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A STUDY ON WATER-BASED TRİBOELECTRİC NANOGENERATORS FOR SELF-POWERED MARİNE ENVİRONMENTAL MONİTORİNG SYSTEMS

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ARTICLE INFO	ABSTRACT
Article history: Received: 2024-10-16 Received in revised form: 2024-10-21 Accepted: 2024-10-25 Available online *Keywords:* *triboelectric nanogenerator, polysiloxane, nylon, origami, self-powered* **2-4 JEL Classifications codes:** O13, N7, P23	*This study focuses on developing an origami-structured triboelectric nanogenerator (TENG) fabricated from nylon and polysiloxane materials. The origami configuration exhibited a superior energy-harvesting capability compared to conventional single-layer designs. The device's output parameters, including voltage and current, were evaluated manually and under stand-alone operational conditions. The hand-operated TENG achieved a peak voltage of 21 V and a current of 2.8 μA. Under autonomous operation, these values were measured at 8.3 V and 1.04 μA, respectively. The results indicate that both external force and operational frequency have a pronounced effect on enhancing the output performance of the TENG. Wave-driven TENGs (W-TENGs) also demonstrated successful energy harvesting from ocean waves, effectively powering low-energy portable devices. These findings underscore the potential for sustainable energy generation in marine environments, positioning TENGs as a viable solution for self-powered marine environmental monitoring systems.*

1. Introduction

In modern times, the growing demand for portable electronic devices—such as smartphones, video cameras, laptops, smartwatches, navigators, and power banks—has significantly influenced daily life, allowing users to engage with technology in a convenient, safe, and efficient manner. This prevalence of devices necessitates reliable and sustainable energy sources to power them. Traditionally, batteries have served as the primary means of electric power supply; however, their limited lifespan and the environmental concerns associated with battery disposal have prompted researchers to explore safer and more sustainable alternatives.

One promising technology that has emerged to meet these energy demands is the triboelectric nanogenerator (TENG) [1-3]. TENGs are versatile devices capable of efficiently harvesting energy from various mechanical sources through the principles of contact electrification and electrostatics. When two dissimilar materials come into contact and then separate, one material acquires a positive charge while the other acquires a negative charge (Figure 1).

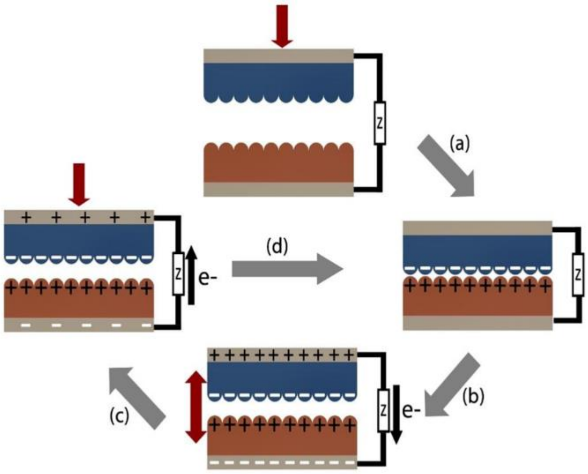

Fig. 1 The mode of operation for contact separation. (a) The pressing phase is when two insulators come into touch with one another due to an external force, creating a triboelectric charge on surfaces. (b) The releasing step causes electron flow between electrodes. (c) A change in the potential difference causes electron backflow when repressing with an external force. (d) The electron flow approaches equilibrium at the point of intimate contact once more is established.

This electrostatic charge remains on the surfaces of the materials as long as they are non-conductive, allowing for an electric current to flow when connected to electrodes [4]. This simple operational mechanism distinguishes TENGs from other energy harvesting systems, enabling them to capture energy from a wide array of sources, including human motion, ocean waves, and wind [5,6].

