Environmentally Safe Triboelectric Nanogenerator: Enhancing PDMS with Silica for Self-Powered IoT Wearable Electronics

Aviva Wang[1], Lixin Wang[2], Xijin Zhang[2]

1. Cary Academy, Cary, NC
2. Sid and Reva Dewberry Department of Civil, Environmental, and Infrastructure Engineering, George Mason University, Fairfax, VA

Abstract

As the Internet of Things becomes increasingly integrated into our daily lives, their large volume and need for periodic power replacement have highlighted how traditional batteries are unsustainable for the next generation of smart devices. Triboelectric nanogenerators (TENGs), which generate electricity from everyday mechanical motion, offer a promising alternative; however, further improvement of their output performance is still required for practical applications. This study investigates the optimized way of making TENGs from silica derived from tetraethyl orthosilicate (TEOS) with electron-attracting abilities and polydimethylsiloxane (PDMS), a common electron-accepting material. Two phases of optimization—first, the configuration, then the fabrication methods—are tested against human skin in ten repeated trials, recording the maximum voltage in each. By taking the average of the maximums, the results indicate that silica can increase the voltage output of PDMS by 80.1% due to surface enhancements and charge trapping sites, as confirmed by an electron microscope. In addition, PDMS-Silica shows voltage output with normal distribution and overcomes the asymmetry in usual PDMS performance. The single electrode TENG created using the PDMS-Silica developed in this study exhibits efficacy on human skin, high flexibility, and biocompatibility, thereby opening the door to wearable electronics, biomedical sensors, and other applications. Both PDMS and Silica are also safe for skin and environmentally friendly, free from forever chemicals (PFAS). Furthermore, their scalability, low cost, and energy generation performance make them applicable to civil engineering applications, such as harvesting electricity from transportation and foot movement, contributing to a sustainable future.

Keywords: triboelectric nanogenerator; single-electrode mode; wearable electronics; energy harvesting; microelectromechanical system; composite materials

1. Introduction

The prevalence of the Internet of Things (IoT) in applications such as entertainment, communication, sensors, health monitoring, and others continues to rapidly expand in modern life [1]. In particular, wearable electronics like smart watches, smart textiles, and other body-integrated devices are also becoming more common, emphasizing lightness, comfort, and flexibility [2]. Conventional batteries have traditionally powered these devices. However, their bulky form, poor flexibility, and need for periodic replacement have made them unsustainable, especially for wearable electronics [3]. Triboelectric nanogenerators, or TENGs, offer a promising solution. TENGs are a novel energy harvesting technology that can convert everyday mechanical motions, such as vibrations, tapping, walking, driving, and more, into electricity [4]. Unlike other renewable energy sources, such as solar and wind, which rely on environmental conditions, mechanical energy is readily available in our daily lives. Therefore, TENGs offer a compelling solution for creating self-powered, sustainable energy systems tailored to the demands of wearable and IoT devices.

TENGs operate using the triboelectric effect, or charge transfer, when two objects come into contact. Out of the four modes (vertical contact-separation, single-electrode, lateral sliding, and freestanding triboelectric-layer), this study focuses on the single-electrode mode (SE-mode). The SE-mode of TENGs uniquely offers a simplified architecture with one grounded electrode and one freely moving triboelectric layer without wires or an electrode [5] (Figure 1). This configuration enables energy generation from motion with minimal structural constraints, facilitating seamless integration into flexible and wearable electronics. The SE-mode is particularly advantageous for applications in self-powered pressure sensors, human-machine interfaces (HMIs), electronic skins (e-skins), and health monitoring devices, due to its low cost, ease of fabrication, and real-time responsiveness to micro-movements [6]. These attributes make SE-mode TENGs a promising platform for next-generation energy harvesting and intelligent sensing systems.

