker, was kept well protected by covering it with PTFE tape such that the conductivity was not lost. After the treatment, the electric continuity was checked on the back side to ensure that it was not lost in the process of

modification of the electrode surface. This was to ensure uninterrupted flow of the induced current during tapping. We compared the output voltage for each of these electrodes at pH 4, 7, and 10, as shown in Figure 3c. The pH 4 solution was prepared by the addition of HCl and the pH 10 by the addition of NaOH.

The differential voltage,  $V_{\text{diff}}$  was compared for the three electrodes, i.e., philic-Al, untreated-Al, and phobic-Al, at three pH values. By differential voltage, we refer to a change in voltage with respect to the base voltage at 0 mL, i.e.,  $V_i - V_0$ where  $V_i$  represents voltage at  $i^{\text{th}}$  volume. From our experiments, we observed that this is a good way to negate small differences observed in the base value and allow an exclusive comparison of the effect of water addition. We observed a consistent increase in  $V_{\text{diff}}$  with increasing pH across all three electrodes, as shown in Figure 3c. This increase in voltage with pH corroborates well with higher charging with an increase in pH, as shown in Figure 3d. Previous studies have



**Figure 5.** (a) Schematic of the LA, (b) output voltage of the LAB-EG at different volumes of water, and the inset shows the zoomed-in view of the voltage profile at 0 mL, (c) schematic of a full-bridge rectifier, (d) time-dependent UV–vis absorption spectra of MB solution, and (d) plot of  $\ln(C_0/C)$  vs time for MB degradation.

shown positive charging of water on a water—polymer interface<sup>34</sup> and an observed increase in charge of water with pH.<sup>35</sup> Similarly, a decrease in  $\zeta$ -potential was observed for the hydrophobic surface with pH at the water—hydrophobic interface.<sup>13</sup> From Figure 3c, it appears that with an increase in electrode hydrophobicity, the output voltage increases. This may be because of better separation between the water and the hydrophobic electrode, which could result in better induction on the electrode surface.

Extension to a Double-Electrode System. In several electrochemical processes, two-electrode systems are required. With a simple modification, a single-electrode (SE) system was converted to a double-electrode (DE) system. A schematic of the modified DE system is illustrated in Figure 4a,b. To fabricate a DE-EG, a sheet of office paper was attached on top of aluminum foil. The paper was used as it is readily available, cheap, easy to work, and our prior experience of using it for the TG.<sup>20</sup> One output was taken from the foil, and the other was taken from the electrode inside the beaker. Figure 4c shows the voltage characteristic of the DE-EG. In Figure S6, we have shown the zoomed-in view of the voltage profile of the DE-EG for different volumes of water. In Figure 4d, the bottom bar chart depicts a differential voltage,  $V_{\rm diff}$ , whereas the floating top bar chart shows the difference in the consecutive voltage readings,  $V_i - V_{i-1}$ , for i = 20 and 30 mL, for the SE-EG and DE-EG, respectively. For both the SE-EG and DE-EG, the jump in the voltage was highest for the first 10 mL added as it has a contribution from the bottom and side walls of the beaker. The subsequent additions only have contribution from the side wall, which leads to a smaller increase in voltage from 10 mL onward, as seen from Figure 4d (top). Furthermore, moving from 20 to 30 mL, we observed an even smaller increase compared to moving from 10 to 20 mL. This may be

due to the increase in separation between the top water surface and the bottom Al electrode. As most of the charge of water stays on the surface, this increase in separation causes a decrease in induced field experienced by the electrode, leading to a smaller rise in voltage.

We were expecting the change in the voltage from the base voltage with the addition of water (or the differential voltage,  $V_{\rm diff}$ ) to be similar for the two systems. The added water was solely in contact with the interior walls of the PTFE beaker, which was the same for both the SE-EG and DE-EG. Since the contacting areas were the same, the charging should be the same, and, hence, the  $V_{\text{diff}}$  should be the same. However, there was a significant increase in the differential voltage with the addition of water for the DE-EG compared to the SE-EG, as shown in Figure 4d. The higher base voltage (at 0 mL) for the DE-EG was expected because of the higher charging of the PTFE with paper than with granite, and this increase was reflected in their base voltage. The higher charging of the PTFE-paper interface for the DE-EG also meant that the water present in the beaker was exposed to higher electric field. We investigated whether the higher voltage jump from the base value for the DE-EG was the result of increased charging in the presence of stronger electric field. We have observed that when tapped on paper, the water in the PTFE beaker exhibited a significantly higher charge than on the granite, as shown in Figure 4e. This confirms that the charge of water scales (or increases) with the external electric field, which was reflected as the jump in output voltage. Previous studies<sup>17,36,37</sup> have also shown such scaling of charge for water with the electric field. It is possible that this scaling of charge was due to the induced charging in the presence of an electric field.

