Hygroelectric Energy Generation

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***Abstract*—This paper presents the design and development of a Hygroelectric Nanogenerator based on the principles of Triboelectric Nano Generation (TENG) used for harvesting energy through interaction of water and triboelectric metal layers. The system employs Teflon (PTFE) and aluminum or copper as the triboelectric layers, chosen for their ability to effectively transfer charge through contact and separation. To enhance output, saw-shaped electrodes are patterned on the surface, with copper wires connected to a multimeter to record voltage generation. When water droplets or streams of water fall on the layered structure, a voltage is induced due to the triboelectric effect, confirming the generation of usable electrical energy. The paper also involves integration of AI through an integrated, trained and tested AI and IOT system to predict the total energy that can be generated on the basis of various conditions and also calculate the total energy generated. All the results are predicted on the basis of original experimentations.This prototype is a demonstration of clean,hydro-based microenergy generation using optimal and economically sourced materials and an efficient setup. The prototype can be potentially scaled to develop scalable, off-grid power sources in humid and rain-fed environments.**

Index Terms — Hygroelectricity, Moisture-based energy, Triboelectric effect, Triboelectric Nanogenerator (TENG), AI integration

I. Introduction

With the immediate rise in demand for sustainable and decentralised energy sources, the scope of innovation in the field of green energy has increased significantly. One of the scientifically led innovative practices this prototype involves is the usage of Triboelectric Nanogenerators which converts mechanical energy i.e energy arising from motion ,pressure,vibration and other physical interactions into usable electrical energy through the principle of contact electrification and electrostatic induction. Among the various adaptations and trials of the TENGs, the Hygroelectric variant taps into and does the efficient conversion of environmental moisture and water droplets into micro-electricity to power small appliances. This presents a clean and economical solution for energy generation in humid or rain-fed climate facing areas all-year around. The core concept of the paper is structured around utilising the water-induced motion on triboelectric materials to produce electric output. Materials such as Teflon-PTFE is known to be highly electronegative and metals such as Aluminium or Copper which lie on the positive end of the triboelectric series are chosen for this prototype.These are layered and enhanced by placing saw-shaped electrodes in between the layers to increase surface area and improve the contact enhancing the charge transfer efficiency. As the water droplets fall or slide across the surface of the TENG,charges are transferred and a potential difference is developed. The voltage is captured through copper wires connected through copper wires connected to a multimeter, demonstrating energy generation.

This paper aims to address limitations of the conventional renewable energy sources—such as poor performance in rainy or overcast conditions—by proposing a low-cost, small-scale Hygroelectric TENG system. Such systems have a potential applications in self-powered sensors, remote monitoring, and IoT devices, particularly in environments where moisture is consistently present. This technology can be employed in mountainous regions such as the Himalayas from where flowing water bodies such as rivers originate and give energy to the habitants and the defence personnel living in such remote areas.

By using different material combinations, electrode designs and flow conditions present in the market and the materials we use culminate and lead an innovative step towards reliable, micro scalable energy generation. The paper also proposes a web app that displays the results which were predicted and calculated by a trained and tested AI model. The module has an accuracy rate of about 87%.

II. LITERATURE REVIEW

A. *Material Systems and Triboelectric Performance*

The Li et al. paper provided us a good understanding about which materials to be select based on its electrostatic behavior. The paper's framework categorized substances by gradients of electron affinity revealing a key understanding that device performance comes from pairing of materials with their maximal difference in their electron transfer..

B. *Waste Stream Utilization and Sustainability*

Dos Santos Kremerl et al. showed an alternative way for fabrication by using industrial byproducts. This paper was significant as it challenged the idea that only perfect, lab-graded materials are necessary. The paper also showed that recycled iron based compounds could also generate measurable electricity. This also showed we can reduce cost and benefit the environment along.

C. *Integrated Energy Harvesting Architectures*

Ren et al. paper showed that if two or more energy sources could work together in conjunction with each other, we could get a better and stable total power generated than if only one source was used. This concept guided us how to do scalability and practically deploy in the real world.

