Original Article

Investigating Charge Dynamics and Performance Optimization through Multimaterial Quantum Interactions in Enhanced Triboelectric Nanogenerators

Akul Punj[1]

British School Jakarta[1]

Abstract: *With growing interest in decentralized energy solutions, improving the consistency and efficiency of TENGs have become a critical challenge. This research investigates the interplay between innate material characteristics and environmental conditions in determining the electrical performance of Triboelectric Nanogenerators (TENGs). This study focuses on three key independent variables: humidity, surface contact, and material selection, to explore their combined effect on output voltage, short circuit current and power output in TENG devices. The hypothesis proposes that specific material pairings, when used under controlled humidity and optimized contact conditions will result in superior and more stable energy output. In high humidity conditions the open circuit voltage was 42V, while for the low humidity conditions it was 56V. Similarly the short circuit current followed a similar pattern being 1.23* µA and 1.61 µA, respectively. *As a result, the power output was significantly greater under low humidity conditions, enhancing energy generation. Moreover, the open circuit voltage almost doubled to 99 volts from 50 volts as surface contact doubled, while the short circuit current perfectly doubled from 1.5 to 3 microamperes. This shows the difference in the triboelectric effect in different conditions and how output power can be maximised. Through systematic experimentation and data analysis, this research aims to uncover performance trends that can inform the design of high-efficiency TENGs. The broader objective is to contribute to the development of reliable, environmentally adaptive energy-harvesting technologies suitable for real-world applications.*

Keywords: *Triboelectric, Nanogenerators, Efficiency, Power, Energy*

Introduction:

A triboelectric nanogenerator (TENG) is a device that converts mechanical energy into electrical energy based on the triboelectric effect[1]. The triboelectric effect occurs when two different materials come into contact and then separate, leading to a transfer of charge/ electrons between the materials due to differences in their electron affinities. This leads to an electric potential difference between the two materials. The electrical charges accumulated on the materials create an electrostatic field. When the materials move relative to each other, this field changes, inducing an electric current that can be used for various applications. As the two materials rub, an equal and opposite charge is generated on both materials and hence, in complete contact state the total static field is zero. Some materials tend to gain or lose electrons quicker than other materials and can be more triboelectric than other materials. The triboelectric nature of materials can be determined by the polarity of different materials. These elements are ordered sequentially in the list known as the triboelectric series, where materials at the top of the chart tend to lose electrons quicker such as glass, mica and polyamide while materials at the bottom gain electrons quicker, these include elements such as Teflon, Polyethylene, Polypropylene etc (refer to figure 1). However, there are multiple factors that can alter and affect the triboelectric conductivity of different materials. Triboelectric conduction, the phenomenon of charge transfer between materials in contact or friction, is influenced by factors including the materials' intrinsic properties (electron affinity, electrical conductivity, dielectric constant), surface roughness, and environmental conditions [2]. The electrical conductivity and dielectric strength of the materials determine their ability to gain or lose electrons, while surface roughness affects the actual contact area and, consequently, the efficiency of charge transfer[3]. Environmental conditions such as humidity and temperature can alter the surface properties and the ionisation of air, impacting charge accumulation and dissipation. At elevated humidity levels, water vapor adsorbs onto surfaces, forming a conductive layer that promotes charge dissipation and reduces static charge buildup. Additionally, humid air enhances ionization and alters electrostatic interactions[4]. For instance, higher humidity can increase surface conductivity and reduce static charge buildup, while temperature changes can affect material properties and surface interactions. These environmental conditions, combined with the intrinsic properties of materials, play a crucial role in determining the behavior and efficiency of triboelectric conduction. To explore these influences further, multiple experiments were conducted to systematically examine how these factors interact and impact charge transfer processes, providing a deeper understanding of their roles in practical applications.