The efficiency and low production costs of TENGs position them as a significant power source for portable electronic devices. Their broad range of applications has spurred rapid development and innovation, leading to the creation of various structures and TENG-based sensors [5]. These sensors facilitate the acquisition of critical information related to environmental conditions, such as pressure, temperature, humidity, and wind speed, enhancing their usability in everyday life. Moreover, TENGs can effectively harness mechanical and wind energy for applications in military technology, outdoor activities like camping, and scientific research conducted in challenging environments, including mining and mountaineering. In the context of marine environmental monitoring, the increasing demand for sustainable and autonomous energy sources has led to significant interest in developing self-powered systems. Continuous, real-time data collection is critical for assessing and preserving marine ecosystems; however, traditional energy sources such as batteries require frequent maintenance and replacement, especially in remote and harsh ocean environments, limiting their effectiveness. This challenge has spurred interest in renewable energy harvesting technologies, with TENGs emerging as a promising solution [7].

The abundant and continuous motion of ocean waves presents a significant opportunity for energy harvesting, making water-based TENGs a viable candidate for powering autonomous monitoring systems. This study explores the development of a water-based TENG specifically designed for marine environmental monitoring. By leveraging an origami-structured TENG composed of nylon and polysiloxane materials, the research investigates its potential to convert ocean wave energy into usable electrical power. Additionally, the study examines the effects of external force and frequency on the TENG’s performance, along with the potential for wave-driven TENGs (W-TENGs) to power low-energy portable devices in real-world marine environments [8-12].

To enhance the output performance of TENGs, significant research has focused on increasing the contact area of triboelectric materials, which is crucial for optimizing energy conversion efficiency [13]. The development of origami structures that incorporate multiple layers represents a promising approach. By increasing the number of contact surfaces, these designs facilitate the generation of more charge carriers, thereby improving current output and overall power generation.

This research work developed a three-layer origami structure TENG using nylon and polyurethane films. Comparisons were made between electrical measurements of a single-layer TENG and measurements of a three-layer TENG with an origami structure. The obtained electrical measurements show that the TENG with the origami structure yields better results, demonstrating higher voltage and current outputs. Consequently, this leads to an increase in the output power of the triboelectric nanogenerator.

2. Materials and experiment

2.1 Materials and fabrication of triboelectric nanogenerator

In this study, we utilized nylon (specifically, nylon socks made from 100% nylon) and polysiloxane (PS) as triboelectric materials due to their favorable charge-generation properties. The preparation process began with the application of a nylon double-sided adhesive to a pre-made aluminum foil substrate, ensuring good adhesion and stability for the triboelectric components. After applying the adhesive, the assembly was allowed to cure overnight, ensuring that the adhesive bond was strong and effective. The following day, we carefully cut 5x6 cm layers from the adhered nylon material and removed any excess to ensure a clean and uniform interface for charge generation. Simultaneously, we prepared the polysiloxane layer by employing a drop-casting method (Fig. 2a). In this process, a controlled amount of PS was applied onto a separate aluminum foil substrate, forming a uniform film. The drop-casted PS was allowed to dry at room temperature for a full day to ensure complete evaporation of the solvent and proper formation of the film (Fig. 2b). Once the drying process was completed, we also cut 5x6 cm sheets of PS to match the dimensions of the nylon layers.

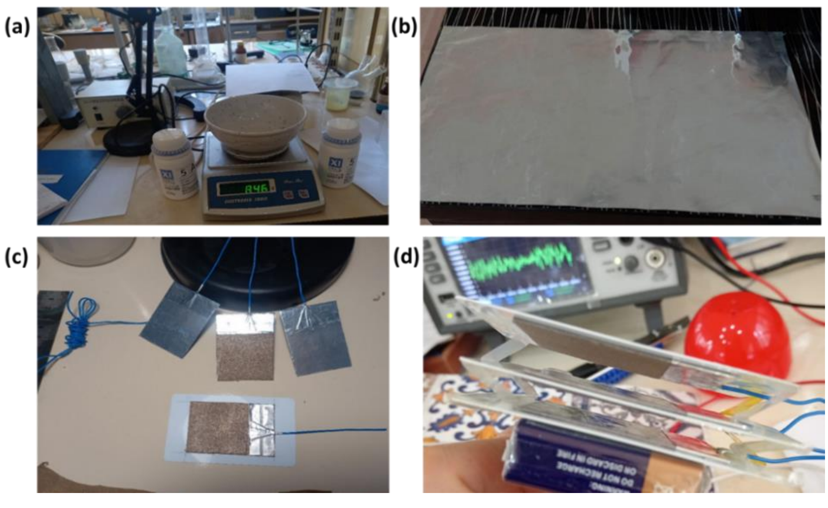

Fig. 2 a) polysiloxane solution; b) investigating of PS films by using drop casting method; c) triboelectric materials; d) prototype of origami structured TENG