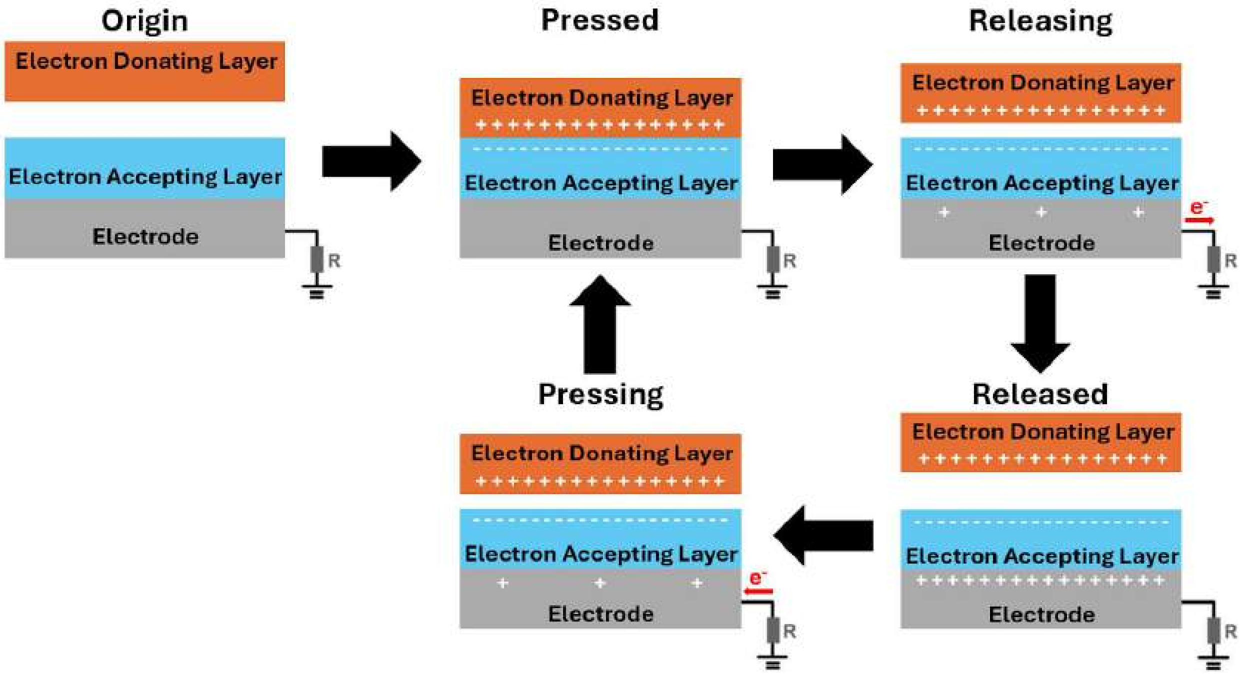

Figure 1. The operating principle of single-electrode mode TENGs. At the origin, the electron-accepting and electron-donating layers are uncharged. When they are pressed, the donating layer gives electrons to the accepting layer, making the donating layer positively charged and the accepting layer negatively charged. When the layers are released, the negative layer repels the electrons in the electrode to reach an equilibrium. Then, while the layers are being pressed again, electrons travel back into the electrode. Graphic created by student researcher using PowerPoint, 2025.

Improvement of the output performance of TENGs is still required for usage toward practical applications [7]. Furthermore, the sporadic variations of output current are a key issue of this technology, impeding reliable operation. This is due to adhesion-induced impulsive separation [8]. Because the triboelectric layers tend to stick together during separation—due to electrostatic attraction, van der Waals forces, and other surface interactions—they do not detach smoothly. Instead, they undergo a sudden, impulsive separation, which distorts the motion profile and causes the amount of charge transferred per cycle to vary, making the TENG output inconsistent. Silica (SiO_2), known for its electron-accepting properties, can potentially improve the performance of TENGs [9]. Silica enhances electron-accepting behavior primarily through its abundant dangling bonds, creating high surface charge density and charge trap sites [10]. Silica could make the output performance more consistent through better charge retention and by stiffening the PDMS matrix. Because silica dries into hard particles, it can make PDMS less flexible and therefore reduce adhesion-induced impulsive separation.

Polydimethylsiloxane (PDMS) is a widely used triboelectric material and has advantages such as flexibility, transparency, and coating ability [11]. Additionally, PDMS can be readily incorporated with other materials to form composite films with tailored properties [12]. This study investigates if silica derived from tetraethyl orthosilicate (TEOS) can increase the output voltage of polydimethylsiloxane (PDMS), a common electron-accepting material used in TENGs.

2. Experimental Methods

2.1 Silica Preparation

Two forms of silica, derived from tetraethyl orthosilicate (TEOS, Sigma-Aldrich), were prepared: a solution and particles, to create different PDMS-Silica configurations.

2.1.1 Silica Solution

A solution was prepared by mixing 2.6 g of tetraethyl orthosilicate (TEOS), 1 g of deionized (DI) water, and 100 µL of hydrochloric acid (36.5 - 38.0%) using a magnetic stirrer on medium speed (the same medium speed is used throughout the subsequent tests) for 30 minutes. Subsequently, 100 µL of sodium hydroxide (32%) was added dropwise using a micropipette while the solution was being stirred; after this, the stirring was immediately stopped (Figure 2).

Figure 2. Finished silica solution with a pipette tip on the left and a magnetic stirrer on the right. Image taken by student researcher, 2025.

2.1.2 Silica Particles

The prepared silica solution in 2.1.1 was transferred to a Petri dish and allowed to undergo gelation at room temperature (Figure 3). After complete drying (~10 hours), the resulting solid silica was ground into fine particles (0.3–1.0 mm) using a mortar and pestle.