Materials and Methods:

2.1. Aim of the research**:** The objective of this research is to investigate the influence of factors on charge dynamics and efficiencies in TENG devices by observing changes in open circuit voltage *(V_{OC})* and *short circuit current (I_{SC}).*

2.2.Objectives :

Measure the *(V_{OC})* for the different conditions being experimented for such as humidity, contact area and triboelectric material

Measure the *(I_{SC})* for the different conditions being experimented for such as humidity, contact area and triboelectric material

Control as many external variables as possible by taking safety measures such as monitoring surface contact

Repeat readings at least 5 times and avoid anomalies results

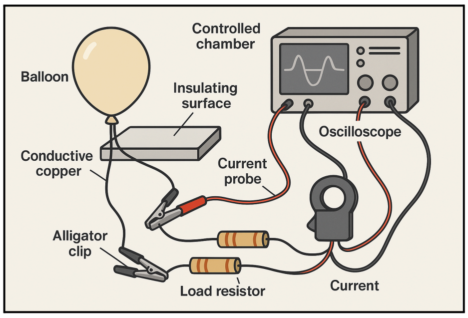
2.3. Materials :

- 2-3 Balloons (rubber as it is highly triboelectric)
- Conductive Copper Tape
- Wood (insulating surface)
- Oscilloscope (DS1052D)
- Current Probe (for *(I_{SC})* and power output calculations)
- Wires and alligator clips (5-10)
- Controlled chamber (humidity control)
- Load resistors
- Signal Generator

2.4. Method **:**

1. Place the balloon(s) inside a controlled chamber (to change the humidity)
2. Cut a piece of conductive copper tape and make it come in contact with the balloon
3. Place the copper tape on the wood(insulator) to prevent leakage of charge and any possible grounding
4. Place a wire in the controlled chamber and connect it to the load resistor From the copper tape sheet, an alligator clip is used to attach a wire that leads out of the chamber and connects to a load resistor
5. Take a second wire from the other end of the load resistor and connect it to a current probe,
6. Connect the current probe to the oscilloscope allowing for real-time visualization and analysis of the electrical signals generated during the experiment.
7. Use a signal generator to adjust the waves formed on the oscilloscope
8. Tap the balloon(s) at regular intervals and observe the changes detected on the oscilloscope.

*Note: A similar setup was used for 2 balloons



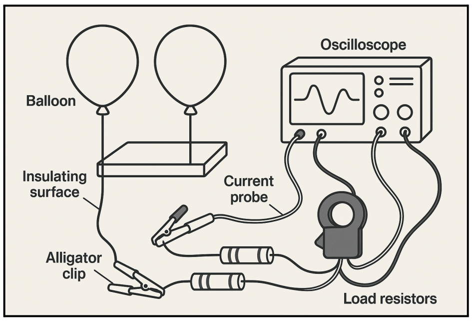


Figure. 1: Experimental Setup

3. Results and Discussion:

3.1 The triboelectric series

The triboelectric series ranks materials based on their tendency to gain or lose electrons during contact and separation. Materials at the top of the series, like glass, hair, or wool, lose electrons easily and become positively charged. Conversely, materials at the bottom, such as rubber, PVC, or Teflon, gain electrons and become negatively charged. The greater the distance between two materials in the series, the stronger the triboelectric charge generated. For example, rubbing a rubber balloon on hair transfers electrons from the hair to the balloon, making the balloon negatively charged and the hair positively charged. This occurs due to differences in electron affinity between the materials. Insulating materials, like rubber, tend to hold static charge longer, while conductive surfaces dissipate it more quickly. The triboelectric series helps explain phenomena like static electricity and has applications in energy harvesting and material design. It highlights how material properties influence charge transfer and retention. The figure below labels both ends of the series occupied by some types of polymeric substance, for example Nylon and PVC. Teflon is the most tribo-negative substance while Nylon is one of the most tribo-positive substances. As multiple different factors affect triboelectric objects, there is no fixed list and controlling so many variables is a particularly difficult task. However, multiple authors conclude the importance of relative permittivity over tribo-electric polarity. Baytekin et al in their work demonstrate that the most oxide dielectric materials like HfO_2, SiO_2, and Al_2O_3, as more tribo-positive than Nylon, where TiO_2 holds the position of being the most tribo-positive in the series [5]. Yet, it is strenuous to control factors like humidity, surface roughness, temperature, force/strain and other mechanical forms of the material being tested. This has been the major debate and the reason for ambiguity in the formation of a universal tribo-electric series.

