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Energy harvesting: Utilizing fabric friction to generate electrical energy

Nuraliza Norawzi [1*], Ili Farhana Mohamad Ali Nasri [2], Wan Nursheila Wan Jusoh [1], Ridwan Yahaya [3]

[1] Fire Safety Research Cluster, Aerospace Department, Malaysian Institute of Aviation Technology, Universiti Kuala Lumpur, 43800 Sepang, Selangor, MALAYSIA.
[2] Fire Safety Research Cluster, Avionic Department, Malaysian Institute of Aviation Technology, Universiti Kuala Lumpur, 43800 Sepang, Selangor, MALAYSIA.
[3] Tropical Research Centre, Science and Technology Research Institute for Defence (STRIDE), Selangor, MALAYSIA.
*Corresponding author: nuraliza.n@unikl.edu.my

KEYWORDS

Triboelectric effect
Dielectric material
Tribomaterial
Energy harvesting
Self-powered sensor
Lateral sliding effect.

ABSTRACT

Recent advancements in renewable energy technology have increased the popularity of triboelectric nanogenerators (TENG), which are energy-harvesting devices. One of the main design challenges for TENGs is the optimization of energy harvesting from lateral sliding motions, LS-TENGs. This study selected copper as the conductor material and used nylon and polytetrafluoroethylene (PTFE) textiles as TENG materials. The objective was to evaluate the performance of these materials in the lateral sliding mode. Multiple analyses, including conductor testing, material selection, and latex glove testing, were conducted. The voltage and current generated during each test were measured using an oscilloscope. According to the study, when the nylon/PTFE/Cu-TENG was manually pushed with a latex glove, a voltage of 6.8 V and a current of 1.8 μA with oscillation frequency measurements was 3 Hz. The use of a latex glove has a positive impact on the generation of voltage and current. In an ongoing experiment, the hand vibration indicators altered from 1 Hz to 6 Hz, resulting in a voltage of up to 8.2 V. Light-emitting diodes (LEDs) were used as indicators. This preliminary investigation provided valuable insights into energy production and promoted the adoption of sustainable energy practices.

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1.0 INTRODUCTION

In today's world, triboelectric nanogenerators (TENGs) have received a lot of interest in recent years as a potential solution for extracting energy from the environment. The ability to efficiently convert various types of mechanical energy from the environment into usable electrical energy makes it crucial considering the exponential increase in global energy demand. Since mechanical energy, including frictional and vibrational energy, is easily accessible and clean, it is becoming more and more popular among all the energy sources. Energy harvesting, also sometimes referred to as energy scavenging or power harvesting, is the process of gathering and converting ambient energy from several sources. TENGs are devices that generate electricity using theories of triboelectricity and electrostatic induction. Due to its potential to offer sustainable and renewable energy solutions for various applications, such as wearable electronics, wireless sensor networks, and autonomous systems, this concept has recently attracted a lot of attention. These solutions have become increasingly common as the use of portable electronic devices has increased. For instance, recharging batteries is necessary, and disposing of their waste poses environmental and human health risks.

The use of portable electronic devices has also increased, and frequent battery recharging has harmed the environment and poses risks to human well-being owing to waste generation. Fabric friction has emerged as an important and sustainable energy source. Researchers are actively exploring methods to harness the triboelectric potential generated by the contact and movement of fabrics against skin or other surfaces. They are also investigating the potential of other materials, such as textiles, to generate triboelectric energy for sustainable power sources. The widespread availability and versatility of textiles make them a practical and effective solution for power generation. Textiles efficiently harness and convert mechanical energy into electrical energy through triboelectricity, thereby offering an efficient and environmentally friendly alternative to conventional power sources. Integrating textiles with triboelectric nanogenerators (TENGs) presents opportunities for sustainable energy generation and the powering of wearable devices. This integration not only facilitates energy generation but also enables the development of self-powered wearable devices, providing users with an eco-friendlier alternative to battery-powered devices. It has the potential to revolutionize the wearable technology industry by enabling continuous and reliable energy harvesting, reducing the reliance on batteries, and minimizing electronic waste.

TENGs have distinct advantages for electricity generation because of their ability to harness mechanical motion and vibrations. Flexible and wearable electronics highly regard TENGs for their ability to convert mechanical energy into electrical energy. Compared with other methods of mechanical energy harvesting, TENGs offer numerous benefits, including high output power, high efficiency, low material costs, and ease of manufacturing. TENGs work by combining the triboelectric effect and electrostatic induction. They can work in four main ways: standing alone, sliding side to side, separating contacts, and using a single electrode. Various approaches, such as increasing the surface area or surface roughness of the triboelectric pair, can enhance the electrical generation of triboelectric nanogenerators (TENGs). It cannot underestimate the importance of fabric friction and its interaction with the TENG mechanism, as friction between materials is fundamental to TENG functionality. An increased friction force results in an improved short-circuit output current, while a cyclic friction force notably enhances the short-circuit output current. The surface morphology and microstructure of the fabric materials, as well as the total surface area that is affected by the microstructure, also have a big effect on how well fabric-based TENGs produce electricity. It is worth noting that excessive friction force, while potentially enhancing TENG performance, can result in a local friction heat temperature, which affects electron transfer and redistribution at the friction interface. Therefore, determining the optimal friction force is critical rather than simply increasing it. In the same way, the surface roughness and dielectric properties of textiles can be improved by using textured yarns and adding structural variations to fabrics (Somkuwar & Kumar, 2022). Furthermore, the creation of triboelectric nanogenerators (TENGs) with alternating grated strips of positive and negative triboelectric materials shows that increasing the contact area, rather than just relying on friction force, can greatly improve the performance (Paosangthong et al., 2019).

