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Review

Research Progress on Friction Nanogenerator Technology for Wave Energy Harvesting

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Abstract: The ubiquitous phenomenon of friction-generated energy, often considered to be of little practical value, has led to the development of a new technology known as friction nanogenerators (FNGs). This innovative technology offers significant potential for the sustained power supply and large-scale harvesting of wave energy, which can be particularly beneficial for ocean sensors. This paper presents an analysis of the current development of FNGs, a detailed description of the principles, operations, and modes of operation of FNGs for wave energy capture, and an investigation of the various FNG structures and their research progress. Additionally, it explores the current challenges and future trends of FNG technology and proposes the integration of FNG technology with other technological fields to provide researchers with a comprehensive understanding of its current status and potential in the field of wave energy harvesting.

Keywords: Friction generation; Friction nanogenerators (FNGs); Global warming; Renewable resource

1. Introduction

With the growth of population and industrial development, the ecological and environmental problems and energy shortages are becoming more and more serious, and the demand for clean energy from renewable sources is becoming more and more urgent. As a

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treasure trove of resources, the ocean possesses abundant resources, among which wave energy, as a broad and sustainable energy resource, has been attracting much attention from researchers. Ocean wave energy, as a hot spot in the field of new energy research, has the advantages of high energy density and wide distribution, and is a clean and renewable high-grade energy source [1,2]. However, the effective collection and utilization of wave energy is still a challenging task [3-5]. Traditional wave energy conversion technologies mainly include wave energy turbines, Tidal energy turbines and wave energy absorbers, but these technologies suffer from defects including susceptibility to harsh environments, high cost and complexity, and certain impacts on the ecological environment. With the development of science and technology, Zhonglin Wang invented the friction nanogenerator technology[6-8].The working principle of the friction nanogenerator mainly combines the friction electrification effect[9-11]and electrostatic field induction[12].This generator can convert wave energy into electrical energy by utilizing the motion of waves and the friction effect between seawater[13-15].When waves pass through the generator, the motion of the waves will generate pressure that causes deformation of the piezoelectric material. This pressure deformation activates the charge separation inside the piezoelectric material and generates a voltage. At the same time, the friction effect plays an important role. When a wave passes through a friction nanogenerator, the friction between the seawater and the generator causes a redistribution of charge, which generates an electric current[16,17].Wave energy conversion technology based on friction Nano generation has the advantages of low cost, environmental suitability and friendliness to the environment, and friction nanogenerators can also be combined with other energy harvesting technologies, such as solar panels[18-21] and wind power generators[22-24] to form hybrid energy sys-tems, which further improve the sustainability and stability of energy sources[25-27]. As can be seen in Fig.1, there is a great potential in the field of wave energy harvesting [28-30]. Friction nanogenerators are being developed or produced in several countries and regions around the world, such as China, the United States, Singapore, and South Korea. It is evident that with the demand for energy and environmental awareness, the global research on friction nanogenerators has been driven. In recent years, because of technological breakthroughs such as advances in material science, innovations in structural design, and developments in integration technology, these results are stimulating researchers to further investigate hot issues such as how friction nanogenerators can improve the output power and efficiency of TENGs, enhance the efficiency of charge generation and transfer, and establish more accurate theoretical models and simulation methods.

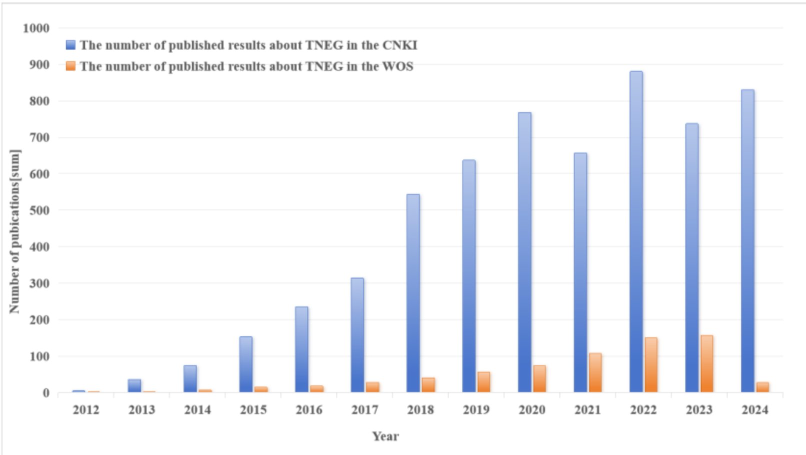


Figure. 1. The Number of published results on friction nanogenerator in WOS and CNKI.