The TENG was then assembled by combining the nylon and PS films with the aluminum foil, creating a layered structure that capitalizes on the triboelectric effect. The interaction between the nylon and polysiloxane surfaces is essential for effective charge transfer, with each material contributing to the overall charge generation mechanism. The resulting triboelectric materials (Fig. 2c), with their unique origami-inspired design, are illustrated in Figure 2d.

2.2 Measurement of output performance of TENG

Nylon and PS are used as dielectric materials and aluminum foil as metal electrodes in the manufacture of triboelectric nanogenerators. Nylon and PS are considered good triboelectric pairs because of their distance from each other in the triboelectric series [14]. Samples of both materials measuring 5x6 cm are cut and glued to the pre-prepared Al foil using double-sided glue. Tests on a triboelectric nanogenerator based on PS and nylon materials were performed using a digital multimeter (DMM6500 6-1 / 2 digit multimeter, Keithley). Temperature and relative humidity during the analysis were 30 ° C, and 53%, respectively.

3. Results and discussion

This research utilized nylon and polysiloxane (PS) materials to craft a TENG characterized by its innovative origami-inspired structure. We assessed the performance of the water-based triboelectric nanogenerator (W-TENG) through comprehensive testing and analysis using a digital multimeter (DMM). Our investigation focused on how the output parameters of the W-TENG, including voltage and current, vary with frequency and applied force (Figure 3). To evaluate the efficiency and functionality of the W-TENG, we measured various electrical parameters under different conditions. As shown in Fig. 3, it was observed that increasing the amplitude of the external force from F=0.3 N to 1 N led to a substantial rise in the voltage output of the W-TENG, from U=1.3 V to 10 V (Fig. 3a). Simultaneously, the current increased from I=0.2 μA to 1.54 μA (Fig. 3b). Figure 3c illustrates the relationship between the maximum values of voltage and current intensity of the W-TENG and the applied force.

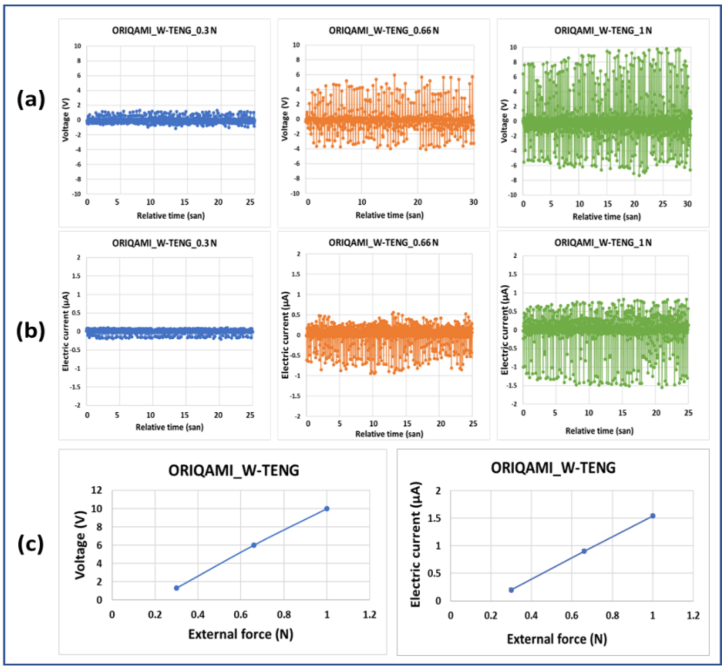

Fig. 3 External force dependence graphs of output parameters of origami-structured W-TENGs: a) Voltage-time dependence of W-TENG; b) Current-time dependence of W-TENG; c) Force dependence of maximum values of voltage and current of W-TENG

These results clearly demonstrate that varying the amplitude of the external force significantly affects the output parameters of the W-TENG. This strong correlation can be attributed to the enhanced interaction between the materials in the W-TENG, specifically nylon and PS . When the external force is increased, these materials come into more extensive contact with each other, resulting in a larger contact area. This increased contact area plays a crucial role in boosting the charge transfer process, as a greater number of charge carriers are generated on the surface during contact. The underlying mechanism driving this phenomenon is based on triboelectric effects and contact electrification principles. As the force applied to the TENG grows, the friction between the contacting materials intensifies, which leads to more significant charge generation.

