Optimizing Triboelectric Nanogenerators: Advances in Efficiency for Sustainable Energy Harvesting

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Abstract:

As a part of STEM curriculum, we were required to tackle specific Egyptian grand challenges through a project with specified criteria during our academic year. We chose to address them by exploring triboelectric nanogenerators (TENGs). TENGs are innovative type of generators that convert mechanical energy, which is friction, into electrical energy through triboelectric effect and electrostatic induction, a concept first demonstrated by Prof. Zhong Lin Wang's team in 2012 [1]. The basic idea behind this project was to use recycled materials, which have a high tendency to lose electrons easily, which naturally have a high tendency to easily lose electrons; this was done to fabricate TENGs into large-scale tiles that convert the kinetic energy of the people into electrical energy, specifically targeting an output of over 150 Joules in 5-minutes frame.

By careful experimentation, this prototype was able to achieve an output of 30 Volts and 0.07 Amperes, achieving a total energy production of 630 Joules and an efficiency of 8.64%. This work highlights the potential of TENGs for providing sustainable energy solutions with widely available recycled materials. The findings suggest that, with future development, TENGs could be an effective option for large-scale energy generation, providing a successful, realistic, user-friendly, and environmentally friendly method for addressing energy needs. The main purpose of this research is to help people, including future generations, who may choose to apply this project in real life.

Introduction:

Every day, the world's demand for energy is increasing. Also, everywhere in the world, alternative energy sources are being used to get the most benefits in the economic field. This work presents a creative solution for the energy crisis by harnessing the triboelectric effect. Previous studies [1] have demonstrated that the triboelectric effect, which relies on friction between materials, has several large-scale applications, there is a lack of research on developing a small-scale, user-friendly device that can efficiently harness this energy for everyday us.

This project focuses on developing an alternative, green energy source leveraging this effect to contribute to the resolution of the energy crisis. The primary objective of this project is to innovate a sustainable, and user-friendly energy source. Our criteria incl-uded ensuring the solution is environmentally friendly, unobtrusive in operation, and easy to use. This led to extensive testing and modifications to optimize the mini prototype for maximum efficiency. It was designed by placing triboelectric materials between two wood planks on the bottom supported by 4 springs on the corners, and in the middle. In addition, there is one on the top. Also, adding some enhancement materials. The design ensures that energy is generated whenever pressure is applied to the prototype.

Materials and Methods:

In the first TENG prototype, shown in Figures (1-2), the prototype was constructed from recycled materials. Figure (1) shows the design of Arch-shaped TENGs that we followed while building the first prototype. A plastic bottle, cut into an arch, formed the outer body and elastic covering, double-sided tape was used to secure the layers of Teflon and aluminum. Figure (2) depict the generator's design. The setup included 24 small TENG units assembled on a lower plank, with an upper plank transferring mechanical force to generate electricity. Springs were placed between planks to reset the upper plank after compression. These TENGs were arranged in two groups of 12 and connected in parallel within columns and in series across columns to balance voltage and current for optimal power.