The objective of this paper is to further advance the development of friction nanogenerator technology in the field of wave energy harvesting. This paper presents an analysis of the background of friction nanogenerators with the objective of investigating their potential for wave energy utilization. This paper begins by describing the current research status of friction nanogenerators in the field of wave energy harvesting and their operational principles. It then proceeds to analyze the development of friction nanogenerators by examining domestic and international friction nanogenerators. In light of the aforementioned review, this paper proceeds to conduct a comprehensive analysis and discussion, identifying several limitations and challenges currently facing the field of friction nanogenerator development. In response to these difficulties, it proposes potential development programs, offering constructive suggestions for a more comprehensive understanding of the role of friction nanogenerators in wave energy harvesting and an outlook on future developments. This paper can be utilized as a reference for guiding the field's development to a certain extent. This paper can be considered a guide for the development of this field.

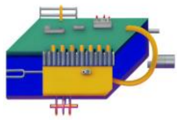
2. Comparing TENG with conventional generators

2.1 Difference between TENG and EMG

Friction nanogenerators (TENG) and conventional generators (electromagnetic generators EMG) are both devices that convert mechanical energy into electrical energy. However, they differ in their operating principles, materials, costs, and applications. The invention of the two devices occurred approximately 180 years apart. In comparison to conventional generators, friction nanogenerators exhibit a number of distinctive advantages. These include their lightweight construction, environmental friendliness, ease of integration into a diverse range of materials, and their ability to operate in low-frequency environments. However, friction nanogenerators may not be as efficient as conventional generators in terms of energy conversion efficiency, stability, and long-term durability.

Table 1. Difference between TENG and EMG.

	TENG	*EMG*

Schema		
Working Principle	Utilizing the principles of friction and electrostatic induction.	Based on the principle of electromagnetic induction.
Manufacturing material	Requires specific friction materials and surface charge density has a large impact on performance.	Requires magnetically and electrically conductive materials, relatively simple structure.
Energy sources	Mechanical energy, e.g. vibration, pressure, fluid flow, etc.	Fossil fuel combustion or natural power such as hydro or wind power.
Frequency requirement for power generation	High or low frequency does not affect TENG power generation.	High frequency (unable to generate voltage at low frequencies).
Energy conversion efficiency	Higher, especially in low frequency environments.	Depends on energy source and technology, usually higher.
Volume and Weight	Lightweight and can be made into films.	Depending on design and energy scale, ranging from portable to large power plants.
Impacts on the environment	Environmentally friendly, no pollution emission.	Depends on type of energy, materials used, manufacturing process, etc.
Application Scenarios	Wearable devices, self-driven sensors, ocean energy harvesting, etc.	Industrial production, household electricity consumption, transportation, etc.
Durability	Short service life needs further improvement.	Proven technology, better durability.
Technology maturity	In rapid development.	Relatively mature technology, applied for many years, widely used in various occasions.

When considered collectively, friction nanogenerators offer a number of advantages in terms of cost, environmental friendliness, and portability. This is particularly the case if they are suitable for the energy supply of small devices and wearables. However, for large-scale energy supply, efficient energy conversion and durability, conventional generators still dominate. Friction nanogenerators have great potential for development, especially in emerging fields such as wearable devices, smart grids, and artificial intelligence. However, they currently face challenges in terms of energy conversion efficiency and stability. As technology continues to advance, it is anticipated that friction nanogenerators will assume a more prominent role in the future.

2.1.1 Electromagnetic-friction electric hybrid nanogenerators

After distinguishing between the two and anticipating their future development, this paper will present an overview of EMG-TENG, a hybrid generator formed by combining TENG and EMG. The combination of the two allows the original disadvantages of each to be solved or even optimized into the advantages of EMG-TENG devices.

In response to the latest research progress of electromagnetic and friction hybridized nanogenerators, Xu Lin, et al. [31] elucidated the principles, materials, structures, and applications of electromagnetic and friction hybridized nanogenerators. They also explained the microscopic charge transfer mechanism of nanogenerators through the most primitive friction initiation phenomenon and electrostatic induction phenomenon. Finally, they targeted the selection of materials and commonly used modification methods for friction nanogenerators. The most commonly used materials for friction nanogenerators, as well as the selection and modification methods for these materials, are introduced. The EMG-TENGs are analyzed separately according to their structures. From the perspective of their mechanical structures, the EMG-TENGs are divided into two categories: vibratory EMG-TENGs and rotary EMG-TENGs. This categorization also demonstrates the concept of universal design of the EMG-TENG structures. The applications of EMG-TENG are summarized, including powering small electronic devices, EMG-TENG-based sensors, and wearable EMG-TENGs. EMG-TENGs have been used in wearable devices and other small electronic devices due to their light weight, small size, and low cost. Nevertheless, the authors and others have identified several limitations of EMG-TENG, including low frequency energy conversion efficiency and the inability to superimpose multi-frequency mechanical energy into electrical energy. Consequently, a future outlook for EMG-TENG is proposed, which includes the development of new technologies to enhance its abrasion resistance and environmental adaptability, as well as improvements to its structural design and material synthesis aspects, application scenarios, and so on.