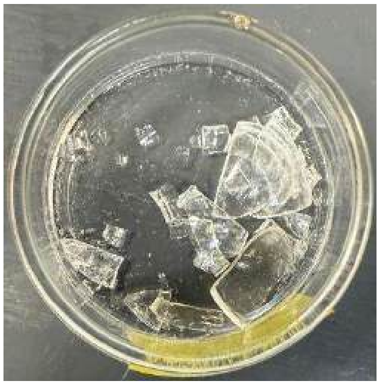

Figure 3. Solid silica after gelation. Image taken by student researcher, 2025.

2.2 Configuration Testing

SYLGARD 184 silicone elastomer kit from Dow Corning Corporation, which includes liquid pre-polymer and curing agent, was used for making polydimethylsiloxane (PDMS). PDMS and silica were combined at different stages to create various PDMS-Silica TENG configurations. Each configuration was tested to identify the best-performing one.

2.2.1 Pure PDMS

Polydimethylsiloxane (PDMS) and a curing agent were mixed in a 10:1 weight ratio using a magnetic stirrer for 30 minutes. The mixture (~8 mL) was then pipetted onto a 6 cm by 6 cm standard aluminum foil substrate and cured in an oven at 70 °C for 1 hour. The resulting configuration is shown in Figure 4a.

2.2.2 PDMS with Silica Particles

Following the initial mixing of PDMS and curing agent (10:1 ratio), silica particles were incorporated into the mixture by stirring with a glass rod until the particles were evenly distributed (a few seconds). The composite solution (~8 mL) was then pipetted onto a 6 cm by 6 cm aluminum substrate and cured at 70 °C for 1 hour, resulting in the configuration shown in Figure 4b.

2.2.3 PDMS with Silica Solution

PDMS, curing agent, and silica solution in the amounts created in 2.1.1 and 2.2.1 were mixed using a magnetic stirrer for 30 minutes. The composite solution (~8 mL) was pipetted onto a 6 cm by 6 cm aluminum substrate and cured at 70 °C for 1 hour, producing the configuration illustrated in Figure 4c.

2.2.4 PDMS Coated with Silica Particles

PDMS was first applied to a 6 cm by 6 cm aluminum substrate and partially cured at 70 °C for 30 minutes. Silica particles were then manually sprinkled onto the surface, followed by an additional 30-minute curing step at 70 °C to ensure adhesion. The resulting sample is presented in Figure 4d.

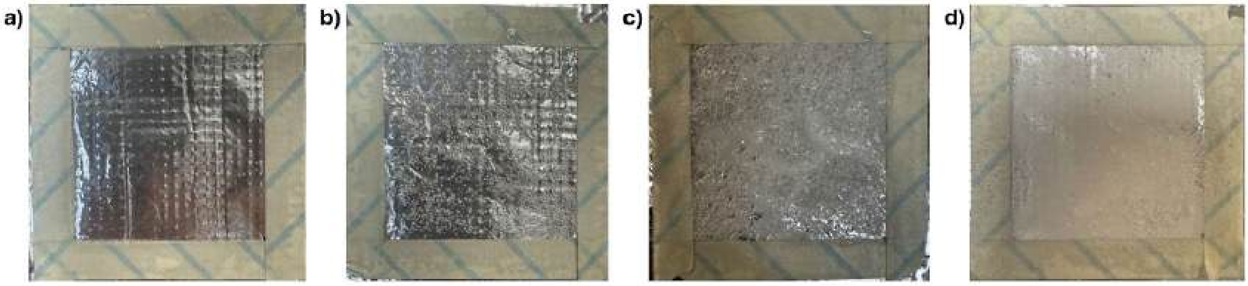

Figure 4. PDMS-Silica configurations after curing (a-d) of the configurations 2.2.1-2.2.4, respectively. Images taken by student researcher, 2025.

2.3 Fabrication Methods for PDMS-Silica Composites

To improve the sensitivity of TENGs, the fabrication of PDMS-Silica composites was optimized by comparing the voltage output from three different methods.

2.3.1 Fabrication Method 1

PDMS and curing agent (~4 mL) were pipetted onto a 6 cm by 6 cm aluminum substrate and partially cured at 70 °C for 15 minutes. Subsequently, the silica solution (~4 mL) was pipetted onto the semi-cured PDMS layer and allowed to air-dry overnight at room temperature (Figure 5a).

2.3.2 Fabrication Method 2

PDMS, curing agent, and silica solution were combined and mixed using a magnetic stirrer for 30 minutes. The resulting mixture was pipetted onto a 6 cm by 6 cm aluminum substrate and left to air-dry overnight at room temperature (Figure 5b).