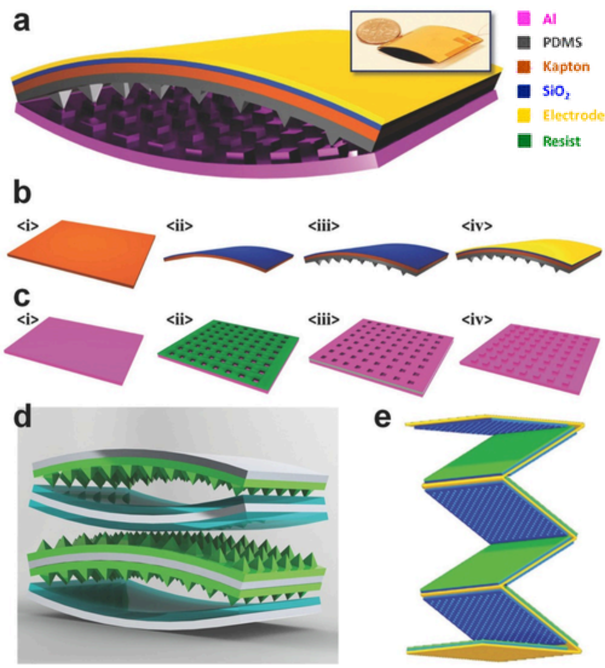
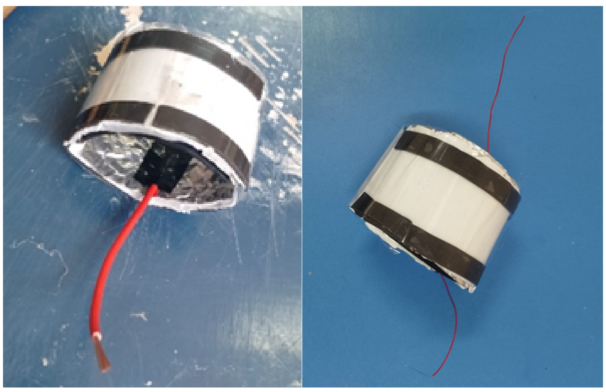
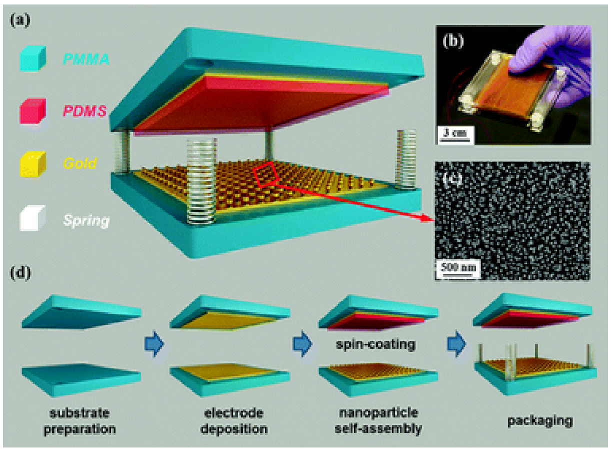


Figure (1): Arch- shaped structure of TENG.



Figures (2): Real pictures of the generator.

For the second prototype, it was meant to be a spring-assisted separation structure as Figure (3) illustrates. We have used three wood planks, two of them with the same dimensions and the third with fewer dimensions than the others. For the the lower wooden plank, we stuck four springs to the corners using cable clips and super glue to make sure that they don't break with much stress, then we stuck into each spring a pipe using super glue with a shorter height than the spring's height. In the middle part of the lower wooden plank, we adjusted a layer of Teflon tape to a sheet of aluminum foil in the same dimensions as the smaller wood plank then stuck them into the plank in layers using double-sided tape. Then, we cut a rubber sheet with the same dimensions as the layer of Teflon and aluminium and stuck it above them using double-sided tape to enhance the triboelectric performance. Figure (4) illustrates the final design of the lower wooden plank.



Figures (3): Main Design.

Figures (4): Lower and Upper wooden plank.

For the smaller wooden plank, on one side we fixed 4 wooden piles in each corner of the wooden plank with nails, each pile with the same length as the pipe. On the other side of the plank, wee put a layer of Teflon and a layer of aluminum on top of it using double-face tape as we did before. Then we cut off the excess edges from the corners using CNC so that they do not rub and fumble with the springs. After finishing, we fixed the small wooden plank to the middle part of the other bigger wooden plank from the side where there are four wooden piles using nails as shown in Figure (8).

In the end, we stuck the wires into the two sheets of aluminum using tape to transfer the current that will be generated and benefit from it. Whenever you press on the generator, the smaller plank will become in contact with the one on the bottom and the triboelectric effect will exist.

Results:

The testing included various criteria, electrical output, energy generation, durability, and efficiency, to assess the effectiveness of TENG-equipped tiles in real-world applications. During measuring the voltages and current for the first prototype, we faced a problem, which was that got a different average voltage shown here in Table (1) and the current wasn't enough. In the first trial, it came out to be an average of 2.43 Volts. In the second trial, it came out to be an average of 2.3 Volts. In the third trial, it came out to be an average of 2.5 Volts. We concluded that the system gives us an average of 2.4 Volts.

Trails	First	Second	Third	Average
Voltage	2.4 Volts	2.3 Volts	2.5 Volts	2.4 Volts

Table (1): Our trials for testing the system.

We investigated that our first system produces 2.4 ± 0.014 Volts as an average voltage with the error of the multimeter and 0.00003 ± 0.003 Amperes as an average current with the error of the multimeter. Next, we calculated the power, which came out to be 2.4 * 0.00003 which equals 0.000072 Watts. Next, we computed the joules, which came out to be 0.000072 * 300 = 0.0216 Joules.