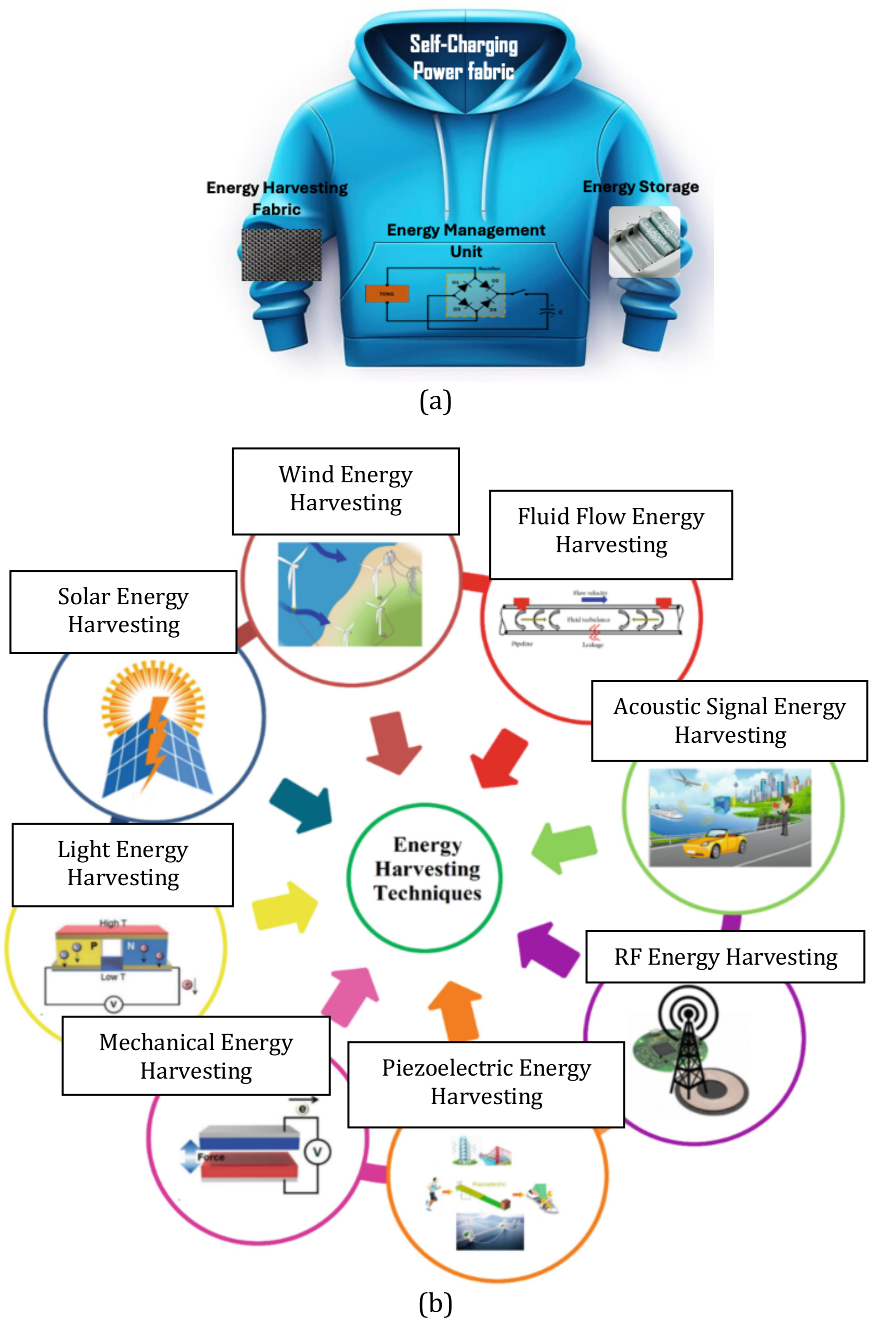

Figure 1: (a) Schematic illustration of self-charging power textiles, including material fabric, energy storage and power unit circuit and (b) Example of energy harvesting techniques.

In summary, the relationship between fabric friction and a triboelectric nanogenerator (TENG) mechanism is complex and multifaceted. While increasing the friction force can improve the TENG output, achieving optimal performance requires a comprehensive approach that considers multiple factors. These factors include the microstructure and surface area of the fabric, and the surface roughness and dielectric properties of the materials used. These findings highlight the importance of a balanced approach that addresses both the friction force and material characteristics to enhance TENG performance (Khwanming et al., 2023; Paosangthong et al., 2019; Somkuwar & Kumar, 2023; Zhang et al., 2023). The study and development of methods and materials for fabric friction energy harvesting encompass various academic approaches. Mechanical energy harvesting from textiles involves piezoelectric, triboelectric, and photovoltaic systems (Chowdhury et al., 2023). For example, incorporating smart piezoelectric fibers into textiles enables the generation of electricity through natural movements, thereby providing power for wearable electronics (Gowthaman et al., 2016). Researchers have also made progress in developing flexible and breathable power generation fabrics that transform biomechanical energy from human motion into stable electricity. These fabrics have dual functionalities as energy harvesters and sensors for monitoring human movement and posture (Qiu et al., 2019). Because they have a large surface area to volume ratio, are strong, and conduct electricity well, 2D materials like graphene could be used to collect energy in electronic textiles (Ali et al., 2024). It is important to consider the comfort and wearability of such textiles, and ongoing research is investigating the impact of functional finishes on textile comfort (Tadesse et al., 2021).

Fabric friction energy harvesting involves diverse and innovative materials and methods, including notable examples such as piezoelectric fibers. The successful integration of these technologies into comfortable and wearable textiles is key to their success and represents a significant area of advancement. Researchers anticipate that the efficiency and feasibility of energy-harvesting fabrics will increase with advancements in materials science and textile engineering, leading to the widespread adoption of wearable electronics (Ali et al., 2023; Gowthaman et al., 2016; Tadesse et al., 2021). The choice of fabric material is important for its electrostatic properties. Natural fibers, such as cotton and wool, have lower electrostatic charges than synthetic fibers, such as polyester and nylon. The combination of natural and synthetic fabrics can optimize the triboelectric effect. Adjusting the ratio of these materials can improve the efficiency of harnessing the triboelectric effect for various applications. Researchers are also exploring the use of nanomaterials to enhance the triboelectric effect and the overall performance of textile-based materials. They are also investigating the integration of alternative energy sources such as solar and kinetic energy to increase efficiency and sustainability. To achieve these goals, researchers are using advanced materials science and engineering techniques, including nanotechnology and biomimicry, to optimize the performance of hybrid textile-based materials. The principle behind the use of fabric friction as an energy source is the triboelectric effect. This effect occurs when the materials come into contact and separate, resulting in the generation of an electrical charge. The efficiency of energy harvesting through fabric friction depends on factors such as surface morphology, roughness, and dielectric properties of the textiles used. For instance, the use of polypropylene and nylon yarn with convolutions and knitted fabric in a three-dimensional configuration result in higher roughness compared to woven fabrics, thereby enhancing the triboelectric performance. Incorporating nanocomposite materials into textiles improves the electrical output and mechanical strength of fabric-based nanogenerators.

Fabric friction, which depends on the triboelectric effect, is a practical energy source. Improvements in textile engineering, like using nanocomposites and changing the structure, have led to better triboelectric outputs. This means that fabric-based nanogenerators are a good choice for self-powered electronics that can be worn. However, researchers still face challenges in optimizing fabric-based energy harvesting, including device stability and durability as well as effective packaging to protect against moisture. Another important objective is to enhance power conversion efficiency. In summary, the triboelectric effect underpins fabric friction as an energy source, capturing and converting small electrical charges generated by fabric motion and contact into usable power through specialized triboelectric nanogenerators. Ongoing research aims to further advance this technology.

