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# Exploring Raindrop Energy Harvesting using Reverse Electrowetting on Dielectric and Triboelectric Effect

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**Abstract**
Reverse electrowetting on dielectric (REWOD) and triboelectric nanogenerators have emerged as prominent developments in the field of droplet-based energy harvesting. Leveraging the triboelectric effect and kinetic energy of raindrops, this paper aims to examine a method of performing REWOD on raindrops while eliminating the need for a bias voltage and external mechanical modulation. The model presented in this paper mimics the typical REWOD set-up, modified to accommodate raindrops - with rainwater as the electrolyte, an aluminum bottom electrode coated with a dielectric (polydimethylsiloxane) and a top electrode fabricated in the form of a lattice. While the contact angle of water on polydimethylsiloxane has been measured and the bounce mechanism of water drops falling with varying velocities on the dielectric have been recorded, the voltage generated could not be measured or amplified due to limitations in the technology available. The paper discusses the rich future prospects, with potential improvements in the experiment design.

**Keywords:** Reverse Electrowetting, Contact Electrification, Electric Double Layers

## 1. Introduction

In a world where depleting fossil fuels and severe environmental degradation is a problem, there is an immediate need for the development of sustainable and renewable energy harvesting techniques. In sight of this, rainwater comes up as a prospective resource for research, having immense potential to serve not only as a renewable energy source, but also a ubiquitous one.

In recent decades, there has been much advancement in the field of energy harvesting from liquid droplets to power miniature devices. When dealing with small liquid droplets with increased surface to volume ratios, capillary forces dominate. Hence, controlling surfaces and surface energies becomes very important. In accordance with this, electrowetting is a method of controlling the apparent wettability of a liquid droplet by applying an external voltage. Electrocapillarity is the basis of electrowetting. Lipmann found that the capillary depression of mercury in contact with electrolyte solutions can be varied by applying a voltage between them. Thus, it may be inferred that an electric field changes the apparent surface tension of the droplet. However, the electrolytic decomposition of water upon direct voltage application to it forces the use of a thin insulating layer between the metal electrode and electrolyte, giving birth to 'electrowetting on dielectric' (EWOD) [1,2].

Stemming from this concept, reverse electrowetting on dielectric (REWOD) came up as a method a generating electrical energy for small scale and low frequency applications. The REWOD set up entails a top electrode (current collector), a bottom electrode coated with a thin dielectric layer, and an electrode placed between them - all connected to a circuit. A bias voltage is provided through the circuit, causing an electric double layer (EDL) to build up at the solid-liquid interface (of the electrolyte and bottom electrode). External mechanical modulations are provided to the droplet by changing the distance between the two electrodes. This repeatedly changes the area of contact between the electrode and droplet, and thus forces a redistribution of charges at the EDL. When their contact area is minimized, the amount of charge that can be sustained at the interface inevitably falls, causing them to flow out of the circuit. This way, REWOD generates an alternate current (AC) [3,4].

Besides REWOD, other promising technologies for droplet energy harvesting have been successfully developed. One of them is the triboelectric nanogenerator (TENG) developed by Wang's group in 2012 [5]. TENG works on the principles of contact electrification and electrostatic induction. When a liquid comes in contact with a solid, instant charge separation occurs, leaving oppositely charges surfaces. Charges flow through the interface until dynamic equilibrium is reached. The newly generated potential difference forces the flow of electrons through a circuit [6]. Similarly, the tribovoltaic effect is observed at the interface of water on a semiconductor surface. As a water drop slides on the semiconductor surface, a transfer of electrons occurs based on the type of semiconductor it is. This results in a direct current (DC) output [6,7,8]. Additionally, Xu and colleagues developed a transistor-inspired droplet-based energy generator based on the bulk effect. As droplets slide on a polytetrafluoroethylene (PTFE), droplet energy is converted to electrical energy and a closed loop electrical system for charge transfer is established [6,9]. Piezoelectricity is another invaluable scientific advancement which relies on the conversion of mechanical to electrical energy. It's based on the intrinsic polarization of a material and doesn't require any external voltage, magnetic field, etc. [6,10]. Looking from this perspective, one possible limitation to REWOD appears to be its need for a bias voltage, which compromises the idea of self-sufficiency. Numerous efforts have been made in response to this notion. Pashupati R. Adhikari et al. (2022) performed REWOD on rough surface electrodes in order to increase the surface area in contact with the droplet [3]. This increased the capacitance that could be created and mitigated the need for a bias voltage. Siddharth Raj Gupta et al. (2023) combined REWOD with electromagnetic induction to generate voltage, eliminating the need to source it externally [4].