In the same year, Vidal, João V, et al. [32] also made a related study on EMG-TENG, in which they analyzed in detail the different structures of EMG-TENG, including rotating, pendulum, linear, sliding, cantilever, flexible blade, multidimensional, and magneto-electric, as well as the following hybrid techniques. The conduction mechanisms of EMG-TENG are also outlined, including the model proposed to understand the physical phenomena involved. In addition, a comprehensive analysis comparing their respective structural designs, external excitations, and power outputs is presented. The results highlight the potential of EMG-TENG to convert unused mechanical motion into electrical energy for both large and small scale applications. In a study by Vidal, João V, et al, it was found that the EMG-TENG can provide more efficient vibrational energy conversion by utilizing its desirable complementary high voltage and high current characteristics as well as a wider operating bandwidth. The TENG is able to efficiently harvest electrical energy from low frequency (<1 Hz) and low amplitude (<1 mm) kinetic energy to provide high output voltages. The EMG-TENG can also be connected in series or parallel or used independently to output high voltages or currents to meet the individual requirements and suitability for specific applications. Finally, Vidal, João V, et al. proposed future research directions, namely optimization of energy conversion efficiency, power management, durability and stability, packaging, energy storage, operational inputs, conduction mechanism studies, quantitative standardization, system integration, miniaturization, and multi-energy hybrid batteries.

Electromagnetic-friction-electric hybrid nanogenerators are energy harvesting devices with potential for a wide range of applications, especially in low-frequency mechanical energy harvesting. With the continuous advancement of technology, such hybrid generators are expected to play an increasingly important role in the field of energy harvesting and conversion in the future. Current research on the combination of electromagnetic induction and friction power generation is still in the exploratory stage, and there is still a long way to go before commercial application. Therefore, through the continuous efforts of more researchers, EMG-TENG will one day be practically applied to human production and life.

3. Advances in friction nanogenerators for wave energy harvesting

3.1 Current state of affair

Triboelectric nanogenerator (TENG) is a new type of energy conversion device, which directly converts mechanical energy into electrical energy by utilizing the frictional electrification effect between materials. As illustrated in Figure. 2, this conversion mechanism boasts a simple structure, high energy conversion efficiency, and environmental friendliness, offering a wide range of application prospects across various fields [33-35].

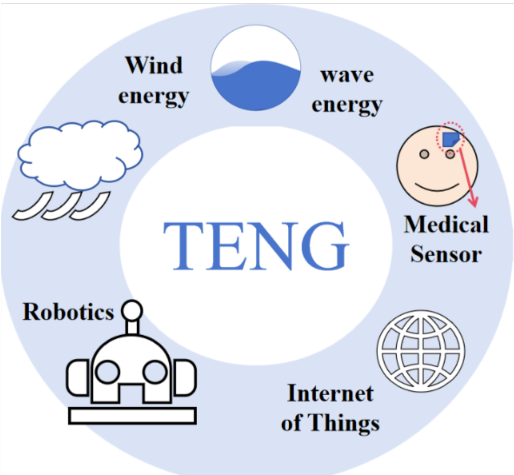


Figure. 2. Application areas of TENG.

In the field of wave energy harvesting technology, the traditional mechanical[36-38] and hydraulic wave energy harvesters[39-41] have made some progress, but there are still some limitations in terms of equipment complexity, maintenance cost, and energy conversion efficiency[42-45].Therefore, the study of new and efficient wave energy harvesting methods has been a research hotspot in the field of wave energy[46-48].The development of friction nano-generation technology presents new opportunities for wave energy harvesting. This technology utilizes the friction between materials to convert mechanical energy into electrical energy, offering the advantages of a simple structure, lightweight design, and low density [49-51].In the field of wave energy, the Friction nanogenerators can capture the fluctuation of waves through devices installed on the water surface or the seabed, convert them into electrical energy, and convert them into electricity that can be used by human beings through electrical energy conversion devices (e.g., inverters). As shown in Table 2, in recent years, great research progress has been made about friction nanogenerators in the field of harvesting wave energy.

Table 2. The History of TENG.