D. *Geographically-Specific Implementation Considerations*

Dana et al. paper showed different case studies that were from tropical areas, humid places, by not just providing theory but also showing practical insights of real world issues in the living and growing environment. This practical scenario gave us a clear view of how laboratory conditions cannot be directly transferred to the environment.

E. *Physical Mechanisms and Stress-Induced Electrical Effects*

Mizzi & Marks article proposed that electrical effects may occur due to any mechanical deformation. Also their study showed that charge generation can occur not just due to difference means like microstructural bending and flexing. Using this framework, we made a device by applying simplistic friction models to complex descriptions of mechanical- electrical interactions.

F. *Quantum-Level Perspectives on Charge Dynamics*

Olson et al. examined theories of how an electron might transfer its energy from one location to another. There were very complicated mathematical equations but as it was built upon a theoretical base which involved well known principles of Physics.

G. *Performance Benchmarking and Achievement Targets*

Huang et al. paper states that devices they have developed meet or exceed the voltage target set by them, which ranges from 1 Volt to greater than that. In the initial experiments we also had produced low voltage, so it was seen as an opportunity for improvement or enhancement rather than failure.

H. *Verification Through Independent Experimental Confirmation*

In 2022 during Physics Publications, there was independent confirmation from many research groups about the models of Flexo-Electricity- Triboelectricity Interactions. This increased confidence in validity of scientific principles, as a collective influence of results derived and combined from various independent laboratory experiments.

I. *RESEARCH GAP*

1. Production Technology

   The present triboelectric nanogenerator production is primarily dependent on laboratory-scale ,costly fabrication methods,thus large scale manufacturing becomes challenging.

2. Availability of Materials

   Numerous studies use rare or ultra-pure materials,limiting practicality and challenging a low cost deployment in real-world environments.

3. Limited Real-World Testing

   Most of the current research displays short-term results.There is a dearth of thorough information on environmental resilience and long-term durability.

4. Insufficient Integration

   AI, continuous monitoring, and adaptive controls—all essential for effective, real-world operation—are rarely included in papers.

5. Lack of Focus on Deployment

   References to "remote application" frequently do not identify particular locations, use cases, or user requirements.

6. Simple Experimental Models

   Many experiments focus on individual factors, overlooking the primary and concurrent environmental changes that influence performance.

7. Incomplete Energy Management and Generation

   Demonstrations of voltage generation rarely touch topics such as power conditioning, energy storage, or real-world energy utilization scenarios.

III. PROBLEM DEFINITION

The highly increasing demand of energy across the globe has been recognised by the IEA-International Energy Agency has reached unprecedented levels with the highest surge in 2024, a surge double the recent average recorded in the last few years. The escalation is driven by many factors such as industrial expansion,increased electrification and usage of energy intensive technologies. Traditional energy sources although efficient,have significant limitations.For example, commonly known renewable hydroelectric power generation is geographically constrained to areas near dams or large water bodies or any area having good access to flowing water and the transmission of electricity from these centralised areas to distant users result in huge and significant energy losses. Secondly, Solar Energy though more flexible in terms of installation and intermittent- is restricted to daylight hours and subject to weather variations. Hence needs additional infrastructure for storage and grid integration.These challenges highlight the importance of locality in energy generation.The ability to produce energy close to the point of consumption reduces transmission losses,enhances grid resilience and energy security.

Here hygroelectricity emerges as a solution to these issues. Unlike hydroelectric and solar systems, these generators operate continuously harnessing the abundantly present atmospheric humidity regardless of time of day or geographic factors. This capability shown by TENG enables distributed local energy harvesting in wide range of areas from dense urban populated areas to remote rural areas. The potential for all around the clock and all-weather adaptable operable technology positions Hygroelectricity as a adaptable and sustainable energy source.