This paper presents another method of performing REWOD, using rainwater as the electrolyte, and taking advantage of its kinetic energy and the triboelectric effect to eliminate the need for not only a bias voltage, but also any external mechanical modulation.

## 2. Materials and Methods

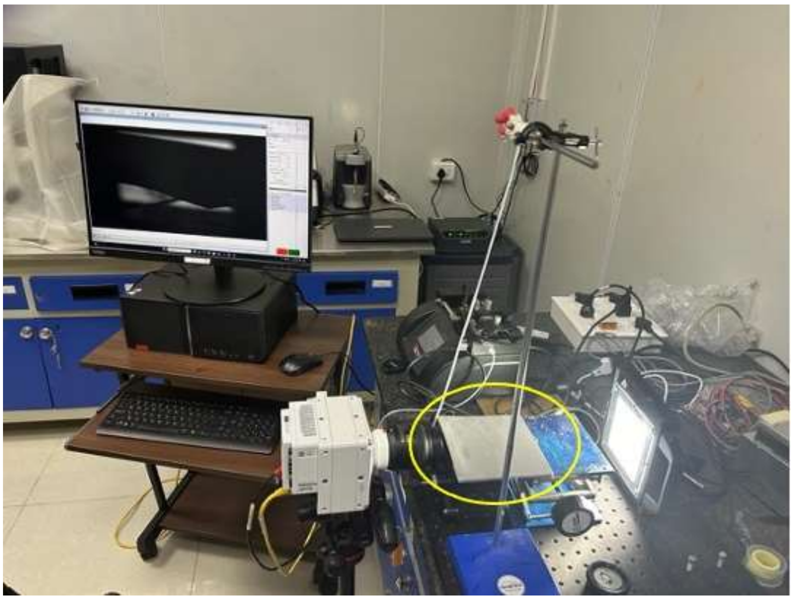
### 2.1. Materials

The main energy harvester consisted of a dielectric material polydimethylsiloxane (PDMS) sample of dimensions 14.5 cm X 14.5 cm, with thickness 2 mm; an aluminum plate of same surface dimensions but thickness of 1mm; and over 5 m of aluminum wire. PDMS was chosen as it is the second most tribo-negative of polymers and frequently used in generating triboelectricity (PET, PVC, PTFE, PVDF, etc.). It is second after PTFE, but still preferred over it as PDMS has greater dielectric and hydrophobic properties [11].

### 2.2. Equipment

A soldering machine was used for fabricating of the top electrode of the energy harvester, as it involves a certain arrangement of aluminum wires. For the testing of the energy harvester, a goniometer was used for measurement of contact angle of water on the PDMS sample. Also, a slow-motion camera, as shown in Figure 1, was used to record the bounce mechanism of the water droplet on the PDMS sample.

**Figure 1: Slow motion camera with PDMS Sample (shown with a yellow circle)**



### 2.3. Methods

#### 2.3.1. Fabrication of the Energy Harvester

The PDMS sample was securely attached to the aluminum plate. The aluminum wire was cut at intervals of 14.5 cm, 35 times; two pieces at opposite ends while the other 33 lie laterally with respect to them, and parallel to each other. This arrangement allowed for a gap of 4 mm between each wire piece, which is ideal to ensure their contact with raindrops which are 2-5 mm in diameter. The wire pieces were soldered at the ends in this position. 2 small extra wires were cut, one attached to one end of this 'lattice' and the other through the bottom end of the aluminum plate.