In this study, we looked at the most important things to think about when changing the conductor materials for lateral sliding mode triboelectric nanogenerators (LS-TENG). We did this by looking at how the open-circuit voltage, short-circuit current, and output power changed with the conductor size. Positions in the triboelectric series determine the triboelectric properties of nylon and PTFE materials, which facilitate significant electron transfer during contact and separation, thereby ensuring charge separation for solid power generation. These materials' surface properties, high surface roughness, and chemical compositions enhance their affinity for charge exchange, promoting a more effective triboelectric effect. Research shows that triboelectric nanogenerators (TENGs) can power light-emitting diodes (LEDs) through sliding motion. A hybrid nanogenerator combining a triboelectric generator with a thermoelectric generator was able to light up 100 commercial LED bulbs. A flexible magnetic array-assisted sliding mode TENG (MA-S TENG) significantly increased output energy and peak power, enabling it to power more than 10 times the number of LEDs compared to a free-standing mode TENG. We have also discussed the potential applications of these devices, especially in the context of wearable power sources for improved energy harvesting.

2.0 EXPERIMENTAL PROCEDURE

2.1 Basic Theories Triboelectric Nanogenerator Under Sliding Motion

The operation of TENGs is based on the coupling of the triboelectric effect and electrostatic induction. The TENG generates opposing triboelectric charges when its two dielectric surfaces come into contact and separate show in Figure 2 (a)(b). This difference in charges creates an electric potential difference that moves electrons around in the external circuit and makes an alternating current output. The ability to control the charge separation process allows for precise adjustment of the electric potential difference, enabling efficient generation of alternating current. This level of control optimizes the efficiency of alternating current generation, offering a dependable and sustainable energy source. Furthermore, we can continuously monitor and optimize the AC generation process for maximum efficiency, ensuring a consistent and stable energy supply, by utilizing advanced sensors and control systems. Additionally, integrating renewable energy sources, such as solar and wind power, into the AC generation process can enhance its efficiency and sustainability, reduce reliance on fossil fuels, and minimize the environmental impact of power generation. Moreover, incorporating energy storage systems, such as batteries, can help store the excess energy generated during periods of high renewable energy production and release it during times of low production, ensuring a stable and continuous supply of clean energy. Additionally, the integration of advanced power electronics and control systems can further optimize the performance of energy storage systems, allowing for more efficient use and distribution of the stored energy.

Research on the basic theories of triboelectric nanogenerators (TENGs) has been extensive, focusing on their fundamental mechanisms. TENGs operate based on the principles of contact electrification and electrostatic induction, with Maxwell's displacement current as the driving force (Shao et al., 2020). TENGs are electrically neutral all the time because they operate at a low frequency, but they can be modelled as lumped circuit elements. This lets standard capacitive models and Norton's equivalent circuit models be created (Shao et al., 2020). Additionally, researchers have explored the output characteristics of TENGs when connected in series or parallel, revealing that parallel connections can increase the voltage, current, and output power, while the performance of the first and last TENGs in the chain determines the output power of series connections (He et al., 2023). In summary, the basic theories of TENGs revolve around their ability to convert mechanical energy into electrical energy via contact electrification and electrostatic induction. Theoretical models based on Maxwell's equations have been instrumental in understanding and predicting TENG performance. Research has also delved into the optimal conditions for power and energy conversion efficiency, as well as the behavior of TENGs under different circuit configurations (He et al., 2023; Shao et al., 2020). These theoretical insights are crucial for optimizing TENG designs and enhancing their practical applications (Shao et al., 2020; Shao et al., 2020; He et al., 2023).

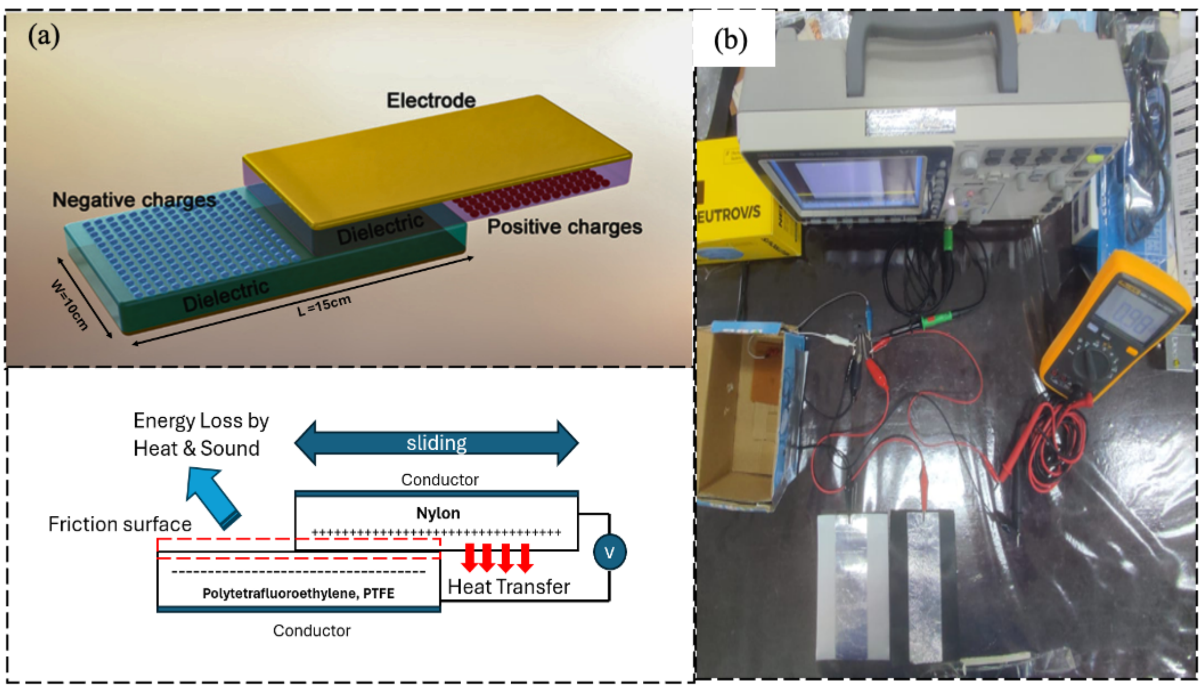

Figure 2: (a) Device structure of an in-plane sliding mode TENG of the dielectric-to-dielectric type and (b) Connection of circuit to measure voltage on nylon-PTFE TENG.