For the second prototype, we have done one trial. The voltage came out to be more than 30 DC volts and the current came out to be an average of 0.07 Amperes which was a real plot twist. The power came out to be 30 * 0.07 which equals 2.1 watts. The joules came out to be 2.1 * 300 which equals 630 Joules which is more than the 150 Joules that we needed. Next, we calculated the efficiency which came out to be (630/7291.2) * 100 = 8.64%. Figures (5,6) represent the outputs that we got during the test plan.

Figures (5): Amperes

Figures (6): DC voltage.

Because TENG components are thin sheets that won't withstand much stress over time, we discovered that their shelf life durability under long-term stress, and long usage isn't that long. Additionally, its components could rip at any time. In our mechanism, the TENGs were able to simulate real-world usage very well and the voltage and current output during simulated usage were consistent with those observed in actual field tests.

Discussion:

Fundamental physics of Triboelectric nano-generators:

Triboelectric nanogenerators (TENGs) are small devices that can power electronics with ultra-low power consumption by harvesting energy from the environment. They convert external mechanical energy into electricity through the triboelectric effect and electrostatic induction. This new and unfamiliar form of energy generator were first demonstrated in 2012 by Prof. Zhong Lin Wang's [1] group at Georgia Institute of Technology.

Research on TENGs has mainly focused

on optimizing designs and exploring applications, with less attention given to material features and properties. There are different modes present in triboelectric nano-generators are:

1. Vertical contact-separation mode

2. Contact-Sliding mode

3. Single-electrode mode

4. Freestanding triboelectric layer mode

Triboelectric effect occurs when two different materials come into contact through friction, transferring charges which can be electrons or may be ions/molecules to equalize their electrochemical potential. When separated, some of the bonded atoms have a tendency to keep extra electrons, and some have a tendency to lose them, possibly producing triboelectric charges on surfaces. Materials that usually have a strong triboelectric effect are likely less conductive or insulators. A TENG is made of two sheets of materials that have distinctly different triboelectric characteristics with one easy to gain electrons and the other one easy to lose electrons.

Electrostatic induction is a technique for producing static electricity in a substance by bringing an electrically charged object near it. For example, when a negatively charged rod and an equally charged balloon come into contact, electrons in the balloon flow away from the rod. When the rod pushes away, the electrons in the balloon spread out uniformly as before. When the rod approaches the balloon, electrons in the balloon move away from the rod; this is how it works.

The TENGs energy conversion entails three steps in the process: generation of charge, charge separation, and flow. For improving the generation of the charge within the TENG, some methods can be introduced. These would involve increasing the contact area between materials, deliberating on the selection of materials with greater differences in their ability to attract and lose electrons, modifying the environmental conditions of temperature and pressure, and changing substrate morphology through surface modifications such as coatings, wrapping, or doping. All these methods further enhance the ability of the material to generate positive or negative charges, hence enhancing the overall eff--iciency of the TENG.

In our project, we depended on the Vertical contact-separation mode of TENGs, where two different types of material sheets are layered on top of each other, with metal layers at the top and bottom of the design. These layers produce different electric charges when they rub. If you lift them apart slowly, a voltage is created because of the gap. The voltage disappears and the electrons return to their initial positions when you let them come into contact again. This mechanism is connected to the operation of triboelectric charges, but we are going modify it by making a special mechanism of the generators in a wooden plank as a tile in real life to use the friction that students produce while running, playing, and walking to generate energy. Figures (7,8) represent the Vertical contact-separation mode in more specific way.

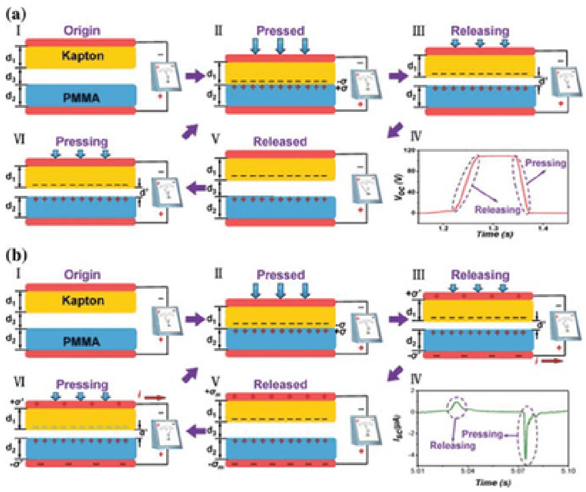


Figure (7): Overlapping of TENG layers.