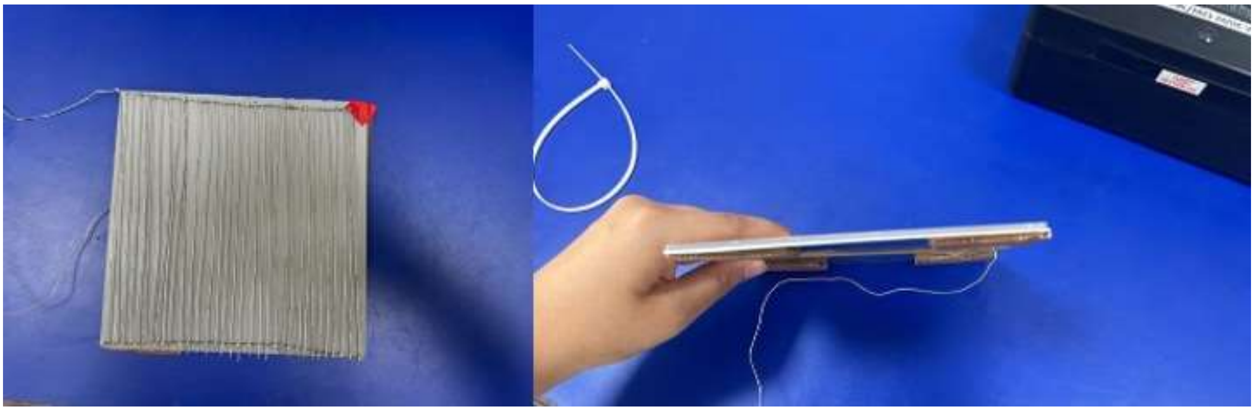
#### 2.3.2. Testing of Energy Harvester

The contact angle of water on the PDMS sample was measured using the goniometer. Subsequently, the bounce mechanism of the droplet hitting the sample was recorded using a slow-motion camera. The droplet was artificially released on the sample from different heights to see the dependance of initial contact area on impact speed of droplet. Later, the energy harvester was tested directly in the rain. For measurement of voltage and capacitance, a multimeter was used.

#### 2.3.3. Theory

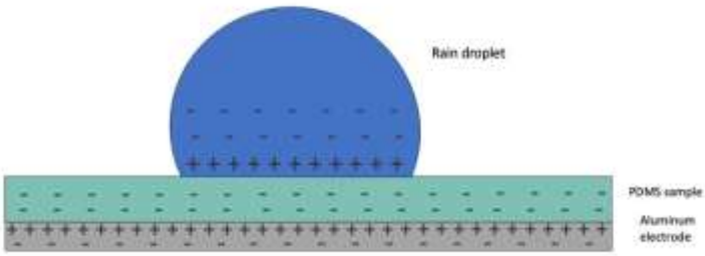
The set up shown in Figure 2 was built to mimic the REWOD set up. The aluminum plate acts as the bottom electrode, the aluminum wire lattice as the top electrode, and the water droplet as the electrolyte. When the water drop hits the PDMS, a positive charge is built up in the droplet, while a negative charge is generated in the PDMS due to contact electrification [12]. As the droplet comes in contact with a hydrophobic surface, its lack of wettability causes the droplet to minimize its area of contact, and we can say that the charge gets electrostatically induced.

**Figure 2: Set Up of Energy Harvester**



Despite being a universal process observed for over 2000 years, no concrete theory on contact electrification has yet been formulated. However, for solid-liquid contact electrification, the theory of electron cloud overlap is widely acclaimed. In this, the molecules of liquid have electron cloud overlap with atoms on the solid surface. Electron transfer is required to create the first layer of electrostatic charges on the solid surface. After this, ion transfer dominates as the electrostatic interactions with the solid surface cause a redistribution of ions in the electrolyte [12,13]. This forms an EDL; the closest layer is of compact absorbed ions is known as the stern layer, while the second layer with ions that are very mobile with loose binding to the surface is called the diffusion layer. Thus, an EDL is formed at the solid-liquid interface without utilizing a bias voltage.

**Figure 3: EDL Formation at Solid-Liquid Interface**




Contact area, which is a function of droplet volume and impact speed, was found to be the dominant controlling factor of charge separation [14], and consequently EDL formation. The impact speed clearly increases as the height from which a droplet is released.

The impact velocities may easily be calculated using formula (1)

$$v = \sqrt{2gh} \tag{1}$$

Where v is the impact velocity, g is the acceleration due to gravity, and h is the height from which the droplet is released. It is important to note that with such low heights, air resistance is negligible.

The terminal velocity of raindrops has been calculated using the relation (2)

$$W = F_D \quad (2)$$

Where W is the weight of the droplet, and $F_D$ is the drag force acting on it. Upthrust is negligible on a droplet. Thus,

$$mg = \frac{1}{2}\rho_0 v^2 C_D A \quad (3)$$

Where m is the mass of the droplet, g is acceleration due to gravity, $\rho_0$ is the density of the fluid (density of air is taken as 1,225kg/$m^3$), v is the terminal velocity of the droplet, $C_D$ is the drag coefficient (which is 0.47 for spheres), and A is the cross-sectional area of the droplet ($\pi r^2$). The droplet is assumed to a spherical due to its surface tension. Taking r=1.75mm to be the radius of the sphere (raindrops have diameter 2-5mm), and the mass as the product of volume and density ($\rho = 1000\text{kg}/m^3$) of droplet,

$$\frac{4}{3}\pi r^3 \rho g = \frac{1}{2}\rho_0 v^2 C_D (\pi r^2) \quad (4)$$

Substituting the known values, we find terminal velocity to be 8.912m/s.