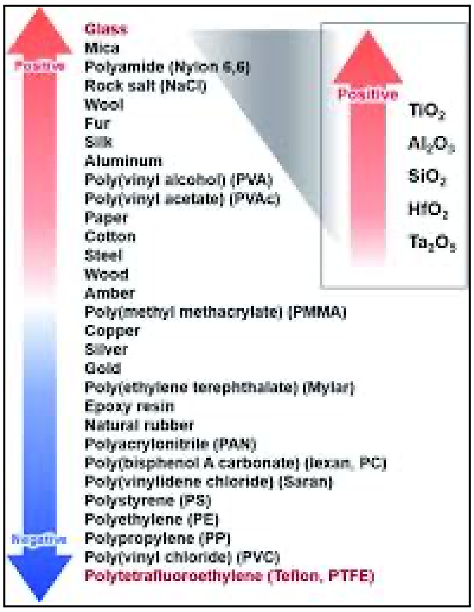


Figure. 2: Triboelectric series listing multiple materials in their electron affinity tendency adapted from work of Kim et al [6]

3.2 Effect of Humidity on Single-Electrode Triboelectric Nanogenerators

A wide range of rigorous experiments were conducted by me to investigate the various factors influencing triboelectricity, ensuring controlled and uniform interactions between materials to achieve reliable results. An investigation was carried out to check how humidity affects triboelectric charge using rubber balloons.

The hypothesis was that as humidity increases the triboelectric effect and simultaneously the open circuit voltage V_{OC} and short circuit current I_{SC} decreases as recorded by the oscilloscope when a single balloon is connected in the circuit. In high humidity conditions (65%RH) the V_{OC} value stabilised at 23V while the I_{SC} stabilised at 1.23 µA. Moreover, in low humidity conditions (35%RH) the V_{OC} value stabilised at 31V while the I_{SC} stabilised at 1.61µA .The experiment was repeated three times for all the time values and the averages were found. This data is observed due to the fact that higher humidity results in more water molecules on the surface, which act as conductive pathways. Moreover, higher humidity reduces surface charge retention by increasing leakage through adsorbed water molecules, lowering bothV_{OC} and I_{SC}. In contrast, low humidity limits water adsorption, allowing charges to build up more effectively. This enhances both voltage and current output, improving overall TENG performance.Consequently, internal resistance and power output vary significantly with humidity conditions.

Using the data above we can calculate the Internal Resistance and Power Output using the formula:

$$R_{Internal} = \frac{V_{OC}}{I_{SC}} \qquad\qquad P_{max} = \frac{V^2_{OC}}{4R_{int}}$$

Variables	High Humidity(65%RH)	Low Humidity (35%RH)
Internal Resistance (MΩ)	18.70	19.25
Power Output (μW)	7.07	12.48

Figure. 3 :Comparison between high and low humidity on Internal Resistance and Power Output

The internal resistance of the TENG was pretty comparable in high humidity and low humidity conditions. Both values were close to 19. However, power output increased notably from 7.07 μW at high humidity (65% RH) to 12.48 μW at low humidity (35% RH). This suggests that humidity had a significant impact on power performance.

However, in figure 12, when humidity was kept at constant at 50% RH we noticed that the power output and V_{OC} was much higher with 1 balloon single electrode than both the low and high humidity conditions. This concludes that as humidity increases till 50% RH the power output also increases, but at higher RH values the power output starts to decline, as evident by the results. This is because of the dual effect of humidity on triboelectric performance[7]. At lower humidity levels (e.g., 35% RH), there is limited surface moisture, which can reduce effective contact and limit charge generation. As humidity increases to a moderate level (around 50% RH), a small amount of surface water can actually enhance contact and charge transfer. However, beyond this point, at higher RH (like 65%), excess moisture begins to form a conductive film on the surface, causing charge leakage and reducing output. This hygroscopic effect increases surface conductivity by providing a pathway for charge carriers, thereby reducing the magnitude of static charge buildup. Moreover, the presence of water vapour enhances the ionisation of air, which can lead to increased charge dissipation and a decrease in the efficiency of charge transfer between materials. This results in a peak at intermediate humidity, with lower outputs on either side.