Despite its potential, the practical implementation of hygroelectric energy harvesting faces many technical challenges such as optimising the contact electrification between water droplets and metal surfaces, then building prototypes which can withstand the impact of falling rain and ensuring correct and efficient conversion of mechanical to electrical energy under different environment conditions. Addressing these challenges is important to convert and build Hygroelectricity from a laboratory concept to a scalable solution for addressing global energy needs.

The paper is structured and designed kept in mind to develop and optimise hydroelectric generators that can efficiently convert water and moisture into usable electrical energy. The work is aimed to bridge the gap between theoretical laboratory potential of this concept into practical application to generate micro energy and broadening this to build decentralised and sustainable energy generation systems.

A. Triboelectric effect

Triboelectric effect is the effect where materials become electrically charged on contact with each other's surface and then distanced. The charge transfer is primarily governed by the material's position on the tribolelectric series. When a material with tendency to lose electrons i.e. metals such as aluminium or copper comes in contact with a material with tendency to gain electrons e.g PTFE, the electrons are transferred from one another resulting in one material being high positively charged and other negative charged.

The amount of charge (Q) transferred can be equated to the capacitance (C) and the potential difference (V) as:

$$Q=C \times V \tag{1}$$

where:

- Q = charge transferred (Coulombs)
- C = capacitance between the materials (Farads)
- V = potential difference generated (Volts)

B. Triboelectric Nanogenerator (TENG)

A Triboelectric Nanogenerator (TENG) is a device that converts mechanical energy into electrical energy using triboelectric effect and electrostatic induction. TENGs has two layers of materials with difference in triboelectric affinities,they are brought into contact and then separated, generating voltage.

The output voltage in terms of displacement is given by:

$$V(x)=C(x)/Q \tag{2}$$

where:

- $V(x)$ = output voltage (Volts)
- Q = transferred charge (Coulombs)
- $C(x)$ = capacitance as a function of distance (Farads)

The capacitance for parallel plate capacitor is given by:

$$C= \varepsilon 0 \varepsilon r A/d \tag{4}$$

where:

- $\varepsilon 0$= vacuum permittivity
- εr= relative permittivity of the dielectric
- A = area of overlap (m2)
- d = separation distance (m)designations.

C. Hygroelectricity

Hygroelectricity stands for generating energy from atmospheric humidity or water droplets. In the process, water molecules interact with the layered surfaces,come in contact with the saw shaped electrode producing electric charge and continuous voltage output. The mechanism enables energy production in places where humidity is abundantly available irrespective of sunlight exposure or specific geographic features

D. Contact Electrification

Contact Electrification is the process where electrical charges are transferred from one material to another when they come in contact with each other and then separated. This is the primary mechanism behind triboelectric effect and is key to the operation of TENG. The efficiency of charge transfer depends on material properties, roughness and environmental conditions.

E. Amplification and Measurement

The voltages generated by TENG is low and needs amplification to give practical output and results. A non inverting op-amp is used here with Gain (G) given by:

$$G=1+Rf/Rin \tag{5}$$

where:

- Rf = feedback resistance (Ohms)
- Rin = input resistance (Ohms)

This voltage can then be measured using microcontrollers.

IV. APPROACH AND METHODOLOGY

The methodology for this paper is a blend of theoretical laboratory understanding and practical implementation. I t aims to maximise efficiency and output of TENG. The process firstly begins with a detailed study of triboelectric effect in metals and electrostatic induction which gave a clear understanding of the materials to use and the overall device architecture. PTFE is chosen for strong electron accepting tendency while copper and aluminium is selected as their electropositive counterparts,based on their place in the triboelectric series. The design emphasized on the use of saw shaped electrodes using copper tape, patterned to increase charge collection and ensure efficient charge transfer during water droplet impact.