	Design innovation	**Device &performance**	**System &prototype**	**Industrialization**
Micro/nano power sources	Textile/insole/in-vivo/vibration mechanical energy harvester	Power enhancement integnty &durability Flexibilty &biocompatibility	Power management Energy storage Hybridization with PENG, EMG, solar cells, etc	Self-charging power pack Self-powered portable/wearable electronics implantable medical devices Self-powered sensing networks
Self-powered sensing	Self-powered tactile/acoustic chemical/acceleration sensing	Accuracy &resolution Stability &durability Miniaturization	Integration with software platform Big data Machine learning Wireless communication	Smart, low-power human machine interfacing infrastructure/environmental/ traffic/tire condition monitoring in-vivo medical biosensing
Blue energy	Electricity generation via water waves, wind, traffic, etc.	Efficiency enhancement Structural design calability &durability	Power management Connection strategy in coordinated network Small-scale optimization	Large-scale blue/wind energy Location evaluation Lifetime cost analysis Environment impact assessment
HV power sources	Portable HV source	Voltage &frequency Portability &safety	Voltage/current boosting circuit Output control platform Integration strategy	Air quality control Personal health protection Alternative power source for HV instrument

3.1.1 Equipment Innovation and Optimization

Researchers are continuously innovating the design and structure of Triboelectric Nanogenerators (TENGs) to enhance their efficiency and stability in wave energy harvesting. For example, special structural shapes, including elliptical [52-55] and cylindrical friction nanogenerators [56-59], have been investigated. Additionally, significant progress has been made in the development of bionic friction nanogenerators. For instance, Yang et al. [60] xamined an O-shaped multilayer earthworm-like triboelectric nanogenerator (OME-TENG) apparatus for the surveillance of ocean temperature and humidity in the proximity of an ocean ranch. Following rectification and parallel connection, the energy harvested by OME-TENG can readily drive a digital hygrometer to monitor the temperature and humidity of the ocean. Additionally, Liu et al. [61] proposed a friction electrodynamic pressure sensor for underwater sensing, inspired by the lateral line of fish. This research will be significant for the application of friction nanogenerators and the development of an unconventional method for underwater sensing. The energy conversion efficiency and sensitivity of TENGs have been successfully improved by using high-performance materials and optimizing operating parameters [62-64]. Among them, Li et al. [62] found that the detection range of FTEP was as wide as 50 kPa with a sensitivity of 0.21 kPa.

3.1.2 System integration and optimization

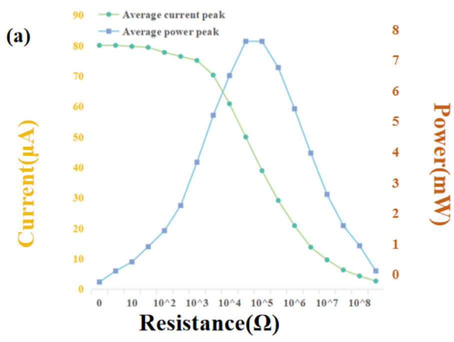
In order to realize the efficient use of wave energy, researchers are also exploring an integrated system that combines TENG with other energy collecting technologies [65] (e.g., solar, wind, etc.). With a view to achieving more efficient and reliable wave energy collection. By optimizing the system layout and control strategies, multiple energy sources can be complemented and efficiently utilized. For example, Shang et al. [66] optimized the control system using pulsed-mode friction electric nanogenerators (TENGs), synchronously triggered mechanical switches (STMS), and other devices, and found that the output voltage and energy of rotating free-standing triboelectric layer pulsed TENGs (RF pulsed TENGs) are maximized.

With the continuous development and improvement of TENG technology, its application prospect in the field of wave energy harvesting becomes more and more broad. However, the current TENG structure design still focuses on the "deterministic" driving force [67-69], and the response to random low-frequency wave excitation tends to be in-termittent pulses [70]. Future research can further explore the TENG structure design method based on the stochastic fluctuation model in order to realize more efficient and stable wave energy harvesting. energy harvesting. Meanwhile, with the continuous emer-gence of new materials and processes, how to apply these new technologies to TENG structures to improve their performance and efficiency is also an important direction for future research. In addition, research on the long-term stability and reliability capability of TENG in the marine environment needs to be strengthened [71].

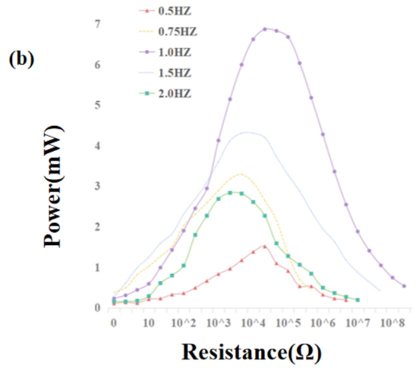
3.2 TENG research development in wave energy harvesting

3.2.1 Output voltage and current

The TENG can produce a certain output voltage and output current during wave energy collection. Its output voltage and current depend on its structure and material, as well as the frequency and intensity of waves. Specifically, as shown in Figure 3, according to the research data referenced to Wang [72], the power generation array composed of four optimized spherical friction nanogenerators has a maximum output power and output voltage of 15.93 mW and 105 V, respectively, and an output current of 225 μA. In general, the voltage and current of the TENG can be adjusted in a wide range to suit different ap-plication requirements. It should be noted that the magnitude of the output voltage and current of the friction nanogenerator in wave energy collection is affected by a variety of factors, including the frequency, amplitude, and speed of the wave, as well as factors such as the structure and material of the friction nanogenerator [73,74].