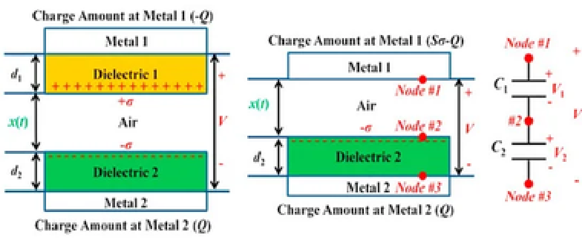


Figure (8): Our trials for testing the system.

The Triboelectric as we said before is when two materials' surfaces touch each other through physical contact which generates static polarized charges, while the electrostatic induction converts the mechanical energy done on the generator into electricity through mechanical separation, which results in a cha-

-nge in the electrical potential. The Triboelectric happens when two atoms' electronic clouds or wave functions entirely overlap (interaction between the electronic clouds or wave functions of atoms when two materials come into close physical contact), resulting in forming a bond between the two atoms, where an equilibrium state with an interatomic distance is formed.

Depending upon their triboelectrification which has been divided into two parts, one is positive and one is negative. Almost all materials have triboelectrification effects (which is called the triboelectric material series), including metals, polymers, wood, etc. Figure (9) show the triboelectric material series. So, if we take this polytetrafluoroethylene with the polyformaldehyde, the highest positive and the highest negative one so automatically it will give you the maximum electricity if we rub these two kinds of materials.

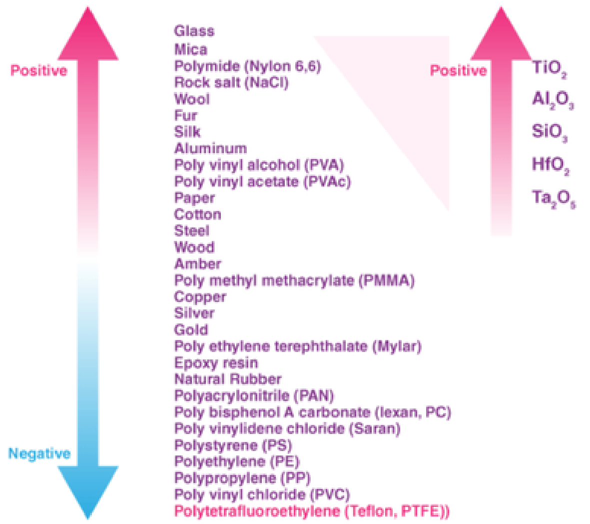


Figure (9): TENG material series.

In a triboelectric nanogenerator (TENG), the movement of charges creates a difference in electrical potential between two electrodes. This happens when the materials in the TENG assembly move back and forth over each other, which disrupts the balance of charges. As these layers repeatedly come into contact and then separate, they produce electrical charges that shift back and forth. This shifting creates a potential difference that alternates between positive and negative peaks, which results in an alternating current (AC) signal. Essentially, the motion of the layers in the TENG causes the e-lectrical charges to move in a way that generates a back-and-forth flow of electricity.

Triboelectric nanogenerators (TENGs) have a wide range of applications, including self-powered keyboards, pressure sensors, wearable devices, self-charging electronic devices, and flexible patches for robotic manipulators. TENGs are advantageous due to their ability to produce high voltage outputs with low current, high efficiency at low frequencies, lightweight design, low cost, and an efficiency of 30 - 60%. They can also operate in various modes and offer a wide selection of materials. However, TENGs have some drawbacks, including weak stability and long-term durability, and it can be challenging to protect their surfaces from environmental factors.

Our first prototype consists of 24 triboelectric nano-generators (TENGs) integrated within two wooden plank structures, designed to harness the friction generated by people's activities in a school environment. These two wooden planks represent tiles in real life. Each generator comprises an elastic-plastic outer layer that was cut into appropriate pieces as an arch-shaped structure to return to its main shape after pressing on it, a layer of Teflon was applied to the inner sides of the plastic sheets above the plastic using double-sided tape, a layer of aluminum that was cut to match the dimensions of the plastic sheets and was applied above the Teflon layer using double-sided tape, and between these two layers we put a sheet of "Graphene oxide" which works as a Catalyst agent, but in our project, we replaced the Graphene oxide with "Rubber" which acts as a negative TENG layer. We chose Aluminum because of its triboelectric effect feature, it is the easiest material that we could get it waste, and Aluminum is the most suitable material to use for many reasons like Availability, strength, Formability, and good conduct of electricity. We chose "Teflon, PTFE." Due to the high triboelectric effect feature on the negative side. Rubber will do the same job as Graphene oxide with the same efficiency. We used rubber because it is easier to get wasted than graphite oxide. A recycled bottle has been cut up to be used as an external frame.