2.3.3 Fabrication Method 3

The composite layer was prepared identically to Method 2. The sample was then cured in an oven at 70 °C for 1 hour (Figure 5c).

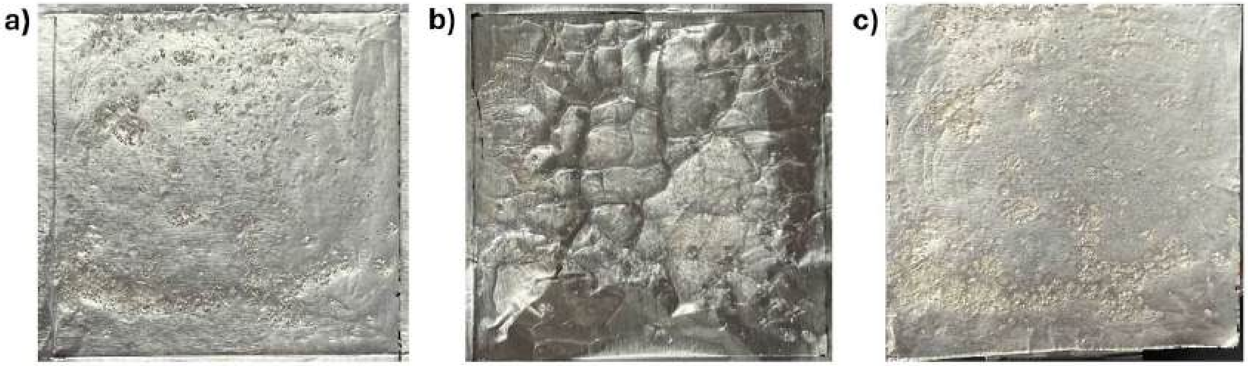

Figure 5. PDMS-Silica methods after curing (a-c) of the methods 2.3.1-2.3.3, respectively. Images taken by student researcher, 2025.

2.4 TENG Voltage Testing

For each configuration, the 6 cm by 6 cm triboelectric layer was cut out. An aluminum strip was attached to the underside of the layer to facilitate electrical contact. The complete device was mounted onto a non-conductive glass substrate to ensure electrical isolation during testing.

Electrical output was measured using a digital multimeter in voltage mode. The positive lead was connected to a grounded metal plate, while the negative lead was attached to the aluminum electrode strip (Figure 6). Each configuration was subjected to ten trials, with each trial consisting of three manual presses using the palm of the hand under consistent pressure and frequency. The peak output voltage from each trial was recorded, and the maximum value among the ten trials was used for comparative analysis across configurations.

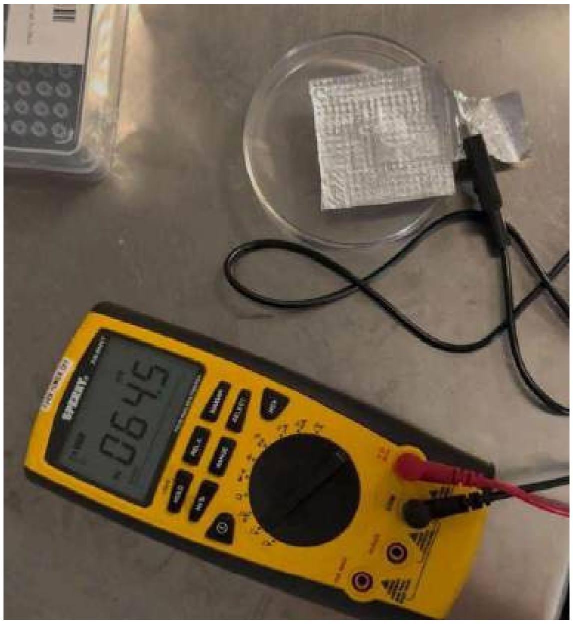

Figure 6. Multimeter and TENG voltage collection setup. Image taken by student researcher, 2025.

3. Results and Discussion

3.1 Optimization of Configurations

Based on the average voltage outputs of various PDMS-Silica TENG configurations, the data in Table 1 supports that PDMS with silica solution that was oven-cured had the best performance. This configuration outperformed PDMS with silica particles and semi-cured PDMS sprinkled with silica particles by 111.4% and 315.9%, respectively.

The p-values of PDMS with silica solution (oven) against the other configurations were calculated using the unpaired two-tailed Student's t-test. As shown in Table 2, both p-values are less than 0.05, confirming that the results are valid and statistically significant. The reason for this could be that the silica solution can be better incorporated into PDMS, creating more charge trapping sites.