(a) Spherical TENG device with five cells of average peak current and average peak power resistance relationships under water waves



(b) Output power resistance curves of a spherical TENG with five units at different water wave frequencies

Figure. 3. The data on the effect of different water waves on TENG are known from the data of Wang Zhonglin's study

Therefore, these factors need to be considered comprehensively to optimize the performance of the friction nanogenerator in the field of wave energy collection field.

3.2.2 Environmental stability

Since TENG needs to withstand various environmental changes in wave energy collecting, such as seawater corrosion, salt spray erosion, etc., its environmental stability in wave energy collecting mainly depends on its material's corrosion resistance and resistance to environmental impacts. Therefore, TENG need to have good corrosion resistance and resistance to environmental impacts to ensure their stable operation under harsh environmental conditions [75,76]. Currently, some studies have conducted experimental and simulation studies on the environmental stability of TENG [77]. For example, Yupeng et al. [78] used TiO_2 nanotube coatings to improve the corrosion resistance and environmental durability of TENG. In addition, Chenguang et al. [79] proposed new design concepts and structural optimization methods, and they constructed and designed a new inorganic-coated friction nanogenerator (FM-TENG) based on a common micro-arc oxidation coating for wave energy harvesting and in-situ self-powered cathodic corrosion protection, which was found to not only be capable of self-repair in the event of damage in the complex marine environment. It also has good output performance with a maximum short-circuit current density of 3 mA/m2 and a power density of 2 mW/m2, which is 3-5 times higher than that of the best commonly used solid-liquid triboelectrification material, polytetrafluoroethylene (PTFE) film-based TENG. This approach provides an idea of the environmental stability and efficiency of TENG in wave energy harvesting. Overall, although the environmental stability of TENG in wave energy harvesting still needs to be further improved, it is be-lieved that the future application of TENG in wave energy harvesting will be broader and more stable with the deepening of related research and the continuous development of technology.

In conclusion, TENG, a novel technology for harvesting energy from the ocean, shows great potential for wave energy harvesting. It is therefore of great significance to study the performance enhancement of TENG in practical applications [80-82]. In the future, through in-depth research on the performance of TENG under different operating conditions, the design of TENG can be optimized, its power generation efficiency can be improved [83-87], and the manufacturing cost and durability of TENG can be solved. This will facilitate the wide application of TENG in the field of ocean energy and the development of more efficient and stable TENG equipment.

4. TENG's mode of operation

4.1 Contact Separation Model

As shown in Figure 4, the contact separation mode [88-92] of TENG is divided into three parts: the contact separation interface, the electrodes and wires, and the energy storage element. Among them, at the contact separation interface, two different materials generate friction charges by contacting and separating and thus creating friction charges; when they contact, one part of the material acquires a positive charge and the other part acquires a negative charge. When they separate, the charge does not disappear immediately, but rather a charge separation is created on both sides of the interface, which generates a voltage, which creates a potential difference, which in turn generates a current, which is then transmitted by a wire to the load device. The energy storage components required for this approach usually include capacitors, batteries, etc. This mode was one of the first to be proposed, and it is widely used in areas such as mechanical energy collecting, self-driven sensors, and biomechanical energy.

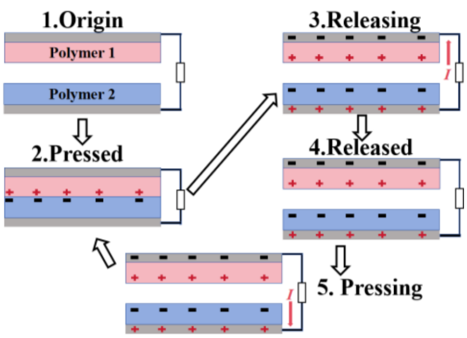


Figure. 4. Schematic of the contact separation pattern of the friction nanogenerator.

4.2 Slide Mode

The slide mode TENG [93]is an effective in-plane, low-frequency mechanical energy collecting technique. As shown in Figure 5, in this mode, the TENG works by sliding two objects relative to each other, creating a friction electric effect, which results in a charge separation between the two objects, generating electrical energy that is then stored by a capacitor or other energy storage device. In sliding mode, the output performance of TENG is affected by a variety of factors, such as the choice of material, sliding speed, and pressure. Generally speaking, the faster the sliding speed and the higher the pressure, the better the output performance of TENG. However, there are some problems with the sliding mode TENG, such as the surface modification of friction material and charge excitation strategy cannot be well applied to this mode, which leads to some limitations in its practical application. Therefore, the energy storage density and efficiency of this system also need to be further improved to meet a wider range of applications.