The elastic-plastic of the bottle is not a good conductor of electricity, and the elastic material will be the best clean choice to act as the outer face of the generator to return to its main shape after pressing on it. We used "Double face tape" to make the layers attached to the external frame. We connected a wire between the two layers to be the path through which the electrons that would be lost from the materials used would pass.

The TENGs are integrated electrical system to make a Tile that generates clean energy by applying force on it during walking. The force will be a pressure that makes the aluminum rub with Teflon and that will cause a loss of electrons that will be through a wire to the "rectifier bridge" to convert AC into DC, "diode" to make the current pass through one direction, then to the battery to store it. Figure (10) represents the proposed electrical system design. The generators are organized into two spectrums, each containing 12 generators, arranged in columns and connected in parallel and series configurations. Springs were adjusted with cable clips on the corner of the wood surface to adjust the pressure distribution, ensuring non-impediment to people activities. 12 Pipes were adjusted above the generators to transfer pressure to whole the system, optimizing energy generation.

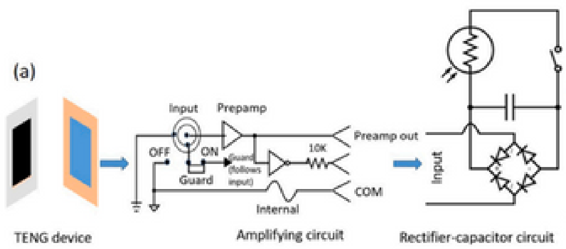


Figure (10): The electrical system.

The springs here will present a big favor to us and to make that clear the idea is when a force is applied on the prototype the springs will contract, and the two layers of the triboelectric generator will make friction and therefore it will generate electricity. After this process is done and the applied force has been reduced, the springs will return to their original position, which will ensure that the generators return to their original position to start a new turn and new process.

Initially, the voltage and current output from the first system were insufficient for our needs. To improve these parameters, we conducted research on methods to enhance the performance of the triboelectric nanogenerator (TENG). Through our study, we found that increasing the surface area of the materials in contact could significantly boost the output voltage and current.

As a result, we decided to remove the 24 individual TENG we had initially constructed. Instead, we opted for a more efficient design, covering the entire surface of the wooden plank with Teflon and aluminum layers. By maximizing the contact area between these two materials, the friction between them during operation produces a much higher electrical output. This design change allowed us to achieve the maximum voltage and current possible from the system, significantly improving the overall performance.

Rule of rubber in the process:

To enhance the performance of the triboelectric nanogenerator (TENG), rubber was incorporated throughout the mechanism of the prototype. This decision was based on several factors that contribute to improving the performance of TENGs:

1. Surface Roughness: Rubber was selected due to its advantageous roughness properties. Increased surface roughness leads to higher friction, which in turn improves the quality and efficiency of the triboelectric effect. The rough texture of rubber enhances the contact area and interaction between surfaces, resulting in increased charge generation.
2. Position in the Triboelectric Series: Rubber's position in the triboelectric series makes it a suitable material for our TENG. When rubber is rubbed against aluminum foil, it becomes negatively charged. This property is crucial for generating a strong triboelectric effect, as it causes efficient charge transfer between the materials.
3. Layer Configuration: Incorporating rubber on one side of the TENG allowed the prototype to have a multi-layered stru-

-cture , significantly boosting power output. This configuration included:

- An energy generating layer formed by the Teflon and rubber.
- A second and third energy generating layers formed by aluminum and Teflon, creating multiple stacks of triboelectric materials.

By maximizing the dimensions of the generator, surface area and the number of layers in the generator, the energy produced was further enhanced. The interaction between these layers generates higher amounts of electrical power compared to a single-layer configuration.

4. Dielectric Properties: Rubber also has excellent dielectric properties, acting as an insulating layer due to its low electrical conductivity. This prevents charge leakage and ensures that accumulated charges remain localized within the TENG system, thereby maintaining a higher charge density and improving overall efficiency.