Configuration	Trial Max Voltage (mV)										Avg (mV)
	1	2	3	4	5	6	7	8	9	10	
PDMS with silica particles	48.3	79.8	80.3	198.8	219.1	107.6	87.1	192.6	86.7	145.4	124.57
PDMS with silica solution (oven)	**64.9**	**87.4**	**178.4**	**262**	**289.2**	**257.3**	**401.5**	**351.4**	**349**	**392.6**	**263.37**
Semi-cured PDMS sprinkled with silica particles	224.2	150	31.2	51.4	18.5	19.9	61.9	6.6	12.9	56.7	63.33

Table 1. Trial max voltage output of different configurations. Table created by student researcher using Excel, 2025.

	PDMS with silica particles	Semi-cured PDMS sprinkled with silica particles
PDMS with silica solution (oven)	0.004197727817	0.00024419605

Table 2. P-values from unpaired two-tailed Student's t-test of different configurations. Table created by student researcher using Excel, 2025.

3.2 Optimization of Fabrication Methods

Based on the average voltage outputs of different methods for creating a PDMS with a silica solution, TENG, the data in Table 3 support the conclusion that PDMS with a silica solution that was air-dried, then oven-cured, had the best performance. This configuration outperformed the other methods by 331.8.% and 248.5%.

The p-values of PDMS with silica solution (air-dry -> oven) against the other methods were calculated using the unpaired two-tailed Student's t-test. As shown in Table 4, both p-values are less than 0.05, confirming that the results are statistically significant. First, air-drying the layer prevented the water in the silica from rapidly expanding and creating air bubbles that decreased conductivity. Subsequent thermal curing decreased the surface stickiness, reducing contact time and thus increasing the amplitude of instant voltage.

Method	Trial Max Voltage (mV)										Avg (mV)
	1	2	3	4	5	6	7	8	9	10	
PDMS with silica solution (oven)	64.9	87.4	178.4	262	289.2	257.3	401.5	351.4	349	392.6	263.37
Semi-cured PDMS with silica solution	30.2	246	352	260	262	199	152	299	196	202	219.82
PDMS with silica solution (air-dry)	12	187.6	176	398	133	451	165	266	556	379	272.36
PDMS with silica solution (air-dry -> oven)	**269**	**328**	**667**	**775**	**1042**	**581**	**1583**	**1603**	**1371**	**1272**	**949.1**

Table 3. Trial max voltage output of different methods. Table created by student researcher using Excel, 2025.

	PDMS with silica solution (oven)	Semi-cured PDMS with silica solution	PDMS with silica solution (air-dry)
PDMS with silica solution (air-dry -> oven)	0.0004818080078	0.0002331541464	0.0006934200982

Table 4. P-values from unpaired two-tailed Student's t-test of different methods. Table created by student researcher using Excel, 2025.

Since all PDMS-Silica optimization data are statistically significant, this research has confirmed the optimized configuration and method for making PDMS-Silica TENG is PDMS with silica solution being air-dried first and then cured in the oven.

3.3 Final PDMS-Silica TENG vs PDMS Baseline

The optimized configuration and fabrication method—PDMS with silica solution (air-dry -> oven)—for this PDMS-Silica layer showed an 80.1% increase in average voltage performance compared to the pure PDMS baseline (Table 5). As seen in Table 5, PDMS Trial 7 exhibited an abnormally high voltage output compared to the rest of the trials. This data point is more than two standard deviations from the mean (Figure 7), matching the expected sporadic variations of output from common TENGs.

	Trial Max Voltage (mV)										Avg (mV)	SD (mV)
	1	2	3	4	5	6	7	8	9	10		
PDMS	348.4	373	220.6	885	244.1	396.9	1977	201.5	322.2	278.5	524.72	546.37
PDMS with silica solution (air-dry -> oven)	269	328	667	775	1042	581	1583	1603	1371	1272	949.1	495.98

Table 5. Trial max voltage output of PDMS and PDMS with silica solution (air-dry -> oven). Table created by student researcher using Excel, 2025.