A key learning was that material selection and the designing of the device is closely linked to one another, as the striking difference between PTFE and chosen metal is important for maximising output. The prototype is coated to ensure zero weathering and corrosion, especially given the exposure to water and varying atmospheric conditions. The prototype design involves stacking layers of PTFE and metal with care taken to minimise resistance loss and maintain consistent electrical contact across the active area

Circuit integration with an op-amp 741 IC is configured as a non-inverting amplifier to increase the low level output voltage generated by the nanogenerator. The circuit is constructed on a breadboard using resistors and 9V cells. The amplified signal is routed to Arduino Uno microcontroller. This lets us monitor real time data of voltage and head of water or humidity monitored by DHT 11 sensor. The Arduino continuously acquires data and visualises it allowing for feedback and optimisation

Using a PVC pipe framework which has evenly spaced pores was constructed so that a natural rainfall and controlled experimental environment is made. So, with the help of this water droplets of same size and velocity was obtained which was then put onto TENG surface. And during this time DHT11 sensor was monitoring ambient humidity and temperature. Voltage measurements was taken multimeter. In that all the data was analysed and fed through Arduino IDE and MATLAB. This was a dual platform approach which gave a detailed visualization of trends and some relationships between key parameters such as output voltage, inclination angle and head of water.

Optimisation is a key process where it involves variation of inclination angle and head of water to identify the optimum condition where maximum electrical output was obtained. Real time data has been collected and the analysis of this dataset gave a clear guideline on the adjustments to the prototype design. The framework involves the study of triboelectric effect,electrostatic induction and models such as capacitor discharge equation and the output power relation.

$$Q=C(t) \times V(t) \tag{6}$$

$$P=V2/R \tag{7}$$

where V denotes the measured output voltage across the load and R represents the load resistance. This expression provided a direct and reliable means to interpret the experimental results and to assess the electrical performance of the device under varying conditions.

Material selection was carried out with careful consideration of both triboelectric behavior and mechanical compatibility.Copper tape and PTFE sheets were chosen as the primary materials owing to their well-established positions in the triboelectric series and their ease of fabrication. In addition, aluminium–PTFE configurations were also developed to enable comparative performance analysis. A3-sized sheets were used for all prototypes in order to increase the effective contact area and improve charge generation. The experimental setup incorporated adjustable mechanical supports, allowing precise control of the inclination angle during testing.

The electrical circuitry and embedded Arduino program were developed and refined through multiple iterations based on experimental observations. Each prototype was initially tested as an individual unit and subsequently combined with other units. Series interconnections were employed to enhance the overall voltage output of the system. Controlled experiments were conducted to study the influence of key operating parameters, and the resulting data were processed and visualized using MATLAB to identify trends and optimal operating regions.

To enable comprehensive system monitoring, the setup was integrated with an Arduino microcontroller and DHT11 sensors, allowing simultaneous measurement of output voltage and ambient humidity levels. This integration facilitated a better understanding of environmental effects on device performance and supported further optimization of the system. Overall, the adopted methodology ensured a systematic, repeatable, and reliable approach to the development and optimization of the Hygroelectric TENG for efficient moisture-based energy harvesting.

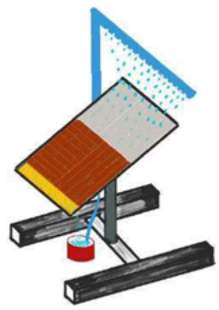

Fig 1: Sketch of the prototype developed

V. RESULTS AND DISCUSSION

In optimal conditions, we observed the highest output voltage which was about 0.25V from the Copper- PTFE Prototype.

Depending on environment and geometrical properties like head of water or inclination angles Aluminium- PTFE Prototype's output Voltage varied from 0.1V to 0.7V.

Also, it was found that at an inclination angle of 5° maximum Voltage can be produced.

At a height of 50 cm, the peak voltage of head of water was achieved.

If multiple Copper- PTFE Prototype and Aluminium-PTFE Prototype are connected together in series in order to achieve total output voltage that can be in hundreds of millivolts.

Utilizing non- inverting op-amp (gain of 10) allowed better measurement of low-level TENG signals. Then including an op-amp with Arduino and DHT11 sensor enabled real time tracking of voltage readings and humidity levels.