In conclusion, the use of rubber in TENGs design significantly improved performance through enhanced surface roughness, optimal positioning in the triboelectric series, efficient multi-layer stacking, and excellent dielectric properties. These factors collectively contributed to a more effective and powerful triboelectric nanogenerator.

There are some concepts that should be familiar in order to understand Triboelectric effect.

Surface charge density (σ) is a measure of how much electric charge is accumulated on a surface per unit area. It is defined as $\sigma = Q/A$, where Q is the total electric charge on A, A represents the surface area.

To understand how time and area act on generating charge, we should understand the formula:

$$Q(t) = \int_{t_0}^{t} \sigma\big(A(t')\big) \frac{dA(t')}{dt'}\, dt'$$

The equation describes how the total charge generated at time t ₁depends on how the contact area changes over time. To fully understand the formula, we will break it out and understand each term. σ(A(t′)) represents the surface charge density on the surface area equals A(t′) at time t′. Also, surface charge density σ can vary depending on the pressure applied on the generator and it can vary by changing the materials. $\frac{dA\,(t\prime)}{td\prime}$ represents the rate of change of the contact area with respect to time. From the previous information, we can observe that the relation between total charge generated and area is a direct relation. The previous equation showed practically how the increasing of surface area can act on charges generated. This is the main difference between the first attempt to make a TENG, and the second one. From the important concepts to understand the triboelectric effect is the capacitance. Capacitance represents the ability of a system to store electrical charge. Capacitance plays a main and crucial role in predicting the output of the TENG. Capacitance is determined by the physical characteristics of the materials involved, such as the surface area, distance between materials, and the dielectric properties of the medium between them. Capacitance is defined as

$$C = \frac{A\varepsilon_0\varepsilon_r}{d}$$

To understand the role of capacitance in the triboelectric effect and how it acts on the output voltage, we should understand the formula: $v(t) = \lim_{\Delta t \to 0} \frac{Q(t)}{\epsilon_0\epsilon_r \int_{A_0}^{A(t)} \frac{dA(t')}{d(t')}\, dt'}$

From the previous formula, we can observe that the capacitance is directly proportional to the area A(t) of contact between the two plates. If the area changes, so the capacitance will vary as well, and the integral $\int_{A_0}^{A(t)} \frac{dA(t')}{dt'}\, dt'$ accounts for the cumulative effect of this change.

The capacitance can help us to predict the output energy using the formula as $E = \frac{1}{2}cv^2$represents energy and V represents output voltage. Overall output energy can be calculated by another detailed formula, which is:

$$\mathbb{E}(t) = \int_{t_0}^{t} \left[-\frac{1}{2} C(t') \left(\frac{dV(t')}{dt'} \right)^2 + V(t') \frac{dC(t')}{dt'} \frac{dV(t')}{dt'} \right] dt'$$

The first term of the formula $\frac{1}{2}C(t')\left(\frac{dV(t')}{dt'}\right)^2$ represents the energy associated with the change of voltage over time. The second term $V(t')\frac{dC(t')}{dt'}\frac{dV(t')}{dt'}$ reflects the energy contribution due to the change of capacitance. The combined effect of varying capacitance and varying voltage. This approach captures the whole picture of how energy is harvested in TENGs.

The results of our testing provide a comprehensive evaluation of the TENG-equipped tiles, focusing on their electrical output, energy generation, durability, and efficiency in real-world applications.

The efficiency of the first prototype was calculated to be 5.8%, a relatively low figure, reflecting the developmental stage of TENG technology. However, the efficiency of the second prototype was notably higher, at 8.64%. This increase in efficiency indicates that the design improvements in the second prototype not only boosted power and energy output but also enhanced the energy conversion process.

A critical finding from our testing was the durability of the TENG components. These components, being thin sheets, are prone to wear and tear over extended periods. Our tests revealed that the shelf life of these components is limited, and they may rip under prolonged stress. This limitation presents a challenge for the long-term application of TENG technology. However, the system's ability to simulate real-world usage scenarios suggests that, with further development, durability issues could be mitigated.

The results indicate that TENG-equipped tiles have significant potential for energy generation in real-world applications, especially with the improvements seen in the second prototype. The substantial increase in voltage, power output, and efficiency from the first to the second prototype highlights the potential for optimization in TENG technology. However, durability concerns must be addressed to ensure the long-term viability of this technology.