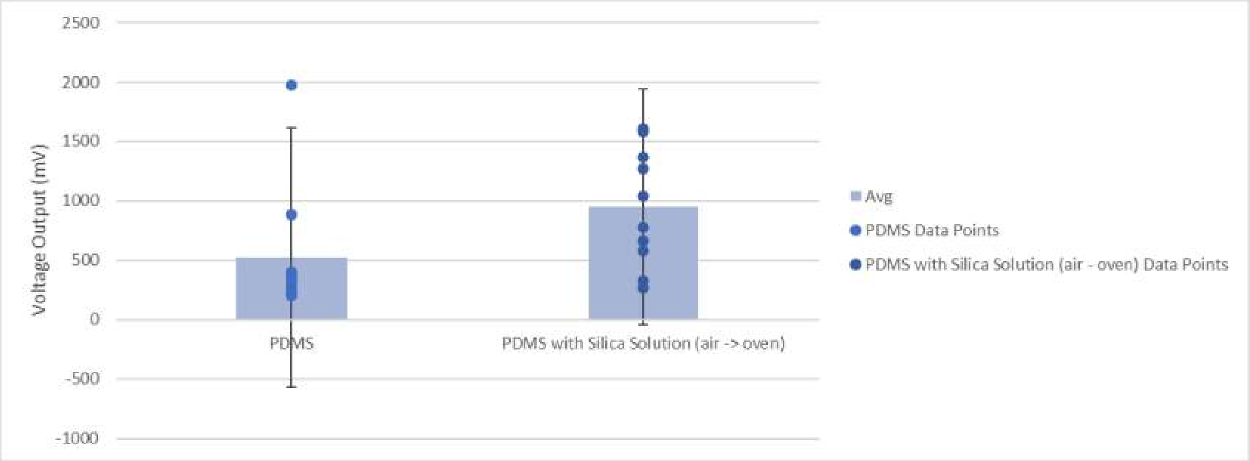

Figure 7. Average Voltage with ±2 Standard Deviation and Distribution. Graphic created by student researcher using Excel, 2025.

The variability of the electrical outputs is a key limitation that disrupts the development of sustainable TENG applications. As shown in Figure 8, PDMS exhibits a skewed, inconsistent distribution of voltage output. On the other hand, PDMS-Silica data exhibits a normal distribution as shown in Figure 9. This means PDMS-Silica minimizes the peak variations while enhancing the power output. The t-test is not applicable for comparing PDMS's skewed distribution to PDMS-Silica's normal distribution.

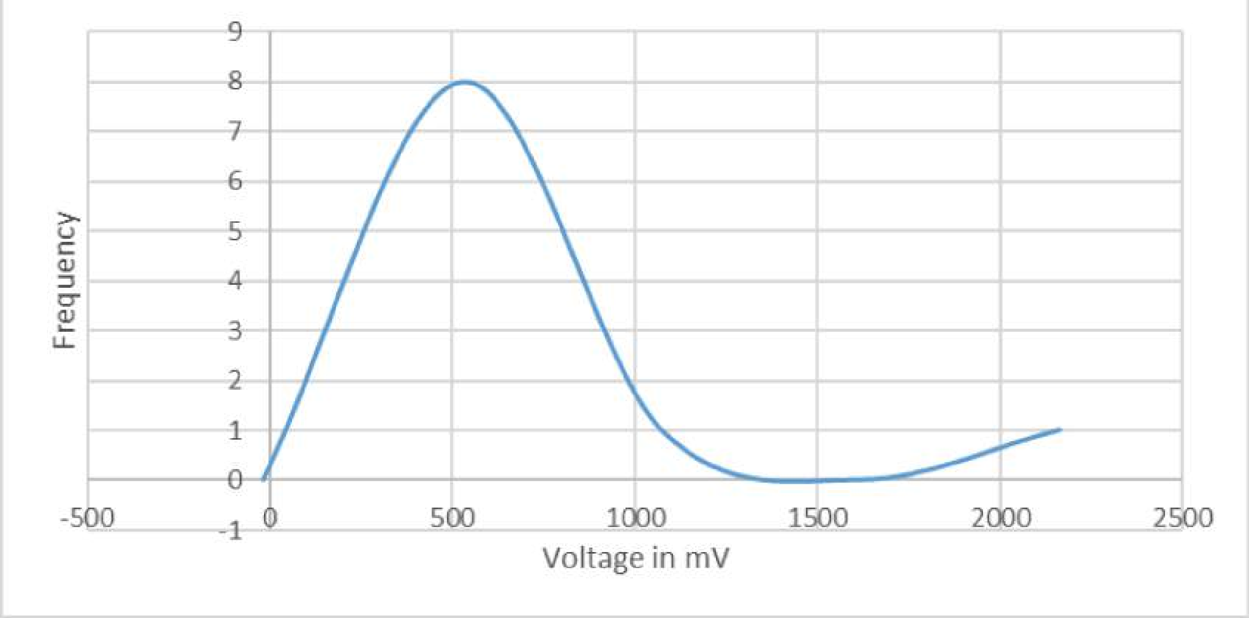

Figure 8. Positively skewed bell curve of the PDMS data. Graphic created by student researcher using Excel, 2025.