2.2 Material and Methods

Various of reproducible TENGs been used in this study. In this experiment, the output power been evaluated in the lateral sliding mode. A triboelectric nanogenerator (LS-TENG) tested using various experimental setups. Choose of the LS-TENG because it is affordable and simple to manufacture, which is an important factor in this study. Although this alternative approach may not be as comprehensive as the traditional methods, it offers a simpler way to showcase the fundamental principles of lateral sliding in TENGs. In addition, this alternative method offers a clearer explanation of the basics of lateral sliding in TENGs.

Material of LS-TENG

The choice of triboelectric materials is crucial for designing triboelectric devices because they directly affect charge polarity and energy conversion efficiency. Material selection also affects the device's stability and durability. Therefore, a thorough evaluation of the properties and characteristics of each material is necessary before making a final decision. Polytetrafluoroethylene (PTFE) and nylon textiles had been chosen as positive and negative triboelectric materials for the LS-TENG device, respectively. Copper foil has been selected as the conductive material. It measured the thicknesses of the materials at various locations using a digital vernier caliper in different areas to determine the average thickness. The selected Nylon fabric, with a thickness of 0.041 mm, as the positive triboelectric material, and PTFE fabric, with a thickness of 0.050 mm, as the negative triboelectric material due to its widespread availability in the market. The materials were cut into rectangular shapes, approximately 10 cm long and 15 cm wide, as shown below. The thickness of a fabric means the distance between its upper and lower surfaces, measured under a specified pressure. The conductor material was placed, consisting of copper foil with a conductive adhesive on one side, at the center of the dielectric material, with dimensions of 15 cm in length and 5 cm in width. It carefully determined the dimensions of the conductor material to ensure optimal performance and efficient energy transmission.

Construction of LS-TENG

The experimental setup used two materials with opposite charges, X and Y. X is a positive dielectric material, whereas Y is a negative dielectric material. The setup included copper foil electrodes and a load. In the lateral sliding mode, nylon (a positively charged triboelectric material) and PTFE (a negatively charged triboelectric material) repeatedly slide over each other in parallel, generating a triboelectric charge. Initiating charge generation involves intentionally sliding the materials into contact, followed by their separation, which generates output energy.

Output Performance of Triboelectric Materials

To evaluate the performance of the triboelectric material, the connected setup shown in Figure 4 was connected to either a digital storage oscilloscope (GW Instek GDS-2072A) or a digital multimeter (Fluke 15 B+). The analyzed results and compared them with previous data to determine the effectiveness of the triboelectric material in various applications. Solder was used to connect five red LEDs on a Veroboard, powered by an LS-TENG AC power supply. We determined the optimal working conditions for the triboelectric material. We connected the anode and cathode to alligator clips on copper foil and placed the LEDs inside the box for visible light. The study aimed to investigate the difference in charge generation between bare hands and latex gloves using the sliding technique of triboelectric materials. The researchers measured the triboelectric effect in real time and analyzed the results to determine the differences in charge generation between bare hands and latex gloves. Previous studies have focused on the properties of latex gloves and their interaction with surfaces, which is central to triboelectric charging. The researchers also measured the triboelectric effect of different materials, such as cotton and polyester, to compare their charge generation capabilities. The experiment used a nylon/PTFE/Cu LS-TENG circuit connection to monitor voltage and output voltage. The researchers also investigated the influence of capacitance on the voltage generated by the LS-TENG using Arduino hardware and MATLAB Simulink software. A 60-second charging and discharging time has been used to protect the Arduino from potential damage. Three capacitors with values of 0.1 μF, 4.7 μF, and 22 μF were used in the experiments.

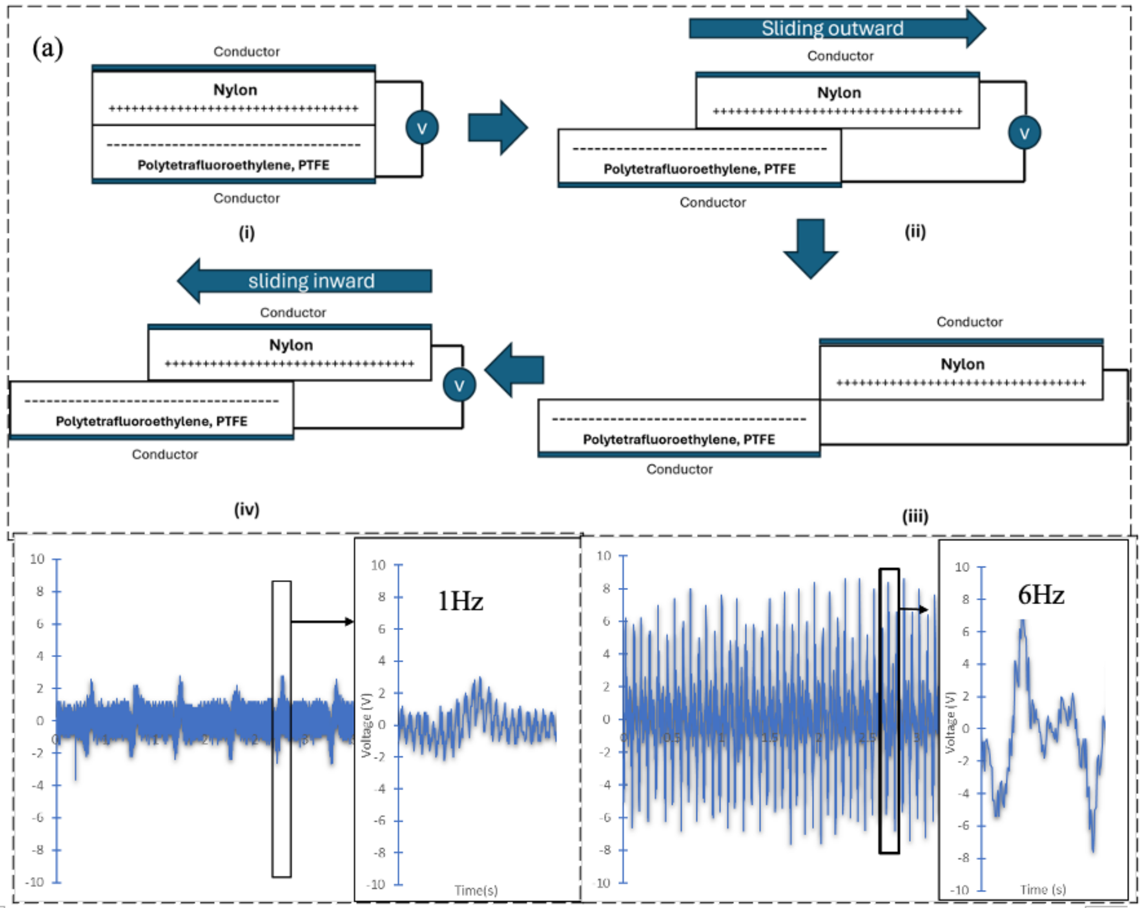

Figure 3: (a) Working mechanism of triboelectric nanogenerator under sliding motion (LS-TENG). The positive triboelectric materials sliding inward and outward to have a contact and separation between the negative triboelectric material (b)(c) Voltage and current output of TENG Component (1Hz and 6Hz).