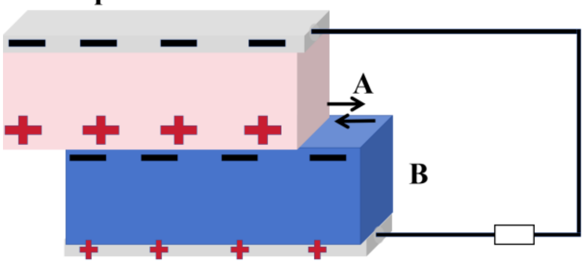


Figure. 5. Schematic of the contact separation pattern of the friction nanogenerator.

There are two operational modes of friction nanogenerators: contact-separation and sliding modes. Both modes rely on the friction electric effect to generate electrical energy but differ in their energy conversion mechanisms. The contact separation mode is concerned with the rapid accumulation and release of charge through contact and separation actions, whereas the sliding mode is focused on the continuous transfer of charge through continuous friction action. These two modes can be employed individually or in combination to enhance energy harvesting efficiency and stability. In practical applications, depending on the specific energy harvesting scenarios and requirements, designers can select the most appropriate operation mode or combine the two to optimize the performance of TENG.

In summary, the TENG device converts collected wave energy into electrical energy and stores it in capacitors. These capacitors can be used for power supply as well as for other applications such as driving small devices or powering small electronic devices. Therefore, we can call the operation of the TENG energy storage system in wave energy collection an efficient and environmentally friendly way of collecting and storing energy with a wide range of applications.

5. TENG's method for harvesting wave energy

The main collecting method of the friction nanogenerator in wave energy collection is by utilizing the mechanical energy generated by wave motion and converting it into electrical energy. Specifically, when the wave moves, the contact surfaces inside the friction nanogenerator produce relative motion, which generates friction and thus voltage. In addition, because friction nanogenerators have a nanoscale structure, they have an extremely high energy conversion efficiency [94-97]. In practical applications, friction nanogenerators can be designed in various forms to accommodate different wave energy collecting needs.

5.1 Buoy-type structures

As shown in Figure 6, in a TENG buoy-type structure, the buoy is typically designed to move up and down in response to the ebb and flow of waves. This movement results in a contact-detachment motion between the buoy and the electrodes fixed to the seafloor, which triggers a friction electric effect. In this process, an electric field is created between the buoy and the electrodes, and when they come into contact and separate, a charge transfer occurs between them, resulting in an electric current. Hyunjun et al.[98]In order to overcome the limitation that the electrical output power obtained from wave energy harvesting by friction nanogenerator systems is usually limited to a few milliwatts, and to support a variety of ocean buoy systems in the TENG buoy-type structure, they proposed a self-powered ocean buoy (SPOB)with a disk-type, soft-contact, mechanically frequency-regulated friction nanogenerator (DSMFR-TENG), which demonstrates the power sup-ply capability of the friction nanogenerator system to the ocean buoy after step-by-step testing. his structure has many advantages, such as simple structure, low cost, easy maintenance, and it can effectively utilize the energy of ocean waves. However, it also has some limitations, for example, the efficiency of energy collecting may be affected by the size and frequency of waves [99].

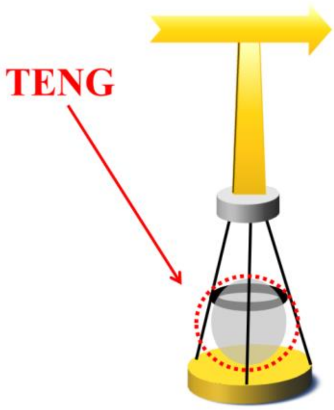


Figure. 6. Schematic diagram of TENG's Buoy-type structure.

5.2 Oscillating Column Structure

The oscillating column (OC) structure of TENG [100-102] is a key design element, which is usually a key component mainly responsible for realizing the generation and control of oscillating motion to generate electric energy. The oscillating arm is usually made of an elastic material that can perform a reciprocating motion within a certain range, and as shown in Figure 7, this structure can effectively increase the contact area and contact frequency to improve the energy conversion efficiency. At the same time, the structural design and material selection of the oscillator arm also affect the performance of the device, such as output voltage, current and power. Therefore, the specific structural design of the oscillator arm can be adapted according to the application scenario and target performance of the TENG [104]. For example, Reilly et al [103] designed and fabricated an OC with tested TENGs of different materials to determine which parameters are critical for im-proving the energy conversion efficiency, which was used to demonstrate the OC-TENG system under simulated ocean waves. Or, for example, Xinyu et al. [105] To increase the operating frequency of the device, the TENG structure of the oscillating arm was designed to respond quickly to input mechanical vibrations with low wear.