These results showed that Hygroelectricity TENG prototype design was able to convert kinetic energy produced by water into electrical energy, by using efficient prototype depending on their geometric and environmental conditions. The Copper- PTFE prototype had produced a stable range of output voltage, while the Aluminium- PTFE prototype produced output voltage which were wider and more extensive in range as it has higher level of electropositivity compared to Copper and gives better outcome when there is any variation in parameters like inclination angle and head of water.

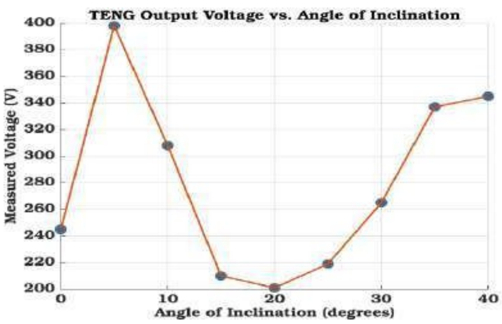

Fig 2. TENG Output Voltage vs. Angle of Inclination

A notable finding is the deviation from the typical bell-shaped trend reported in literature for inclination angle optimization. In this study, the maximum voltage was observed at a very low angle (5°), likely due to the direct positioning of the water source above the aluminium sheets, which increased droplet contact time and charge transfer. So, at high angles when the water droplet falls and slides very rapidly it results in reducing the interaction time and the output voltage. This shows that the angle of water and its delivery geometry is very important.

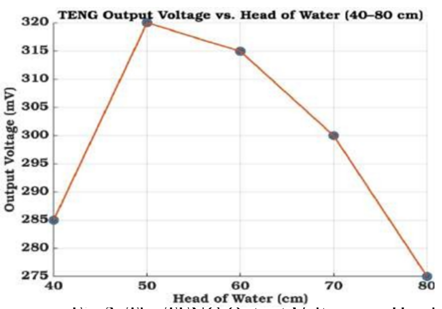

Fig 3. The TENG Output Voltage vs. Head of Water (40-80 cm)

Parameters like head of water (vertical distance) increased the voltage output by about 50cm due to higher droplet impact velocity.There was a was an appreciable rise and fall as the partition of the droplet and dispersion decreased the efficiency.This trend is consistent with previously established findings regarding droplet-driven TENGs, in which an optimal impact velocity enhances energy conversion until droplet instability starts to have a negative effect. Moreover,adding the circuitries in series produced great outputs .Monitoring the parameters with real time analysis through integration of Arduino improved optimization. The observed correlation between higher humidity and increased voltage output supports the potential of Hygroelectric TENGs for continuous, local energy harvesting in moisture-rich environments.

Fig 4. TENG's

Overall, these results demonstrate the viability of Hygroelectric TENGs as a clean, scalable, and locally adaptable energy solution, with practical performance strongly influenced by device geometry, water delivery, and environmental conditions. Not only that it is clean and sustainable also.

We have made two trained and Tested AI models. One is Linear Regression Model and other is Random Forest Regression Model. After taking real time data it calculates its average and predicts how much energy can be generated further on the basis of pervious data.

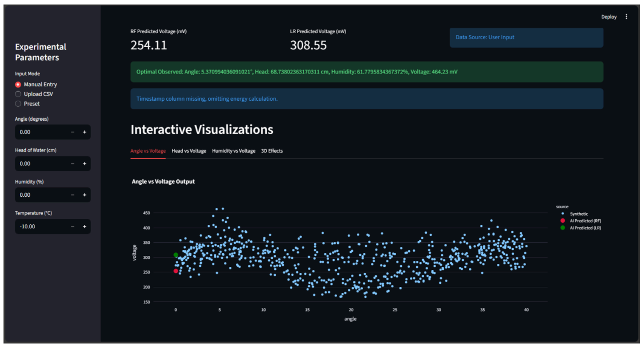

Fig 5. Dashboard showing Final results

Also, we have a detailed table showing different parameters that effect the output.