3.3 Effect Of Water On Static Charge

Water's effect	
Time (seconds)	Time the balloon stuck on average
10	0
20	0
30	0.5

Fig. 4: Effect of water on how long the balloon stuck on the wall

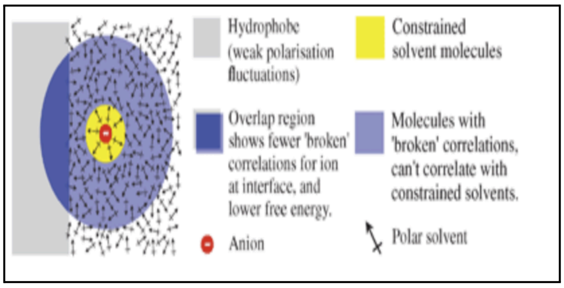


Fig. 5: Charge on waters surface [9]

Multiple repeat readings were taken when water was exposed to triboelectric objects and charged for the balloon. This was tested using wet hair and the rubbing duration between the hair and balloon was varied, between shorter time periods (10 seconds) and longer time periods (30 seconds). No significant difference was detected between the two time periods. The 0.5 seconds stick for the 30 second time, would be considered negligible due to reaction time and other inferences. These results are so because water impacts triboelectric charge by preventing charge buildup through several mechanisms. Water molecules absorb onto the surfaces of materials, forming a thin layer of moisture. This moisture increases surface conductivity, providing a pathway for charge carriers to dissipate, thereby reducing the accumulation of static charge. Additionally, water enhances the ionization of the surrounding air, creating more free ions that can neutralize static charges. The increased dielectric permittivity of humid air also weakens electrostatic interactions, reducing the efficiency of charge transfer between contacting materials. Together, these effects prevent significant triboelectric charge buildup in the presence of moisture.

3.4 No Incrementation period

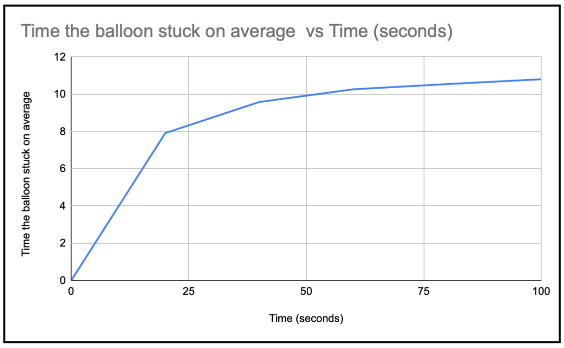


Fig. 6: The no incrementation period visualised for the rubber balloon

The first line graph informs us about how long we need to rub the balloon against our hair, till static electricity build up stops increasing. Based on the results the gradient of the graph dies down slowly until approximately 100-120 seconds when there is a 0-increment period. The observation that a rubber balloon reaches the no incrementation period for static charge after 120 seconds of rubbing can be attributed to several factors unique to the material properties of rubber and the experimental conditions. Rubber is an excellent insulator with high surface resistivity, which allows it to retain static charge effectively and resist dissipation into the surrounding air or through contact with other surfaces. During the initial 120 seconds, the continuous rubbing between the balloon and hair facilitates steady electron transfer due to the triboelectric effect, with the rubber balloon becoming negatively charged. However, as the balloon's surface becomes increasingly saturated with electrons, the electrostatic repulsion between like charges on the surface starts to resist further charge transfer. This repulsion eventually outweighs the driving force of the triboelectric interaction, slowing down and ultimately halting further accumulation of charge. The relatively long 120-second duration can also reflect a gradual charge leakage process, as the environment (e.g., low humidity, minimal conductive contact) is likely reducing dissipation rates. This time frame highlights the capacity of rubber to hold static charge for extended periods while reaching saturation more gradually compared to less insulating materials.