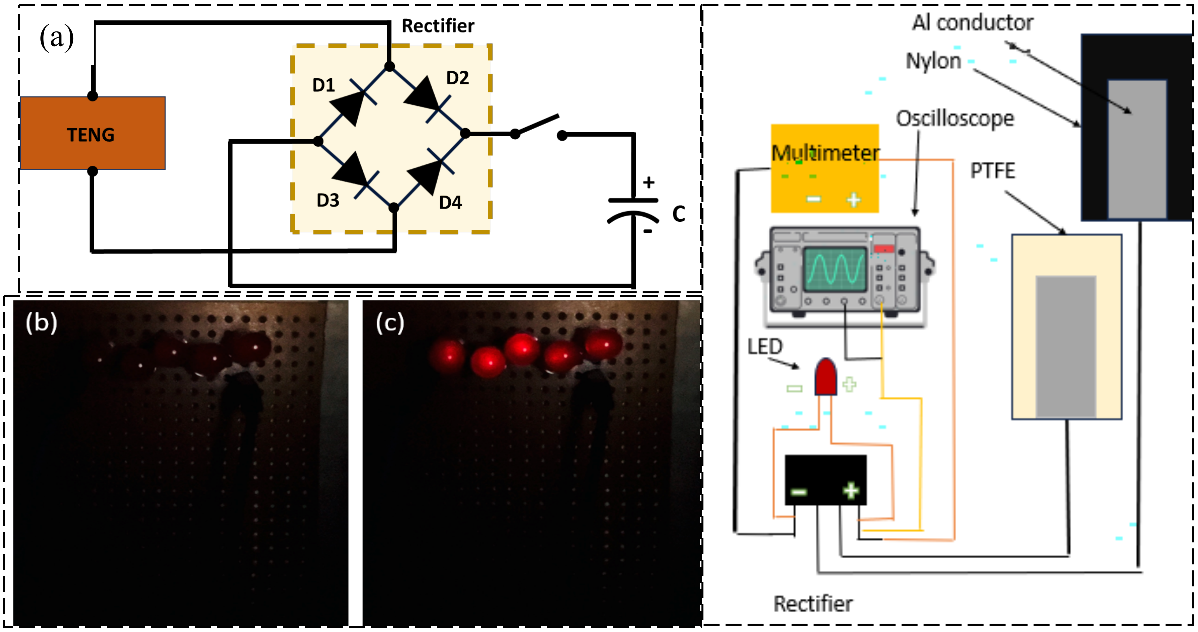

Figure 4: (a) The equivalent circuit of the LS-TENG was connected to a bridge rectifier circuit to produce a DC output voltage. Schematic diagram of LED arrays connected to LS-TENG (b) LED without light up during sliding outward (separation mode); (c) LED light up during sliding inward (contact mode).

3.0 RESULTS AND DISCUSSION

The following section presents the results of each experiment. Herein, we present the results of studies that used LED lighting and measured the voltage and current to demonstrate the performance of the LS-TENG. Initially, the experiment involved manually sliding the red LEDs, both with and without gloves. All tests used PTFE as the negative dielectric, nylon as the positive dielectric, and copper as the conductor material with a frequency oscillation of 2 Hz.

3.1 Performance of Triboelectric Material: LED Test

The LED brightness test was conducted by measuring the luminosity of the light emitted by the LED. The red LED requires a small amount of voltage and current to illuminate because it has a lower forward voltage of 1.6V, which produces red light at wavelengths between 620 nm and 750 nm. When the triboelectric and conductive materials come into contact, the output current flows across the LED terminal. Therefore, the LED array for the nylon/PTFE/Al LS-TENG can be directly used without a rectifier circuit. The results clearly show that, as the contact sliding pressure increases, the LEDs become brighter, and there are no LED lights during outward sliding, which is referred to as the separation mode (Figure 4 (a).

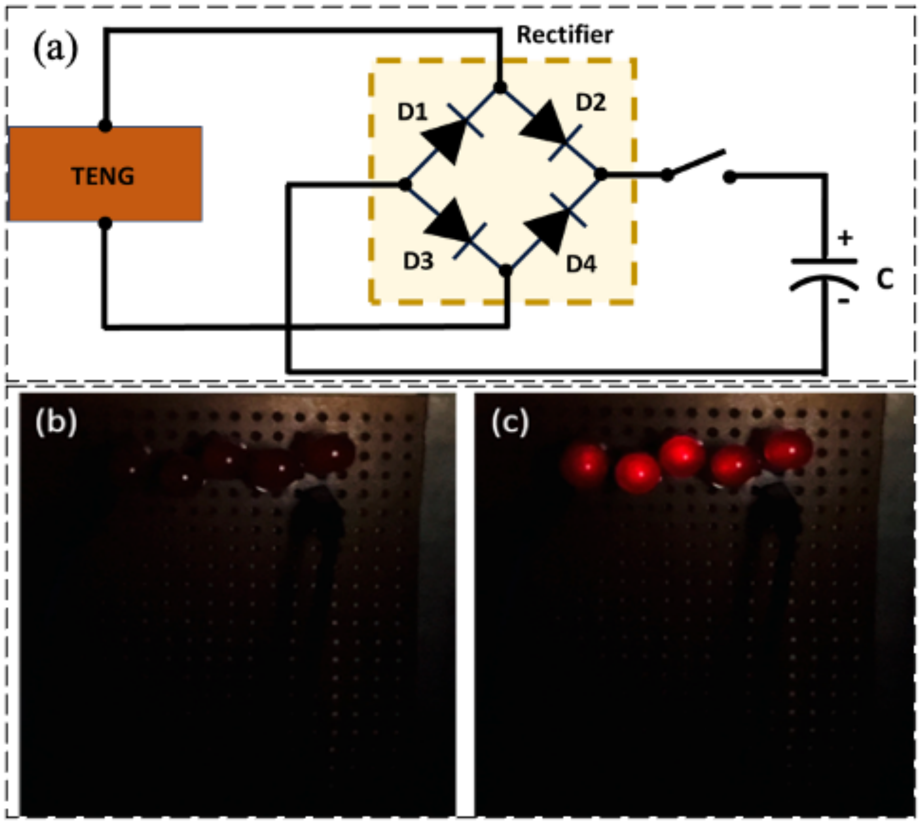

Figure 4: (a) The equivalent circuit of the LS-TENG was connected to a bridge rectifier circuit to produce a DC output voltage. Schematic diagram of LED arrays connected to LS-TENG (b) LED without light up during sliding outward (separation mode).