Table 1- Comparison of materials

Parameter	Aluminum	Copper
Durability	Moderate resistance to corrosion, forms oxide layer,lightweight and strong	Higher corrosion resistance, heavier and less flexible
Cost	Affordable and easily available, and cost-effective	More expensive due to material and processing
Electrical Conductivity	Good conductor with increased	Excellent conductor; stable

	electropositivity characteristic and it increases charge transfer	and accurate electrical output
Mechanical Properties	Lightweight, flexible, easy to shape it or form	Rigid and more prone to fatigue; less flexible, tear when foil
Advantages in TENG Use	High voltage due to electropositivity; lightweight and easy to handle	Stable and durable performance; ideal for lasting electrodes
Disadvantages	Oxidizes without protective coatings, reducing conductivity	Heavier; costly; foils can tear or deform under mechanical stress
Surface Treatments	Anti oxidation coating like thin oxide layer, polymer coating.	Using layers like graphene or polymers.
Life Span	Upto 1 year	1-2 years
Surface area	If the surface area is increased the voltage increases by 100-400 percent of normal voltage.	
High Pressure	Material like CNT doped PET, thick di-electric polymers can be placed in between the plates.	

Table 2- Comparison between conventional and Triboelectric Nanogenerator

Parameter	Conventional Energy	Triboelectric Nanogenerator (TENG)
Cost	High due to infrastructure, continuous fuel purchase, and maintenance expenses.	Significantly lower by using affordable materials (PTFE, aluminum, copper), simple assembly; estimated ₹200–₹500 per device
Cost per Volt Output	Expensive as centralized generation involves fuel and distribution losses.	Approx. ₹1–₹5 per volt, competitive especially for small to medium scale production.
Scalability	Limited by geographic and resource availability; requires large infrastructure build.	Modular design enables flexible expansion; roll-to-roll embossing or textile-based production can mass-produce components efficiently.

VI. CONCLUSION

TENGs are useful in harvesting energy from water .When water molecules interact with the surface of the metal,there is contact electrification between the water droplet and the metallic surface.This energy forms the basis of TENG electricity.For,this an electron accepting layer of PTFE and an electropositive layer of copper or aluminium is used.The results portray a measurable voltage under predefined rainfall and temperature in various conditions.

Key findings are:

- Efficiency : Significantly high output voltages were found by using copper-PTFE and aluminium-PTFE.The electro positivity of aluminium is greater compared to other metals which provides a broad and also high voltage range while using aluminium devices in the experiments and simulations.
- Sensitivity: Environmental factors such as high rainfall,temperature conditions affect the output highly .It was also seen that geometric parameters like low inclination angle and head of water portrayed improved outputs.
- Integration and scalability: The total output was further amplified by a series connection of the individual devices. Secondly,integration of Arduino and humidity sensors enabled better monitoring and real time analysis.
- Environmental adaptation: The various results observed under different rainfall and temperature conditions ensure its low cost and high effectiveness in diverse conditions.

The analysis validates that Hygroelectric TENGs provide clean,localized,and scalable energy production and are found most efficient in moisture -rich environments.
The identified trends and performance indicators are consistent with the latest developments in the sector, and the approach offers a solid foundation for additional optimization and practical implementation.
Future research will primarily focus on improving the stability under fluctuations in environmental conditions and large scale applications as off-grid energy solutions.