3.5 Oscilloscope Experiments regarding (V_{OC}) and (I_{SC}) for single electrode and contact mode

Various different triboelectric experiments were conducted using an oscilloscope and a conductive copper tape. This tape was used because it provides a highly conductive surface for transferring and collecting charges generated during contact and separation. It ensures minimal resistance in the electrical pathway, enabling accurate measurement of triboelectric effects. Additionally, its adhesive backing allows easy application to various materials. Through the oscilloscope experiments factors such as open circuit voltage, short circuit current and output power were measured in single-electrode TENG made up of the balloon.Two sets of experiments were conducted. The first focused on a single-electrode mode TENG using copper tape as the electrode. The second examined a contact-mode TENG, where a vertical tapping mechanism was used to induce contact and enable charge detection. Both methods were tested with two different surface areas: a larger setup using two balloons and a smaller one using a single balloon. By measuring (V_{OC}), the experiment determines the maximum voltage the device can produce under no load conditions, while the I_{SC} measurement captures the maximum current the device can generate under short circuit conditions. The balloon oscilloscope helps visualize and analyze these electrical characteristics over time, while the copper tape provides the necessary connections to complete the circuit and facilitate measurements. This experiment is crucial for evaluating the device's performance and efficiency under different conditions.

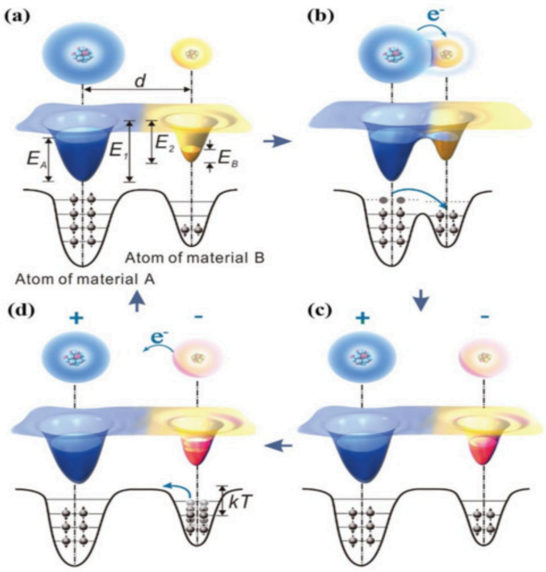


Fig.7: An electron cloud model for contact electrification between two materials (**a**) before contact, (**b**) in contact, (**c**) after contact, and (**d**) the charge release from the atom [10]

When one balloon was used and connected to the conductive copper tape, the peak V_{OC} was detected to be 50V when the balloon was in contact mode . When the balloon was in single electrode mode the V_{OC} dropped to 35V. Similarly, this was also observed for short circuit current (I_{SC}). When the balloon was in contact mode, the short circuit current peak was detected to be 1.5 μA which then dropped to 1.28 μA when the object was in single electrode mode due to the decrease in the charge transfer rate.

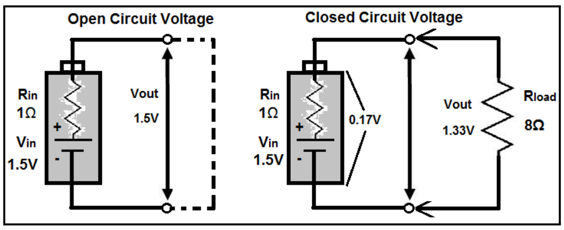


Fig. 8: Voltage behaviour in open and closed circuit conditions

The Open Circuit Voltage (V_{OC}) in a triboelectric nanogenerator (TENG) arises due to the combination of the triboelectric effect and electrostatic induction. When two materials with different electron affinities, such as a balloon and conductive copper tape, come into contact and then separate, electrons are transferred between them, creating a charge imbalance. This imbalance generates an electric field between the materials, inducing a potential difference across the connected electrodes. In an open circuit, where no current flows, this potential difference is measured as the (V_{oc}), representing the maximum voltage the system can achieve under the given conditions. The increase in Open Circuit Voltage (V_{oc}) when an object is rubbed in a triboelectric nanogenerator (TENG) is mainly the reason for enhanced charge transfer, improved surface contact, and stronger electric field generation between the TENG. The triboelectric effect causes electrons to transfer between materials based on their electron affinities, and touching increases the effective contact area and pressure, maximizing charge exchange. This action reduces microscopic air gaps and improves adhesion, leading to a higher surface charge density[11]. The stronger electric field generated by these charges results in a greater potential difference when the surfaces are separated. Additionally, the dynamic motion of touching and removing the object introduces polarization effects in the TENG devices that sustain higher charge densities. This mechanical input optimizes the interaction of material properties, such as dielectric constants. This ensures maximal charge separation and a transient peak in (V_{oc}) during the touch-and-release process as observed by the experiments conducted.