Using these methods, it was observed that the larger the contact area, the better the contact between the materials and the rougher the surface of the material. The relation in larger contact area generally leads to increased adhesion between two materials. A larger contact area generally leads to increased adhesion between two materials. This is because more surface molecules come into contact, forming stronger bonds. In addition, a rougher surface can increase friction, which can be both beneficial and detrimental. It can provide better grip or traction, but it can also lead to increased wear and tear. This can also be explained by the fact that the surface properties of both the materials, such as their chemical composition, material surfaces, and charge transfer, can influence the amount of electricity generated. The convergence of the material-specific properties is responsible for the ability of nylon/PTFE/Cu to produce higher current levels for LED lighting. Yin et al. (2020), on the other hand, employ a mechanical regulation mechanism to stabilize and control the energy output from irregular motions. In summary, these studies collectively demonstrate the potential of TENGs to power LEDs under sliding motion, with each proposing unique methods to optimize energy harvesting efficiency and output. The ability to illuminate a significant number of LEDs indicates the practical application of these TENGs in various scenarios, including wearable electronics and environmental energy harvesting (Kim et al., 2016; Tang et al., 2019; Yin et al., 2020).

3.2 Impact of Latex Gloves on Voltage Produced

The following data demonstrate the performances of various triboelectric material pairs. The results of this study can be used to determine the most efficient triboelectric material pair for practical applications. A bridge rectifier was integrated into the circuit to evaluate the output voltage and current, and measurements were performed using digital multimeters. The experimental data collected from the bridge rectifier and multimeters were analyzed to identify the optimal triboelectric material pairs for practical applications, which can significantly impact the design and efficiency of future generators and energy-harvesting devices. The nylon/PTFE/Cu LS-TENG produces a DC voltage of 1.1 μA when it attracts current. The performance of the LS-TENG materials was assessed on slides with and without latex gloves. The electrical signal was measured using a digital oscilloscope. The voltage generated without a latex glove was 2V (Figure 5(a)), while the voltage generated with a latex glove was approximately 3.8V (Figure 5(b)). The current generated with the LS-TENG materials when sliding with gloves was 1.8 μA, as measured using a multimeter. Wang et al. [21] reported that impacting the porous PTFE S-TENG with latex resulted in higher output performance compared to impacting it with bare skin. Wang et al. [21] conducted a study which revealed that a porous PTFE S-TENG exhibited improved output performance when impacted with latex compared to bare skin, underscoring the importance of incorporating various materials in electrode design for improved performance. This elucidates the significant difference in latex's ability to attract electrons compared to PTFE and explains why the rough surface of the latex glove primarily contributes to the potential positive effects of using latex gloves, particularly when the sliding motion on a triboelectric nanogenerator reduces friction between the sliding surfaces.

The study by Wang et al. [21] demonstrated that the incorporation of different materials into the electrode design can significantly affect the device's performance. Understanding the unique properties of materials, such as the ability of latex to attract electrons and the rough surface of latex gloves, can lead to improved performance and reduced friction in triboelectric nanogenerators. This can result in a smoother and more efficient movement, thereby enhancing the overall functionality and energy production of the nanogenerator. Additionally, the reduced friction and resistance contribute to the nanogenerator's longer lifespan by reducing wear and tear over time. This increased durability allows the nanogenerator to maintain its efficiency and effectiveness for a longer period, further enhancing its practical applications in various fields. Furthermore, latex gloves can act as insulators, preventing the leakage of electrical charges during sliding motion. This ensured a higher level of charge accumulation and retention, further improving the efficiency of the nanogenerator. The inclusion of latex gloves in triboelectric nanogenerators offers several advantages. First, it can reduce friction, which extends the lifespan of the device and sustains its performance. Moreover, latex gloves can provide a more pleasant and secure experience for the user, protecting against direct contact with potentially hazardous or unclean surfaces during sliding.

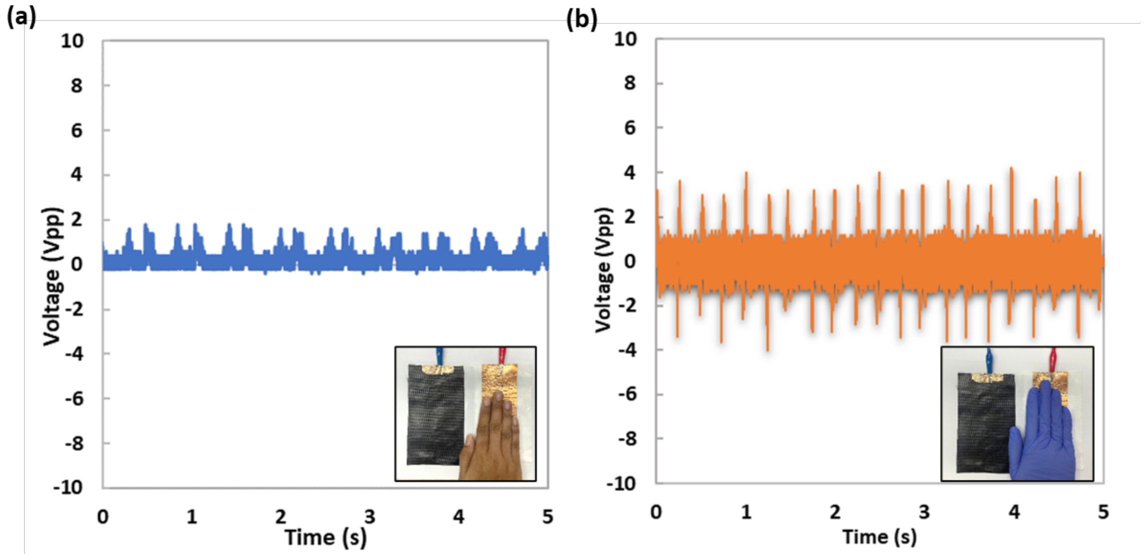

Figure 5: Output voltage produced by the LS-TENG by hand sliding (a) without latex glove (bare hand) and (b) with latex glove.