VII. APPENDIX

A. Detailed Calculation

1. Output Power Calculation
   The output power of the TENG can be calculated using:

$$P=V2/R \tag{9}$$
$$P=R/V2 \tag{10}$$

where:

- V = output voltage measured
- R = load resistance (Ω)

2. Capacitance and Charge Transfer

The TENG is a capacitor based on time-varying factors.

$$Q=C(t) \times V(t) \quad (11)$$

where:

- Q = charge (C)
- C(t) = capacitance as function of time (F)
- V(t) = voltage as function of time (V)

Capacitance for parallel plate geometry:

$$C=\varepsilon 0 \varepsilon r A/d \quad (12)$$

where:

- ε0 = vacuum permittivity
- εr = relative permittivity of dielectric
- A = area of overlap (m22)
- d = separation distance (m)

3. Amplifier Gain

For the non-inverting op-amp circuit:

$$G=1+Rin/Rf \quad (13)$$

where:

- G = voltage gain
- Rf = feedback resistor (Ω)
- Rin = input resistor (Ω)

B. Raw Experiment Data

Table 3- Inclination Angle vs. Output Voltage

Inclination Angle (°)	***Output Voltage (mV)***
0	*245*
5	*398*
10	*308*
15	*210*
20	*201*
25	*219*
30	*265*
35	*337*
40	*345*

Table 4- Head of Water vs. Output Voltage

Head of Water (cm)	***Output Voltage (mV)***
40	*285*
50	*320*
60	*315*
70	*300*
80	*275*

C. MathLab Code for Data Voltage

1. Inclination Angle vs. Voltage

```
angle = [0, 5, 10, 15, 20, 25, 30, 35, 40];
voltage = [245, 398, 308, 210, 201, 219, 265, 337, 345];
figure;
scatter(angle, voltage, 80, filled'); hold on;
plot(angle, voltage, '-o', 'LineWidth', 1.5);
set(gca, 'FontName', 'Bookman Old Style', 'FontSize', 12);
xlabel('Angle of Inclination (degrees)', 'FontName', 'Bookman Old Style', 'FontSize', 12);
ylabel('Measured Voltage (mV)', 'FontName', 'Bookman Old Style', 'FontSize', 12);
title('TENG Output Voltage vs. Angle of Inclination', 'FontName', 'Bookman Old Style', 'FontSize', 12);
grid on;
```

2. Head of Water vs. Voltage

```
height = [40, 50, 60, 70, 80];
voltage = [285, 320, 315, 300, 275];
figure;
scatter(height, voltage, 80, 'filled'); hold on;
plot(height, voltage, '-o', 'LineWidth', 1.5);
set(gca, 'FontName', 'Bookman Old Style', 'FontSize', 12);
xlabel('Head of Water (cm)', 'FontName', 'Bookman Old Style', 'FontSize', 12);
ylabel('Output Voltage (mV)', 'FontName', 'Bookman Old Style', 'FontSize', 12);
title('TENG Output Voltage vs. Head of Water', 'FontName', 'Bookman Old Style', 'FontSize', 12);
grid on;
```

3. Combined 3D Scatter Plot

```
angle = [0, 5, 10, 15, 20, 25, 30, 35, 40];
height = [50, 50, 50, 50, 50, 50, 50, 50, 50]; % Example: all at 50 cm
voltage = [245, 398, 308, 210, 201, 219, 265, 337, 345];
figure;
scatter3(angle, height, voltage, 80, voltage, 'filled'); xlabel('Angle of Inclination (degrees)', 'FontName', 'Bookman Old Style', 'FontSize', 12);
ylabel('Head of Water (cm)', 'FontName', 'Bookman Old Style', 'FontSize', 12);
zlabel('Output Voltage (mV)', 'FontName', 'Bookman Old Style', 'FontSize', 12);
title('Combined Effect of Angle and Head of Water on TENG Output Voltage', 'FontName', 'Bookman Old Style', 'FontSize', 12);
grid on;
colorbar;
set(gca, 'FontName', 'Bookman Old Style', 'FontSize', 12);
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VIII. ACKNOWLEDGMENT

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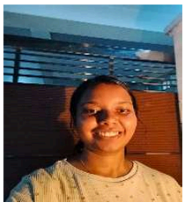

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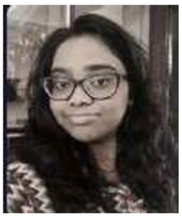

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