In TENGs, the effectiveness of energy conversion is highly dependent on the surface interaction of the materials involved. Enhanced surface interaction not only increases the charge density on the contact surfaces but also improves the efficiency of charge separation when the two materials come apart. This separation creates an electric potential difference, resulting in a higher voltage output. The relationship between the output parameters and contact area is critical; as the contact area increases, there is a corresponding rise in the density of static charges on the surface. This phenomenon is a direct result of the triboelectric effect, where the transfer of electrons occurs due to the frictional contact between dissimilar materials. Consequently, a larger contact area not only increases the quantity of generated charges but also enhances the overall efficiency of the energy harvesting process.

Moreover, the greater mechanical deformation due to the increased force also contributes to the efficiency of the TENG. When subjected to higher external forces, the material's structural flexibility allows it to bend or compress more, promoting even more substantial charge transfer through repeated contact and separation cycles. This dynamic response of the TENG to varying forces is critical for optimizing its performance in energy harvesting applications.

As shown in Figure 4, the variation of the TENG's output parameters as a function of frequency exhibited a trend closely resembling that observed with changes in external force. Specifically, as the wave frequency increased from 1 Hz to 3 Hz, the voltage output of the W-TENG rose significantly, from 6.9 V to 11 V (Fig.4a), while the current output increased from 0.6 μA to 1.47 μA (Fig.4b). Figure 4c illustrates the relationship between the maximum values of voltage and current intensity of the W-TENG and the frequencies.

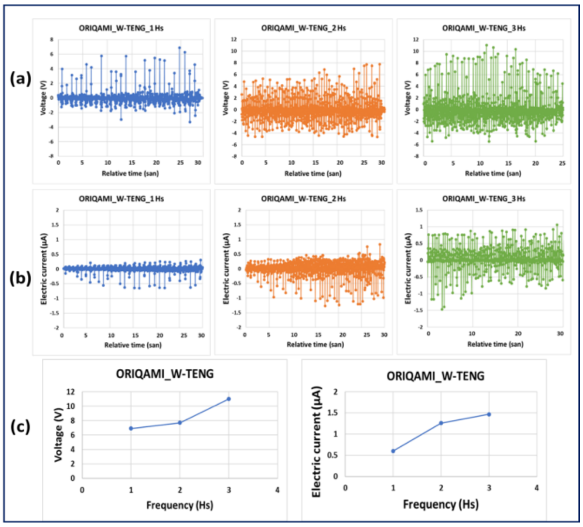

Fig. 4 Frequency dependence graphs of output parameters of origami-structured W-TENGs:
a) Voltage-time dependence of W-TENG; b) Current-time dependence of W-TENG;
c) Frequency dependence of maximum values of voltage and current of W-TENG

This upward trend in output parameters is indicative of a strong correlation between the applied frequency and the TENG's energy generation capabilities. The underlying mechanism for this frequency-dependent increase in output parameters can be attributed to the intensified material contact at higher frequencies. As the frequency of the applied force rises, the nylon and PS materials undergo more frequent cycles of contact and separation. These rapid cycles of interaction lead to a greater accumulation of triboelectric charges on the surface of the materials, thereby enhancing the overall charge density available for energy conversion. This effect is primarily due to the dynamic behavior of the triboelectric layers during high-frequency oscillations. With each successive contact, the speed of charge transfer and separation increases, causing a more efficient buildup of surface charges. As a result, the electric potential difference generated between the layers becomes larger, which directly translates to a higher voltage output. Concurrently, the faster charge movement also boosts the current output of the W-TENG, as a greater number of electrons are displaced per unit of time.