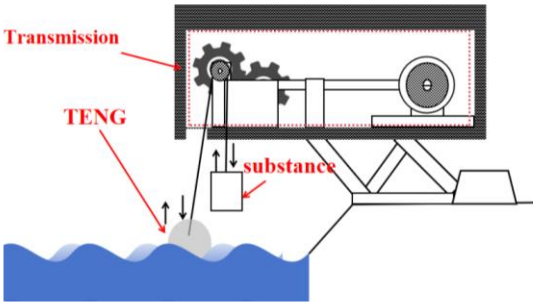


Figure. 7. Schematic diagram of TENG's Structure of the Oscillating Arm.

5.3 Subsea structures

A subsea structure TENG is a device that utilizes the frictional electrical effect created by the flow of seawater to generate electricity. Such devices usually consist of two different pieces of material, for example [106], As shown in Figure 8, Marine Current Turbines built a device consisting of a pair of 16-meter propellers and a central tower fixed to the bottom of a channel, where the propellers are connected to the central tower.

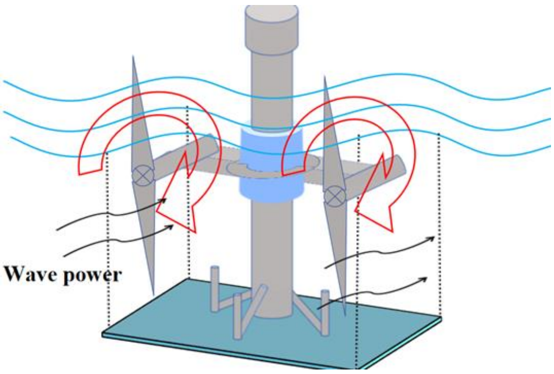


Figure. 8. A device made by a Marine Current generator to collect wave energy.

OpenHydro designed a seabed-mounted turbine with a central motor as the only moving component. These are typical examples of collecting tidal energy. When seawater flows through these two pieces of material, they create a separation of charges due to their different friction electric effects, which creates voltages and currents. The device utilizes the friction electric effect to convert the energy of seawater flow into electricity. The advantage of this generator is that it can effectively utilize ocean energy and does not cause much impact on the marine environment. However, most efforts are still focused on stationary TENG due to their simple structural design and device fabrication, but the inherently unavoidable wear and tear problem on solid surfaces and high environmental sensitivity (e.g., humidity and atmospheric pressure) severely limit the durability and stability of stationary TENG [107,108] and hinder their further application in long-term power supply and high-precision self-powered sensors.

5.4 Wave-driven rotating device

Hao et al. [109] developed a stackable friction nanogenerator (S-TENG) based on the advantages and disadvantages of wave-driven TENG. This forms multiple channels carrying polytetrafluoroethylene spheres between each layer of aluminium electrodes of the device. The peak power density of the S-TENG was found to reach 49 W/m3 under the experimental study by Hao et al. Furthermore, after optimization, the S-TENG is no longer susceptible to changes in excitation direction, allowing it to be more flexibly integrated into a variety of platforms under practical conditions. In practice, Hao et al. demonstrated that the S-TENG can self-power many compact ocean buoys. However, this research has not yet reached the level of wave-to-wire model, indicating that the task of researching wave-driven TENG is still a long way from completion.

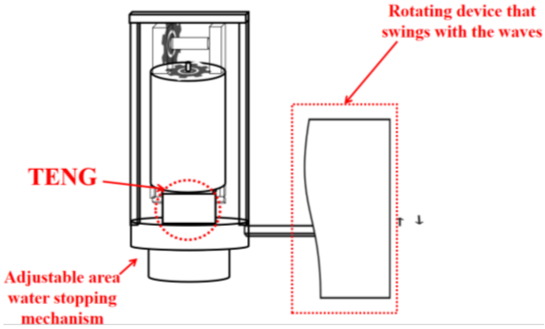


Figure. 9. Schematic diagram of TENG's Wave-driven rotating device.

5.5 Flexible structure

As shown in Figure 10, the flexible structure of the TENG [110-112] is a unique TENG device design that draws inspiration from the natural structure of seaweed. This construction is intended to lower production costs while increasing the TENG's stability and efficiency [113]. The primary components of this apparatus are two sheets of PTFE, conductive ink-covered PET, and conductive ink-covered fluorinated ethylene propylene (FEP). The device's structure is intended to be extremely flexible and adaptive, enabling it to function effectively in a variety of settings and situations without the need for extra protection. Furthermore, the utilization of conductive ink and plastic materials results in comparatively inexpensive manufacturing costs for this structure, hence facilitating mass production and increasing application popularity. This TENG structure has several uses across numerous industries in addition to having a great deal of promise for wave energy gathering. One efficient method to achieve the self-driven operation of underwater sensors for the Marine Internet of Things (MIoT) is to use it, for instance, for the energy supply of offshore buoys and underwater power plants. For instance, it can be utilized for energy supply of offshore buoys and underwater power plants. Furthermore, this TENG device structure's great degree of flexibility and adaptability makes it useful in wearable technology, smart homes, smart transportation, and other areas, improving our lives' ease and opportunities.