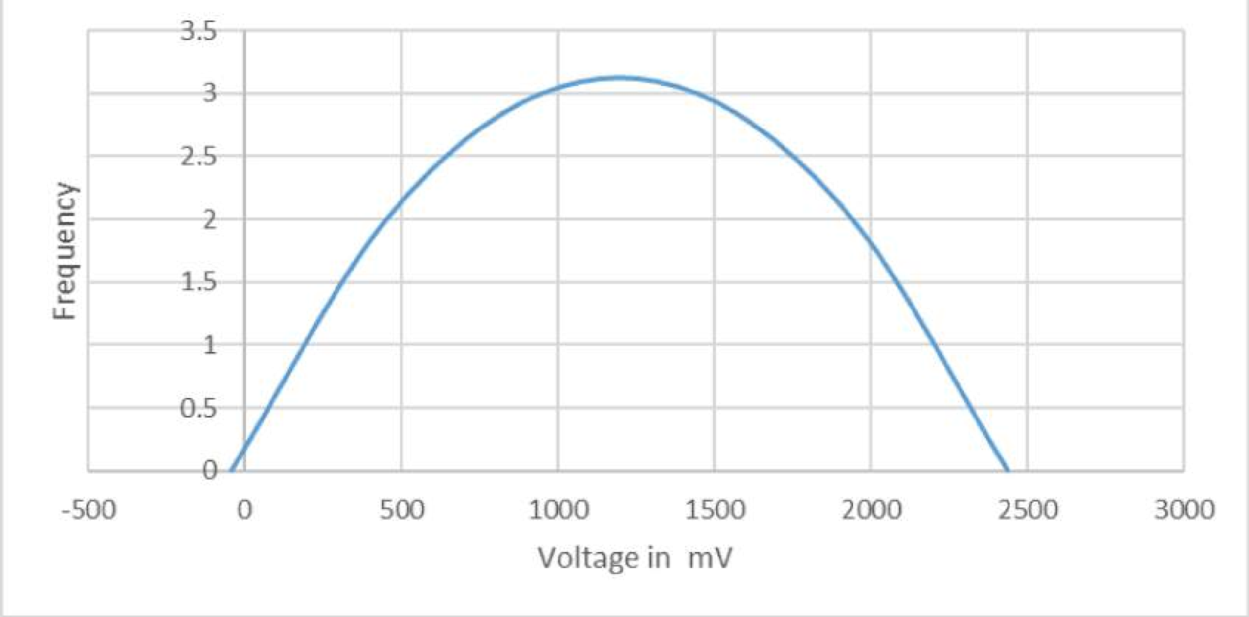

Figure 9. Normal bell curve of PDMS with silica solution data. Graphic created by student researcher using Excel, 2025.

3.4 Discussion of Results

Silica improved the PDMS' electron-accepting abilities in two ways. The silica helped enhance the surface by creating ridges, increasing the surface contact area, and thus allowing for more pathways for electrification (Figure 10). Additionally, silica is known to possess a high density of surface trap sites due to its dangling bonds, which facilitate the accumulation and retention of negative charges. These trap sites reduce the rate of charge dissipation and improve the material's ability to accept and store electrons during contact electrification, explaining the improved voltage output.

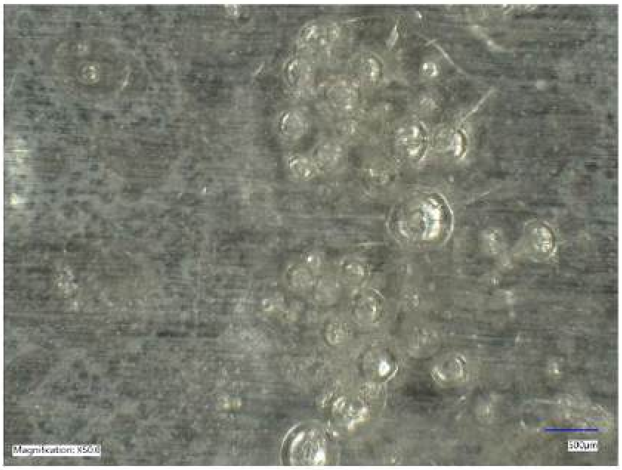

Figure 10: PDMS surface enhancements due to silica. Image taken by student researcher using an electric microscope, 2025.

There are two possible ways that silica makes the performance of PDMS more consistent. Firstly, silica's aforementioned charge trapping sites hold on tightly to electrons. Thus, even if the separation is slightly irregular, the charges do not dissipate quickly, so the electrical output per cycle is stabilized. This reduces fluctuations that would otherwise arise from imperfect detachment. Secondly, silica's hardness stiffens the PDMS matrix when combined, so the layer deforms less, decreasing adhesion-induced impulsive separation. There could be more possible reasons for this improvement in consistency that should be explored to improve future TENGs.