Additionally, the increased frequency amplifies the mechanical vibrations within the TENG structure. These vibrations cause more intense mechanical deformation of the triboelectric materials, thereby maximizing the contact area during each cycle. With a larger effective contact area, more charges can be generated and separated, leading to enhanced triboelectric performance. This mechanical amplification effect explains why the TENG exhibits a more pronounced response at higher frequencies, which is crucial for optimizing its efficiency in various energy-harvesting applications. At higher frequencies, the time interval between each contact-separation event is reduced, meaning that the system experiences less charge leakage between cycles. This reduction in charge dissipation ensures that the charges accumulated on the surface are more effectively utilized in generating electrical output, thereby improving the TENG's overall energy conversion efficiency.

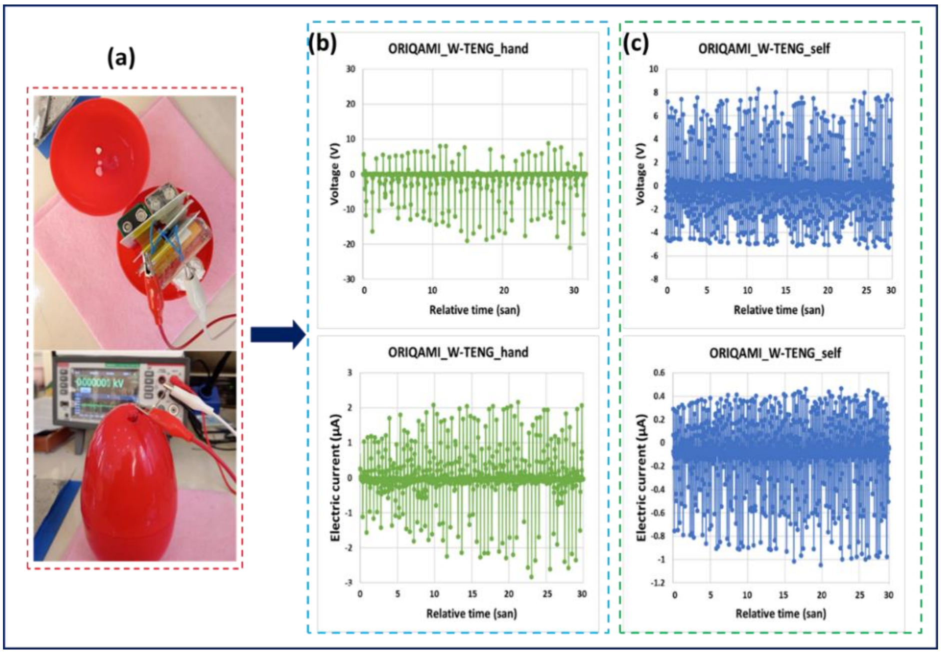

Fig. 5 a) Practical operation of the W-TENG; b) W-TENG voltage and current versus time graphs (manual case); c) W-TENG voltage and current versus time graphs (self-powered case)

Experiments were conducted on the W-TENG prototype, fabricated as depicted in Figure 5, to evaluate its performance under different operating conditions. The output parameters of the

W-TENG, specifically voltage and current, were systematically tested under both manual operation and self-powered system conditions. In the manual operation mode, the maximum voltage achieved by the TENG reached 21 V, with a peak current of 2.8 μA (Fig.5b). Under the self-powered (real mode) conditions, the maximum voltage and current values were 8.3 V and 1.04 μA, respectively (Fig.5c). These results clearly demonstrate the significant influence of external force and frequency on the enhancement of the TENG's output performance. The higher voltage and current values observed during manual operation can be attributed to more controlled and forceful interactions between the triboelectric layers, which lead to an increased contact area and more effective charge transfer. Conversely, in the self-powered mode, the relatively lower output is likely due to the variable and less intense force applied during natural operational cycles, which nonetheless still generates sufficient energy for low-power applications.