3.3 Effect of Increasing the Frequency Oscillation

Figure 6 displays the results of a frequency test, conducted between 1 Hz and 6 Hz. The results indicate a direct correlation between the material contact, electron transfer, and triboelectrification. Various factors, including the surface properties of materials and environmental conditions, can influence this relationship. At approximately 1 Hz, the voltage measures approximately 3.4 volts (Figure 6(b)), while at 6 Hz, the voltage increases to 8.2V (Figure 6(c)). These findings suggest that higher voltage is associated with stronger hand slide strength, highlighting the importance of frequency in voltage generation in triboelectric nanogenerators (TENGs). Therefore, it can be concluded that manipulating the voltage and frequency can significantly impact TENG efficiency and output, making them essential considerations in design and application. When two materials come into contact, a triboelectric effect occurs, resulting in electron exchange and the creation of an electric charge. This phenomenon, known as the triboelectric effect, is highly relevant in electronics. By harnessing this effect, faster and more efficient electronic devices can be developed. an efficient electronic device. Increasing the contact and separation cycles and contact frequencies made it easier for charge to separate and electrons to move. This caused more electric charge to build up and a higher output voltage. However, changes in the frequency of material contact have significant implications for voltage generation in TENGs, providing opportunities to optimize their performance in energy harvesting applications. Therefore, a comprehensive understanding of the factors influencing the material contact frequency is crucial for maximizing the voltage generation in TENGs and improving their efficiency in energy harvesting. Research on the impact of increasing the oscillation frequency on TENGs yields varied findings, highlighting the complexity of system dynamics. According to Cao et al. (2024), the dynamic behaviour of a freestanding TENG (F-TENG) system stays the same across operating frequencies.

This shows that the system is robust in terms of its output characteristics. Lv et al. (2022) did an interesting study on an ultra-weak mechanical stimuli-actuated single-electrode TENG (UMA-TENG) to find out how the driving frequency affected the electrical output and how well the energy was converted. These findings suggest that TENGs can perform well across different frequencies, particularly in applications involving ultra-weak mechanical stimuli. To summarize, the effects of increasing the oscillation frequency on TENGs are diverse. While some TENG systems maintain consistent output characteristics across frequencies (Cao et al., 2024), others benefit from higher frequencies, resulting in an improved power output (Jiao et al., 2023; Lv et al., 2022). These results show how important it is to look at the design and use of TENGs individually when figuring out how the oscillation frequency affects their functionality (Cao et al., 2024; Jia et al., 2023; Lv et al., 2022).

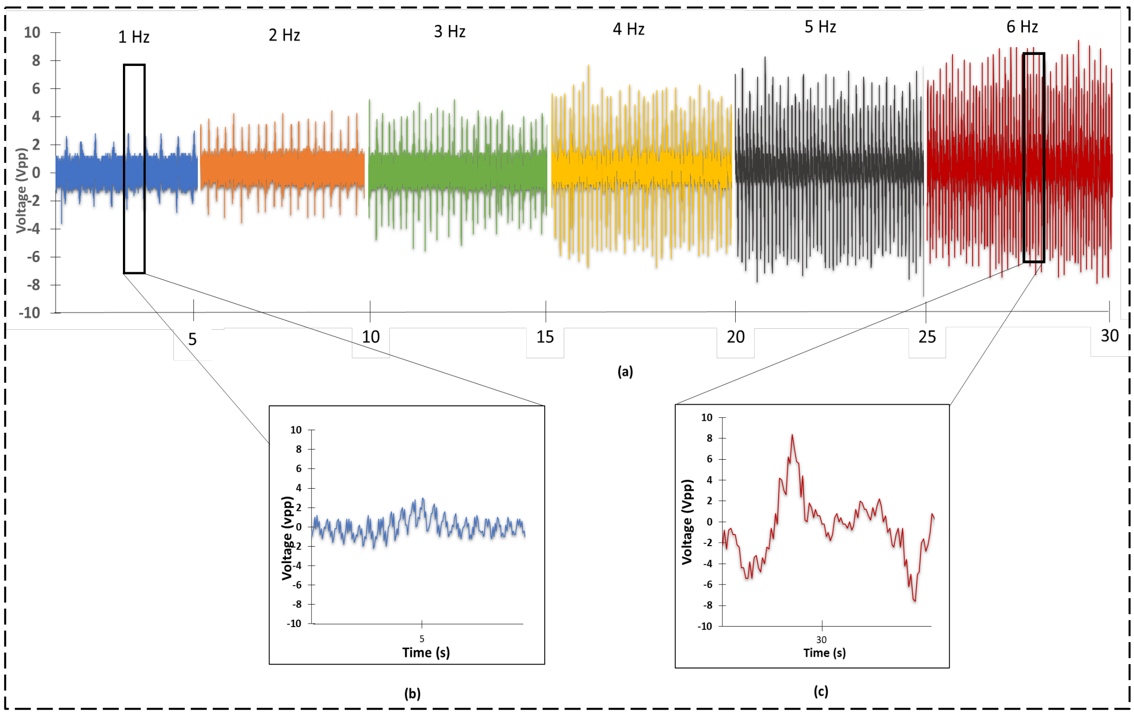

Figure 6: Voltage graph produced when conducting the test with different frequency oscillations between 1 Hz and 6 Hz b) Zoom version of the voltage waveform produced at 1 Hz frequency. c) Zoomed version of the voltage waveform produced at 6 Hz.