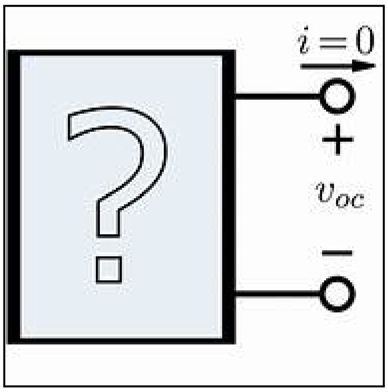


Fig. 9: open circuit voltage representation

The increase in Open Circuit Voltage (V_{oc}) from 35 V to 50 V when the object changes mode can be specifically linked to the triboelectric properties of rubber, such as that of the balloon. Rubber is highly electronegative and lies near the bottom of the triboelectric series, meaning it has a strong tendency to attract and retain electrons. When the balloon (rubber) is in contact mode against a material with a different position in the triboelectric series (e.g., copper tape, which is less electronegative), the mechanical action maximizes the charge transfer due to enhanced surface contact. This increased interaction allows rubber to capture more electrons during contact. Additionally, rubber's insulating nature prevents charge dissipation, ensuring that the charges generated remain localised on the surface for a longer duration. The dynamic motion of tapping and separating amplifies the charge transfer efficiency by creating a stronger initial electric field, which directly increases the (V_{OC}). The transition from 35 V to 50 V is a direct result of rubber's capacity to sustain high surface charge density when subjected to repeated contact and separation, as well as its ability to maintain the charges without significant loss to the environment.

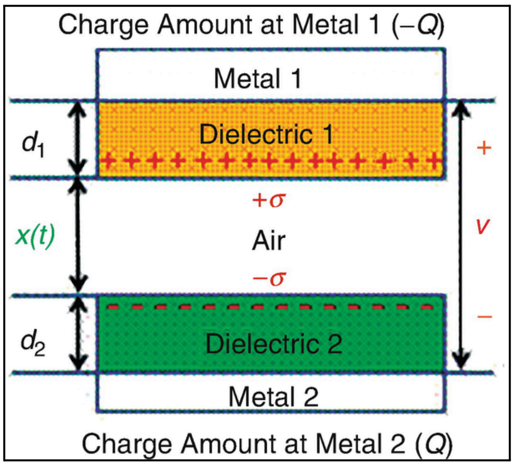


Figure. 10: Theoretical model of a contact-mode TENG [12]

The increase in Short Circuit Current (I_{SC}) when the object is in contact mode is primarily due to the enhanced mechanical interaction between the materials, which leads to more efficient charge transfer. When the object is touched, the triboelectric surfaces undergo a more significant deformation or compression, increasing the contact area and allowing a larger number of electrons to be transferred between the materials. This creates a greater charge imbalance. As the object is then removed or separated, the rapid change in the contact area and the sudden increase in separation distance causes a stronger electric field to form. This drives a higher current through the short circuit. The dynamic motion of touching and removing the object causes a faster charge separation, which in turn leads to a higher rate of current flow compared to a static or slow process.