Moreover, the study highlights the effectiveness of W-TENGs in harvesting energy from oceanic wave motion, showcasing their potential for sustainable energy generation in marine environments. Figure 6 illustrates the potential practical applications of these W-TENGs. These W-TENGs were able to successfully convert mechanical energy from ocean waves into electrical energy, which was sufficient to power portable electronic devices (Figure 6). This capability underscores the feasibility of deploying TENGs as reliable and eco-friendly energy solutions for offshore and marine-based applications. The successful implementation of wave-driven TENGs opens new avenues for renewable energy technologies, particularly in harnessing ambient energy from natural sources like ocean waves. The robust energy conversion mechanism of TENGs, based on the principles of triboelectric and electrostatic induction, makes them well-suited for applications in remote or underwater environments where traditional energy sources are not viable.

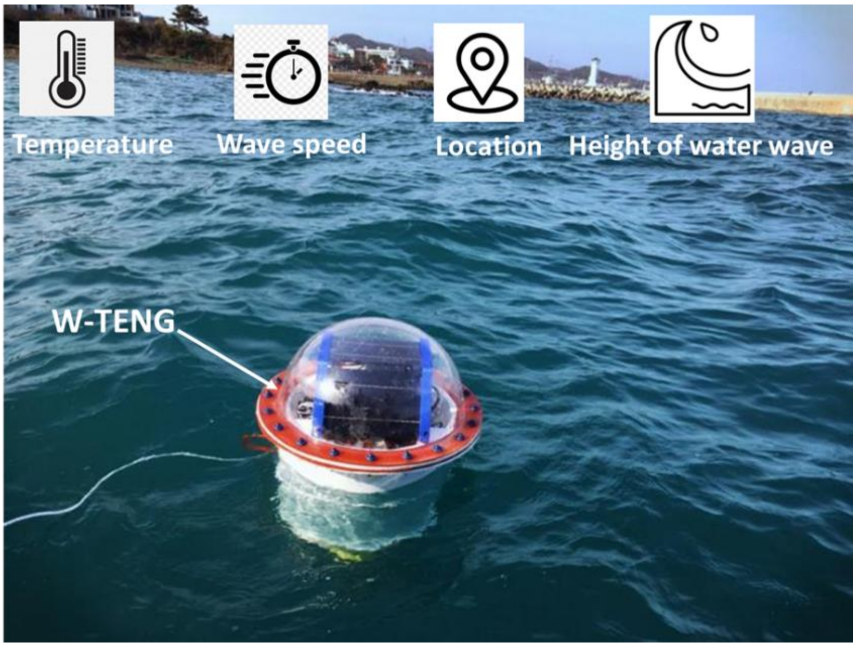

Fig. 6 Application areas of W-TENGs

Furthermore, the scalability of TENG systems presents an opportunity to integrate these devices into larger networks for distributed energy harvesting, contributing to the development of self-sustaining power grids in marine and coastal regions.

4. Conclusion

In this study, we explored the performance of a wave-driven triboelectric nanogenerator (W-TENG) utilizing nylon and polysiloxane (PS) materials, designed with an innovative origami-inspired structure. Through comprehensive testing, we investigated the effects of varying external force and frequency on the W-TENG's output parameters, such as voltage and current. The results showed a significant enhancement in the energy generation capabilities of the W-TENG as both the amplitude of the applied force and the frequency increased. These improvements were primarily attributed to the increased contact area between the triboelectric layers, leading to a more efficient charge transfer and a greater accumulation of surface charges. Our findings highlight the critical role of mechanical deformation and dynamic interactions in optimizing the performance of the W-TENG. The frequency-dependent behavior demonstrated that higher frequencies lead to intensified material contact and rapid cycles of charge transfer, which contribute to improved voltage and current outputs. Additionally, the successful performance of the W-TENG under manual and self-powered conditions further validated its versatility in different operational modes. In conclusion, the W-TENG's innovative design and the successful implementation of wave-driven energy harvesting underscore its potential as a promising technology for renewable energy generation. The correlation between the applied force, frequency, and output performance of the TENG points to a pathway for optimizing its efficiency, making it suitable for a range of applications from portable electronic devices to larger-scale marine energy systems. Future developments in material engineering and structural design could further improve the efficiency and scalability of TENGs, solidifying their role in advancing sustainable energy solutions in diverse environments.

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Conflict of interest

On behalf of all authors, the corresponding author states that there is no conflict of interest.

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