3.4 The Electrical Energy Is Stored Using a Capacitor

The capacitance values used in the experiment were 0.1 μF, 4.7 μF, and 22 μF, respectively. Figures 7(a), (b), and (c) show the time-dependent voltages observed for different frequencies and capacitor values. The waveforms in Figures 7a, b, and c demonstrate the varying voltage levels over time for different capacitor values and frequencies. Analyzing the waveforms depicted in these figures is crucial for gaining a better understanding of the relationship between capacitor value and frequency. The triboelectric materials underwent a 120-second process, which consisted of a 60-second charging phase followed by a 60-second discharging phase, with an oscillation frequency ranging from 1 Hz to 3 Hz. The three graphs illustrate the time required for the capacitor to reach its maximum charge and display the maximum voltage attained by the capacitor during the charging process. Figure 7(d) presents data indicating that capacitors with smaller values require less time for full charging and have a limited energy storage capacity. Therefore, the value of the capacitor significantly influences the stored energy and the duration of full charging. Selecting an appropriate capacitor value based on the specific requirements of the application is essential; on the other hand, the 22 μF capacitor takes longer to fully charge but can store a larger amount of energy. Nonetheless, it should be noted that the 22 μF capacitor was charged up to 5 V, which exceeded the voltage limit of the Arduino board. These findings suggest that capacitors with higher capacitance take more time to reach full charge compared to those with lower capacitance. When a capacitor reaches its maximum charge, it has the highest energy-storage capacity. Triboelectric nanogenerators (TENGs) harness the energy they generate during discharge to power existing sensors. This ability of TENGs to harness energy during discharge enables seamless operation of existing sensors. Capacitors, specifically designed for this purpose, widely recognize the phenomenon of electrical energy storage (Morris, 2010). The emergence of supercapacitors, a more recent technological advancement, has garnered significant attention owing to their exceptional power density, extended cycling time, and rapid charging capabilities, rendering them suitable for applications such as hybrid cars (Godse et al., 2014). Factors such as the composition of the carbon material and the construction techniques used in supercapacitor fabrication influence capacitance, which is directly proportional to the stored energy in energy storage systems (Godse et al., 2013; Godse et al., 2014). It's interesting that the usual way of figuring out how much energy capacitors store, using the formula ½ CV^2, has been questioned when it comes to the voltage-dependent capacitances found in semiconductor power devices. Consequently, researchers have implemented circuit design modifications to address the issue of reverse charging in stored energy capacitors, as this phenomenon has the potential to affect their lifespan and efficiency (Liu et al., 2014). Also, the discovery of negative capacitance in ferroelectric materials is a big step forward for making electronics that use less energy. It challenges what we thought we knew about how capacitors behave when they are exposed to voltage (Khan et al., 2014). Capacitors are fundamental components for the storage of electrical energy, offering enhanced performance characteristics. Researchers have learnt more about the capacitance of different materials and how capacitors work in different situations. This has led to more accurate calculations for energy storage and the possibility of game-changing uses in the electronic field (Godse et al., 2013; Godse et al., 2014; Jadli et al., 2020; Khan et al., 2014; Liu et al., 2014; Morris, 1996). Combining dielectric capacitors and ultracapacitors in a hybrid approach aims to increase the amount of energy that can be stored even more. This shows how capacitor technology is always changing (Albina et al., 2007).

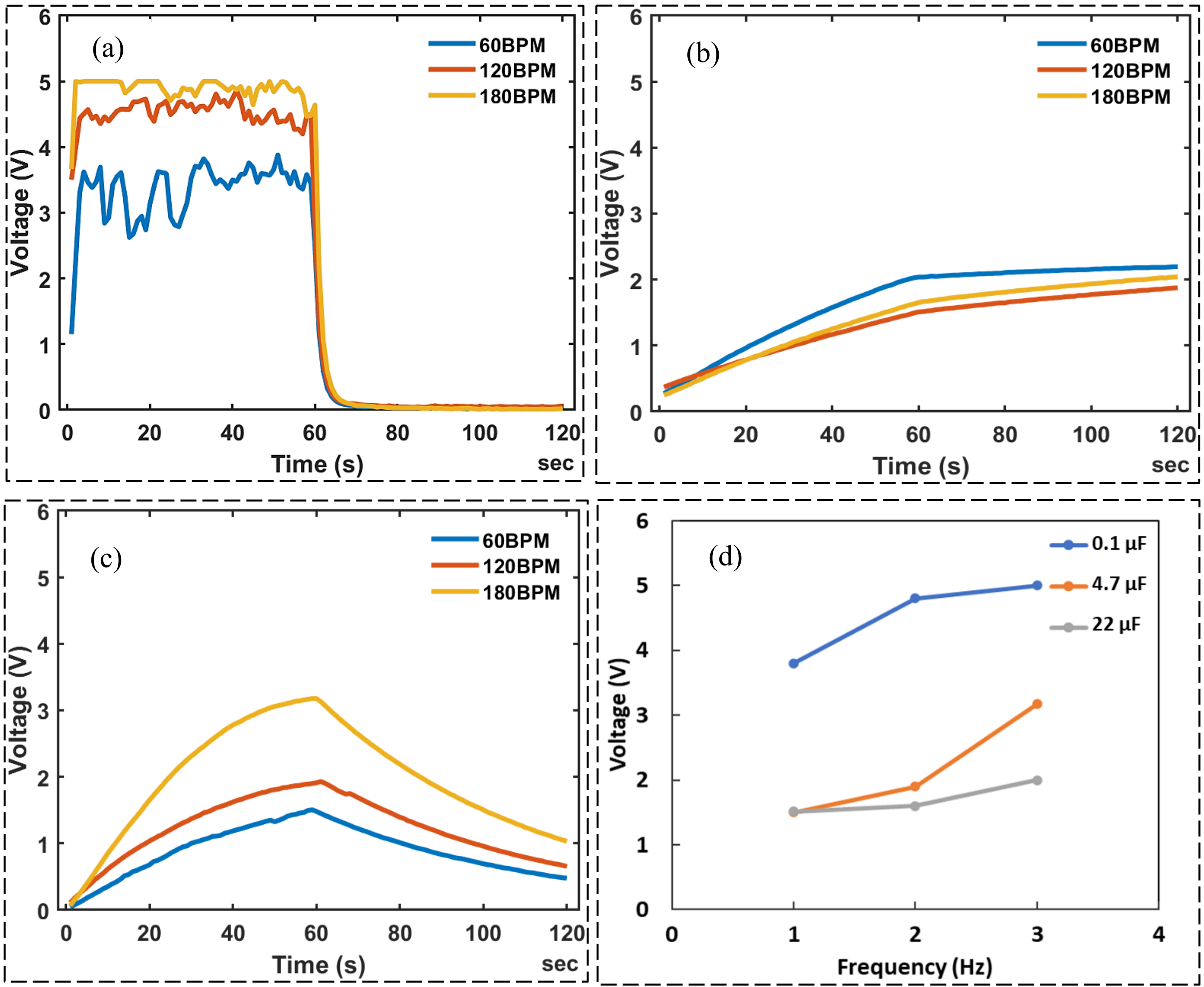

Figure 7: Charging and discharging voltage graph created when performing a capacitance test with (a) 0.1 μF, (b) 4.7 μF and (c) 22 μF (d)Compilation result capacitor at the frequency between 1 Hz and 3 Hz.

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CONCLUSIONS

In conclusion, this research demonstrated the use of PTFE/Nylon as triboelectric materials, and aluminum and copper as conductor materials. The operating mechanism of the fabricated LS-TENGs is based on contact and separation by hand tapping, with one material gaining electrons and the other losing electrons. The comparison of conductor materials, aluminum and copper, provides information on the function of conductor materials in LS-TENG systems. This study contributes to the understanding of ideal materials for effective energy transfer within these systems by examining gaps in conductivity. The output voltage and current were measured using the digital multimeter and oscilloscope with a frequency oscillation of 2 Hz. As a result, the configuration of the fully covered conductor PTFE/Nylon/Cu LS-TENG was able to generate a high voltage of up to 78.8 V and a low current of 1.2 μA. This project contributes to a better understanding of TENG technology and sets a path for practical applications in energy harvesting.

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