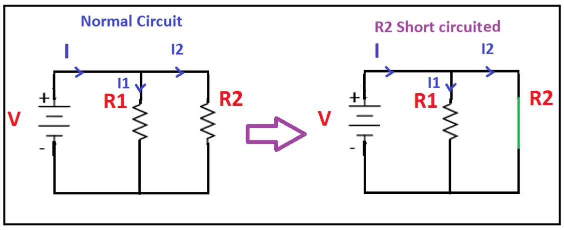


Fig.11: Current distribution in a parallel circuit before and after short circuiting R2

The increase in Short Circuit Current (I_{SC}) from 1.28 to 1.5 when the rubber is in contact mode can be explained by the enhanced charge transfer and electrostatic induction that occur during the mechanical deformation of the rubber. When the rubber is touched or pressed against another material (such as copper tape), the contact area increases, which allows for a more efficient transfer of electrons between the surfaces. Rubber, being an insulating material, has a tendency to accumulate charge on its surface when it interacts with other materials that have a different electron affinity, resulting in a larger charge imbalance. Rubber is an effective material for triboelectric nanogenerators (TENGs) due to its high elasticity, flexibility, and insulating properties. As a dielectric material, rubber can accumulate a significant charge when it comes into contact with materials of differing electron affinities, such as metals. Its ability to deform under mechanical stress increases the contact area, enhancing charge transfer efficiency. Rubber's flexibility allows it to undergo repeated mechanical deformation without degrading, ensuring consistent charge generation. These factors could have played a significant role in Rubber's effectiveness in an increase in short circuit current.

When two balloons were used in the experiment instead of 1, both the Short Circuit Current (I_{SC}) and Open Circuit Voltage (V_{OC}) approximately doubled due to the combined effect of charge generation and separation from both balloons. Each balloon generated its charge when rubbed or touched, and by using two balloons, the total amount of charge generated effectively doubled. This results in an increase in the charge imbalance between the two surfaces, which leads to a higher V_{OC} when the balloons are separated. Similarly, when the balloons are short-circuited, the increased charge transfer from both balloons creates a higher current flow, resulting in a doubled I_{SC}. The combined interaction of both balloons increases the overall surface area for charge generation, and the greater total charge enhances the electric field between the surfaces, amplifying both the voltage and current. Thus, using two balloons essentially adds the charge contributions from both, increasing the overall triboelectric effect. Similar observations are seen in other materials also.

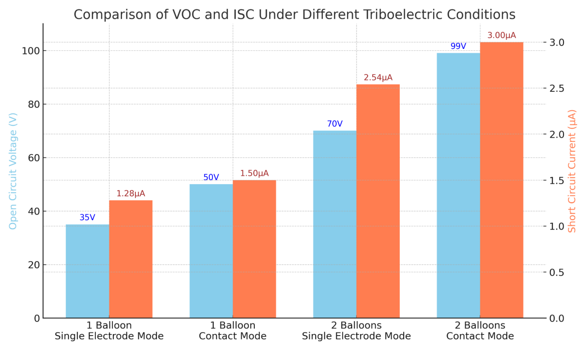


Fig.12: (VOC) and (ISC) changes visualised in different experimental setups

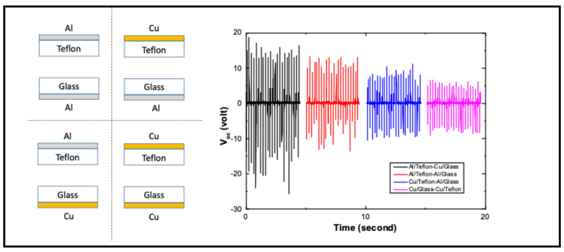


Fig.13: Combination of Al and Cu electrodes with teflon and glass as tribo- materials and their corresponding open circuit voltage, VOC [13]