After impact, the droplet tends to regain its spherical shape due to not only its inherent surface tension, but also the hydrophobicity of the PDMS sample. This is a crucial step as reducing the solid-liquid interfacial area is what forces the redistribution of charges at the EDL. So, measurement of the contact angle of water on PDMS is important.

Clearly, taking advantage of contact electrification, the kinetic energy of raindrops, and the hydrophobicity of PDMS, the need for a bias voltage and mechanical modulation has been eliminated. Besides this, the mechanism described for REWOD is followed. The capacitance must be generated at the solid-liquid interface. The maximum capacitance generated is given by the following equation

$$C = \frac{\varepsilon_0 k A}{d} \quad (5)$$

Where $\varepsilon_0$ is the vacuum permittivity, k is the dielectric constant of PDMS, A is the maximum contact area, and d is the thickness of the PDMS sample [4].

The contact of the positively charged droplets with the aluminum wire lattice will allow for the formation of a positive terminal, while the aluminum plate, in contact with negatively charged PDMS forms the negative terminal. However, it must be noted that rather than generating an AC current here, a variable DC output is expected.

## 3. Results and Discussion

The energy harvester, or more specifically the PDMS sample, was tested to ensure it satisfies the criteria to be utilized in the experiment. The contact angle of water on it as well as a droplet's bounce mechanism was recorded.

The contact angle of water was measured to be well above 90° as shown in Figure 4, so we can confirm the PDMS sample is hydrophobic.

**Figure 4: Image showing Contact Angle of Water on PDMS Sample Measured using Goniometer**

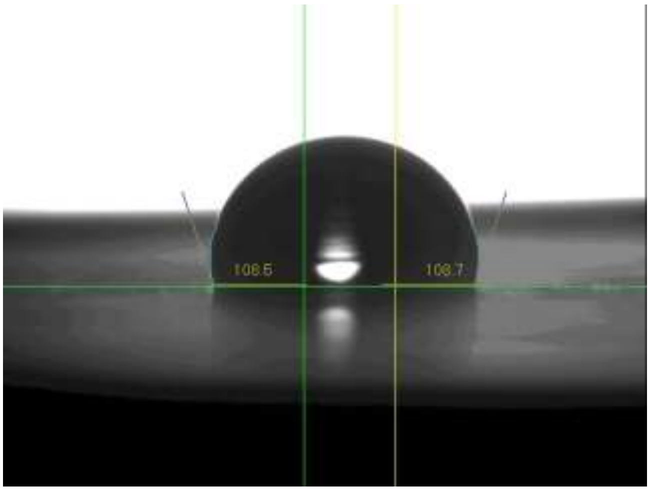
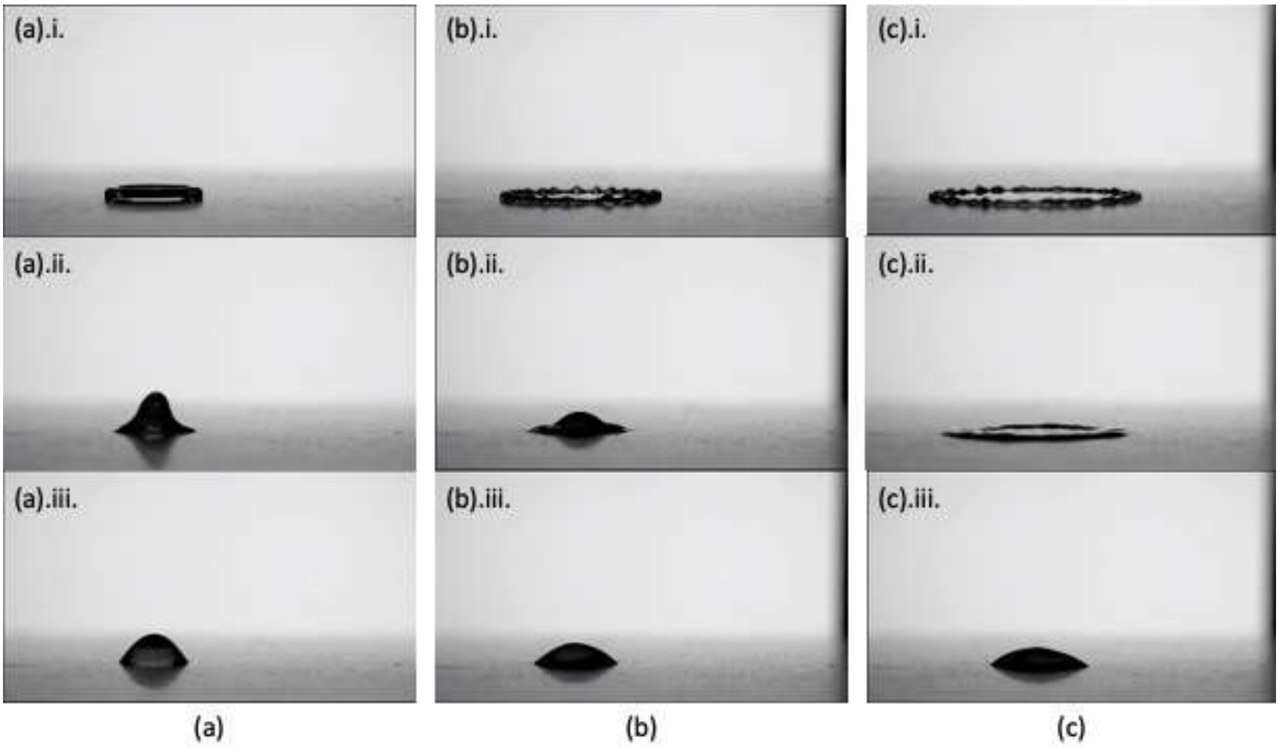