The energy harvesting capability of the DE-EG was used to power multiple LEDs (37 in total), as shown in Figure 4f. This demonstrates the utility of such systems in powering lowpower electronics. We have tested the potential of such a power source for the treatment of wastewater containing dyes. A 3D-printed LA was used to do continuous tapping on the PTFE beaker fixed steadily to a buret stand. Much like the DE-EG, the LA-Beaker (LAB-EG) system is a two-electrode system. An Al-foil with paper attached on top was fixed on the rail of the actuator with the support of thick cardboard. A wire was attached to the foil as an output. The beaker, as before, had an electrode attached to the bottom, to which a wire was attached as another output. The two output wires were attached to two gold coated silica wafers acting as electrodes, which was inserted into a small beaker containing MB solution.<sup>20</sup> Figure 5a shows an illustration of the setup. As the rail of the actuator moves, the paper taps on the bottom of the beaker. This continuous tapping leads to the negative charging of the PTFE. The up-and-down movement of the rail produces an oscillating electric field between the two charged surfaces. This generates an electric current through induction at the electrodes. The tapping frequency of the LA was 2.5 Hz, as shown in Figure S7. The voltage output of the LAB-EG is shown in Figure 5b. The inset displays a zoomed-in base voltage (0 mL) profile. The Figure S8 shows a close-up view of the voltage profile for different volumes of water. The AC was converted to DC using a bridge rectifier and a filtering capacitor (100 nF) to smoothen the output DC voltage, as shown in Figure 5c. For the degradation, the electricity generated by the system was transferred to a small glass container filled with 6 mL of 2.5 ppm aqueous solution of MB with 100 ppm of NaCl. To enhance the output voltage, the tapping was performed with 20 mL of water in the beaker. It has been previously reported that the presence of salt increases the conductivity of the solution, which helps in the degradation process.<sup>38</sup> Furthermore, the presence of Cl<sup>-</sup> produces various oxidants at the anode that promote the oxidation of the dye and hence faster degradation.<sup>39</sup> The degradation of MB was monitored periodically using a UV-vis spectrophotometer.

A decrease in MB peak intensity was recorded as the tapping progressed, confirming the degradation, as shown in Figure 5d. The degradation rate, k of the MB solution was calculated from the slope of the linear fit to the first-order equation,  $\ln(C_0/C) = \ln(A_0/A) = k \cdot t$ , where  $C_0$  and  $A_0$  and C and A are the concentration and absorption at time, t = 0 and t, respectively, at 664 nm, as shown in Figure 5e. The degradation rate, k obtained was 0.028 (h<sup>-1</sup>) from the linear fit. The degree of degradation achieved was limited by the low power of the micro servo motor, which restricts the sloshing effect, resulting in a diminished electric output. The technique appears promising for harvesting energy from water currents.

**Note on Sustainability.** The methodology presented further improves electrostatic energy harvesting, a sustainable means of energy generation. The use of water in the process further improves the sustainability aspects as the only additional material needed for the enhanced energy generation is water, which is sustainable. Various types of mechanical energy may be used for the operation, including wind, water flow, etc. The utility of the process at multiple scales of operation may be visualized, at both micro- and macro scales.

# CONCLUSIONS

In this study, we have shown enhancement in the electrical output of the EG by the addition of water. We demonstrated, through various measurements, that the charging of water was responsible for the increased output. We further identified the sloshing of charged water in the beaker during tapping as the primary mechanism for the observed enhancement. Furthermore, the study explored the influence of pH on electrodes with different wettabilities and electric fields on the charging of water and resulting output voltage. Experiments on the effects of pH on output voltage have shown that increasing the pH led to a more pronounced charging of water and, consequently, an increase in the output voltage. Similarly, an increase in external electric field was observed to increase the charging of water, resulting in an increased output voltage. This means that both contact (streaming) electrification and induction charging could contribute to the electrification of water. The electricity generated could be used to power low-power electronics, as demonstrated by lighting multiple LEDs. We also showed that such systems could be useful in the treatment of wastewater containing a dye. Furthermore, the conclusions drawn in this work could be useful in diverse areas such as mass spectrometry, energy harvesting, electrospinning, electrowetting, electrohydrodynamic coatings, microfluidics, materials synthesis, electrophotography, and inkjet printing.

# ASSOCIATED CONTENT

# **Supporting Information**

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acssuschemeng.4c01860.

Tapping frequency distribution of the beaker using a hand, peak voltage calculation, illustration of peakvoltage calculation from a single pulse, output voltage of the SE-EG with the electrode covered, bar chart showing the contact angle of electrodes, FESEM images of electrodes, zoomed-in view of the voltage profile of DE-EG, tapping frequency distribution of the LA and its photograph, and zoomed-in view of the voltage profile of LAB-EG (PDF)

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#### **Author Contributions**

V.K., R.N., and T.P. conceptualized the project. V.K. performed the experiments. P.S. assisted in characterizing the samples. All the authors contributed to writing the manuscript.

## Notes

The authors declare no competing financial interest.

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