3.6 Efficiency in TENG devices :

Open Circuit Voltage (V_{OC}) and Short Circuit Current (I_{SC}) as mentioned above are key parameters that directly influence the efficiency of triboelectric nanogenerators (TENGs). V_{OC} represents the maximum potential difference generated between two materials when no external load is connected, while I_{SC} refers to the maximum current flow when the circuit is closed. A higher V_{OC} means that more energy can be delivered per unit charge, allowing the TENG to effectively drive high-voltage applications or charge energy storage devices more efficiently[14]. On the other hand, A higher I_{SC} indicates a greater flow of charge per unit time, leading to an increased power output during operation. This is especially beneficial for applications requiring higher current, such as powering electronic loads or sensors. The power output of the TENG, given by P=V · I, depends on both voltage and current. An increase in V_{OC} or I_{SC} leads to a higher power output, provided the external load is optimized to match the internal impedance of the TENG. The efficiency of a TENG depends on optimizing both parameters, as a high V_{OC} enhances energy storage capability, and a strong I_{SC} improves the energy transfer rate to external loads. These factors are influenced by the material properties, surface area, and environmental conditions. For instance, maximizing the charge density and improving contact area can increase both V_{OC} and I_{SC}, enhancing the overall power output and energy conversion efficiency of the TENG. Thus, balancing and optimizing V_{OC} and I_{SC} are fundamental for achieving high-performance TENGs.

As the internal resistance is an inverse of short circuit current the higher the short circuit current the lower the internal resistance. The formula shows that the lower the internal resistance the more the power output and the higher the open circuit the more the power and thus the efficiency.

$$P_{max} = \frac{V^2_{OC}}{4R_{int}}$$

Variables	1 Balloon (single electrode)	1 Balloon (contact mode)	2 Balloons (single electrode)	2 Balloons (contact mode)
Internal Resistance (MΩ)	39.06	33.33	34.14	30.94
Power Output (μW)	16.00	18.75	71.63	79.20

Through this, it is evident that as the contact surface area increases the power increases while the internal resistance reduces. The contact mode generates a higher power output compared to the single electrode mode too.

3.7 Derivation of Energy produced in TENG devices (single electrode and contact mode) :

Energy in electrical systems and TENG devices can be found by :

$$E = \int_{T_0}^{T_1} V(t) \cdot I(t)dt$$

In TENG devices as the V_{OC} and I_{SC} do not remain constant as they follow a wavy pulse a realistic assumption would be that they follow a half sine waveform. Through this we can deduce the equation for the power output

$$P(t) = V_{Peak} \cdot I_{Peak} \cdot sin^2(\frac{\pi t}{T})$$

From this we can derive the energy equation to be :

$$E = \int_0^T P(t)dt = V_{Peak} \cdot I_{Peak} \cdot \int_0^T sin^2(\frac{\pi t}{T})dt$$

We can now assume a pulse duration of 0.1 seconds based on the typical time scale of one mechanical interaction in manually operated TENG setups. This assumption reflects realistic behavior observed in oscilloscope traces and standard practice in triboelectric energy research. This gives us

$$E = V_{Peak} \cdot I_{Peak} \cdot \int_0^{0.1} sin^2(\frac{\pi t}{0.1})dt$$

From this we can figure out that :

$$\int_0^T sin^2(\frac{\pi t}{T})dt = \frac{T}{2}$$

This gives the final energy formula which becomes :

$$E = V_{Peak} \cdot I_{Peak} \cdot \frac{T}{2}$$

TENG	Energy Produced (μj)
1 balloon single electrode mode	2.24
2 balloons single electrode mode	8.89
1 balloon contact mode	4.51
2 balloons contact mode	14.85

Through this we can see that energy produced increases with a higher contact area while simultaneously a contact mode produces more energy than a single electrode mode. As mentioned earlier this is because energy output increases with larger contact area due to improved charge transfer efficiency. Contact mode outperforms single electrode mode, as the direct mechanical interaction generates stronger triboelectric signals.

4. Conclusion:

Many factors affect triboelectricity, research in this field is still growing and new discoveries and findings are still coming out. Many factors such as the material of the TENG, humidity, contact time etc affect triboelectricity significantly as observed both through basic experiments and through electron transfer observed by the oscilloscope in TENG devices when charge is created. These variables influence the efficiency and performance of TENGs, making it essential to understand the precise mechanisms behind charge generation and transfer. Furthermore, the interplay between material properties, such as electron affinity, flexibility, and surface roughness, along with external conditions, requires more thorough investigation to optimize TENG design for practical applications. Moreover, the triboelectric series helps us understand the tribo-negative and tribo-positive materials and the effects they have on charge transfer.

Through these external conditions efficiency and energy production can be maximised for maximum output production.

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