**Figure 5: Shape of Droplet upon Impact on PDMS Sample Captured at Different Points of Time when Released from Heights (a) 3.7cm, (b) 17.4cm, (c) 43.3cm**




The series of images in Figure 5 clearly demonstrates the bounce mechanism of water on the PDMS sample; how they initially lay flat by virtue of their kinetic energy and then tend to regain their spherical shape. It also depicts the dependence of maximum contact area between the droplet and PDMS on impact velocity. Using the above relation, the velocities for the cases depicted in Figure 5 (a), (b), (c) are calculated to be 0.85 m/s, 1.85 m/s, and 2.91 m/s respectively. Raindrops fall with terminal velocity 8.912 m/s, and will thus have much greater contact area than the above demonstrated cases.

Despite validating the experiment set up, definitive results could not be obtained due to technological constraints. It is believed that if a capacitance was generated at the interface, it was too small to be

accurately measured using a multimeter; more advanced technology would be required to make accurate measurements at the micro or even nano scale.
To increase the measure of the capacitance generated, future researchers may adopt some improvements in the experimental design. As seen from the formula of maximum capacitance generated, capacitance depends on the interfacial area and the thickness of dielectric. Increasing the cross-section of the energy harvester and decreasing the thickness of the dielectric (from 2 mm that was used to ideally 100 nm [3]) is expected to directly raise the capacitance of the system. Additionally, the PDMS sample may be made superhydrophobic to encourage a more radical shape change as water droplets regain their shape after falling on the surface. Bringing the contact angle of water on the sample to above 150° will cause greater charge redistribution at the EDL.
For testing the model in a controlled environment rather than directly in rain, the energy harvester can be tested in a vacuum tube by dropping a certain number of water droplets on it. The vacuum tube will need to be of sufficient height to as to mimic the terminal velocity of rain; it was found to be 2.27 m. Be sure to not use distilled water as that is not a conductor of electricity, unlike rainwater which can be ionized due to the salts it contains. This testing method provides the advantage getting accurate measurements of capacitance generated with known controlling factors such as the rate of droplets falling on the surface, or the droplet volume.

## 4. Conclusion

The experiment conducted has the potential to join the ranks of other renewable droplet energy harvesting systems. The work done was able to justify the use of PDMS as the dielectric, validate the bounce mechanism of the droplet falling on the PDMS sample, and showed the variance of contact area with impact velocity. The obvious limitation of this paper is the inability to measure the capacitance generated, which can't be measured without sophisticated technology. Some other possible points of improvements could be decreasing the thickness of the dielectric, using a superhydrophobic coating over the PDMS sample, and using a sample of larger surface area to maximize capacitance.

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