4. Conclusions

This study successfully developed and optimized a novel PDMS-Silica TENG for self-powered electronic applications. By systematically varying the configuration and fabrication, the results support that the incorporation of silica into PDMS significantly enhances triboelectric performance, achieving an 80.1% increase in average voltage output compared to pure PDMS. This is attributed to improved surface morphology, enhanced charge retention via silica-induced trap sites, and increased interfacial contact area, allowing the new PDMS-Silica TENG to attract electrons, and thus produce more electricity (Figure 9). Furthermore, the new PDMS-Silica TENG has a more consistent voltage performance, making it more suitable for practical uses. This could be for two reasons: its charge-trapping sites stabilize output by preventing rapid charge loss during irregular separation, and its stiffness reduces deformation and adhesion-induced impulsive separation.

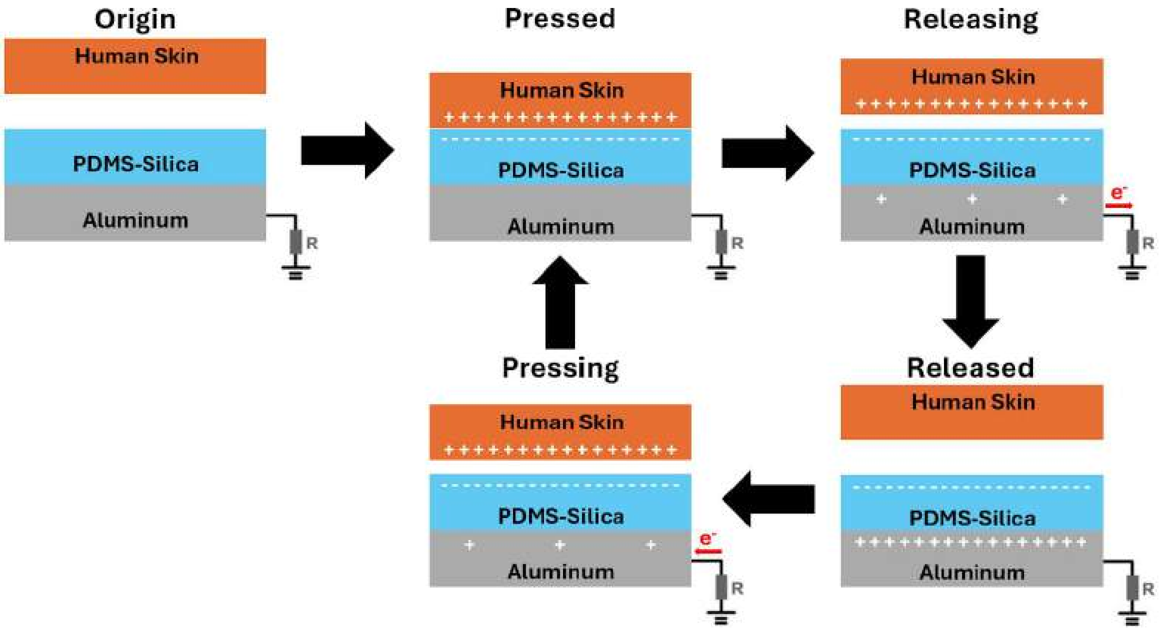

Figure 9. Working mechanism of the final PDMS-Silica TENG. Graphic created by student researcher using PowerPoint, 2025.

The PDMS-Silica TENG exhibits several desirable properties, such as mechanical flexibility, efficacy with human skin, and straightforward, low-cost fabrication. The SE mode has a simple design with minimal wiring. Additionally, both PDMS and silica are biocompatible and safe for the environment, containing no PFAS, promoting seamless integration with body-integrated devices. These qualities open the door to applications like wearable electronics, biomedical sensors, smart textiles, and more.

Additionally, this novel TENG's scalability, low cost, and energy generation performance make it applicable to civil engineering, so future work could also explore harvesting electricity from transportation and foot movement using this TENG. These directions could enable the development of next-generation sustainable, self-powered systems for a wide range of IoT and broader applications.

5. Future Work

Many different experiments and data collections were not able to be conducted due to a lack of time (i.e., the time constraint of the summer program). Future work concerns conducting more experiments to investigate additional properties (e.g., tensile stress/strain, degradation), further improving the performance, or testing real-world applications. The following are experiments/ideas that could be implemented:

- Confirm why the PDMS-Silica TENG had a much more consistent performance by testing how tensile force affects the tensile stress and strain of the PDMS-Silica layer.
- Investigate the degradation of this device's performance over time and over multiple uses to investigate real-world applicability.
- Further improve the performance by adding more chemicals that can increase electron-accepting ability, surface contact area, etc.
- Research ways to store the instant voltage of each tap.
- Integrate this single-electrode PDMS-Silica TENG into a wearable device to test the performance.
- Use the PDMS-Silica layer developed here in contact separation mode for civil engineering applications.

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