Future work should focus on improving the efficiency and durability of TENG components, possibly through the use of more robust materials or protective coatings. Further testing under various environmental conditions and load scenarios will provide a more comprehensive understanding of the performance and limitations of TENG-equipped tiles in real-world applications.

In the process of improving the project's outcomes, we looked over a lot of research papers and took out several theoretical nuggets that helped us perform better. Upon implementing these ideas in real-world situations, we discovered that certain aspects could be executed successfully while others could not. For example, triboelectric nanogenerator research proposed that a large surface area may lead to a considerable improvement in performance. By extending the area from 53 cm to 4550 cm, we were able to use this principle and raise the power output from 218 joules to 630 joules, a 100.35% increase. As increasing the surface area for the generator will increase the fractioned- distance and maximize the number of different charges that lead to the potential difference and generating the energy. Another article also stressed how crucial it is to choose the right application for the generator. We looked over several locations and found that the place had a lot of foot traffic. In light of this, we decided to use our generator as a tile so that energy might be produced by the friction created by moving pedestrians. During the journey of crafting the prototype and evaluating its performance, we observed some areas to improve when this idea is employed in a real-life situation. For increasing surface area as much as possible to get the most count of charged electrons and selecting suitable materials from triboelectric series as you increase the space between the materials in the series the more you get differentiation of charges. Also, make sure that the triboelectric materials are clean as much as you can since it has an impact on performance because the uncleaned layer of material isolates this material from being on the progress, and increasing the quality of those materials. In addition, adding an optimizer device that regulates the force applied to the system is essential. Also, the environmental choice is critical to the project as dry environments can enhance the performance and a humid environment can hinder the progress. Recognizing the importance of choosing materials according to where they are in the triboelectric series is a significant theoretical advancement. Materials are ranked in the triboelectric series based on how likely they are to receive or lose electrons. Materials tend to become more negatively charged at lower points in the series and more positively charged at higher points. As we saw before in the triboelectric material seris, improving charge separation through an increase in the difference in locations of certain materials in the series is essential to optimizing the performance of a triboelectric nanogenerator (TENG).

Despite their promising applications in energy harvesting, TENGs face several limitations that hinder their large-scale deployment and performance optimization.

1) **Low Power Density:** TENGs, while efficient in converting mechanical energy into electrical energy, tend to generate relatively low power densities compared to other energy harvesting technologies like piezoelectric and electromagnetic generators. This limitation reduces their applicability in high-power-demand applications.

2) Wear and Durability Issues: Since TENGs rely on physical contact between materials to generate electricity through the triboelectric effect, long-term use can lead to wear and degradation of the materials. This reduces the efficiency and operational lifespan of the device.

3) Environmental Sensitivity: TENGs can be sensitive to environmental factors such as humidity and temperature. High humidity levels can interfere with the triboelectric charge accumulation process, significantly reducing the output power. Similarly, variations in temperature can affect material properties, impacting the performance.

Complexity in Design Optimization: Achieving optimal performance from TENGs requires careful design of surface structures, material combinations, and electrode configurations. This complexity can make the fabrication process expensive and time-consuming, limiting the rapid commercialization of TENG-based devices.

Energy Storage and Integration Challenges: Integrating TENGs with energy storage systems, such as batteries or capacitors, can be challenging due to the high-voltage, low-current characteristics of TENGs. Effective power management strategies are required to ensure efficient energy harvesting and storage, adding complexity to system design.

Conclusion:

This research effectively illustrates the potential of triboelectric nanogenerators (TENGs) as a sustainable and innovative solution to Egypt's Grand Challenges, especially within the topic of energy generation. By utilizing recycled materials, our project not only showcases an ecologically friendly approach but also proves that TENGs can harness everyday kinetic energy effectively. The prototype created during this study achieved an energy output of 630 Joules with an efficiency of 8.64%, illustrating the practicality of TENG innovation for practical applications.

While the current output meets a fraction of the targeted energy production, the results are promising and underscore the adaptability of this technology. The findings recommend that with further refinement and optimization, TENGs might play a significant role in large-scale energy generation, especially in urban environments where human activity provides a consistent source of kinetic energy.

Future research should focus on improving the efficiency and durability of TENGs, investigating diverse material combinations, and integrating this technology into real-world settings. As we see ahead, the proceeded improvement of TENGs holds the promise of providing a sustainable, user-friendly, and impactful solution to the growing global energy demands, especially in regions striving for greener alternatives.

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