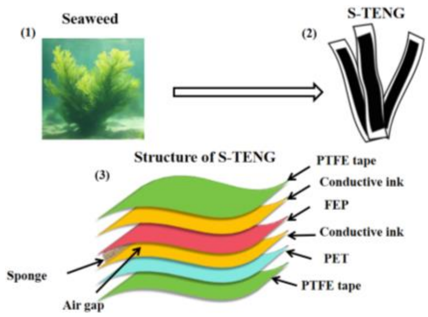


Figure. 10. Schematic diagram of TENG's Flexible structure.

Table 3. Performance comparison between TENGs of different structures

	Buoy-type structures	Oscillating Column Structure	Subsea structures	Wave-driven rotating device	Flexible structure
Working Principle	Using the friction electric effect of a buoy moving up and down with the waves	Using the friction electric effect produced by the reciprocating motion of an oscillating column	Exploitation of friction electric effects produced by changes in seafloor pressure or geological activity	Converts wave energy into electrical energy by using wave-driven rotating parts.	Friction electric effect using deformation of flexible materials
Energy conversion efficiency	Depending on the size and frequency of the wave, it is usually suitable for low to medium frequency wave energy collection.	Depending on the amplitude and frequency of oscillation of the column, wave energy may be applicable to a specific frequency range	The dynamic nature of the subsea environment requires special designs to improve efficiency	Dependent on the design of the wave-driven rotating device and the input of wave energy	High, because flexible materials can effectively capture all kinds of motion energy
Environmental adaptation	Better, can work on the water for a long time	Medium, more affected by waves and currents	Less favourable. The seabed environment is complex and may require special materials and protective measures	Suitable for use in areas with active waves. The effect of waves on rotating parts must be taken into account.	Excellent, flexible structure resists bending and twisting

It is important to note that the specific form and design of friction nanogenerators for wave energy collecting depends on a variety of factors, including the characteristics of waves, the location and available space of the energy collecting device, and the trade-off between cost and efficiency. Therefore, according Table 3，for different application scenarios, its customized design and optimization may need to be further investigated to improve its energy conversion efficiency and stability.

6. Artificial Intelligence Combined with Friction Nanogenerators

Artificial Intelligence (AI) is a broad field that seeks to develop theories, methods, technologies and applications that can simulate, extend and augment human intelligence. It includes several subfields such as machine learning, deep learning, and natural language processing. Machine learning is a core subfield of AI that focuses on developing algorithms that enable computers to learn from data and make decisions or predictions without explicit programming instructions. Machine learning algorithms can be further categorised into different types such as supervised learning, unsupervised learning and reinforcement learning. An algorithm is a well-defined set of computational steps for solving a particular class of problems or performing a particular computational task. In the context of machine learning and artificial intelligence, algorithms usually refer to the mathematical processes used to train models and extract knowledge from them. In short, all machine learning algorithms are algorithms, but not all algorithms are machine learning or artificial intelligence. Machine learning algorithms are algorithms designed to learn from data, while AI is a broader framework that encompasses a wide range of techniques and methods, including machine learning.

The convergence of artificial intelligence (AI) and friction nanogenerators (TENG) is emerging as a burgeoning field of research with the potential to address the challenges inherent in the design and optimization of friction nanogenerators, as well as to facilitate the advancement of next generation nanogenerator systems. The combination of these elements, in the form of physics-based AI inverse design, performance optimization of rotating friction nanogenerators, AI-enhanced mathematical model, and the combination of friction nanogenerator arrays and machine learning, has enabled researchers to gain a deeper understanding of friction electric phenomena, discover new conducting and dielectric materials, and optimize contact interfaces to improve the performance of friction nanogenerators. This paper will briefly list a few examples of AI and TENG optimized in conjunction with each other.

6.1 Optimizing the performance of TENG through the Gray Wolf algorithm

Liu and Lu [114] propose a new method for parameter identification of generator excitation systems based on the improved Gray Wolf algorithm. This algorithm employs a group-seeking partitioning strategy and a nonlinear decreasing strategy of con-vergence factor to enhance the standard Gray Wolf optimization algorithm. The authors apply this method to the identification of generator excitation systems and demonstrate that it yields high identification accuracy and stability. Furthermore, they argue that this method represents a novel and effective approach for nonlinear parameter identification.

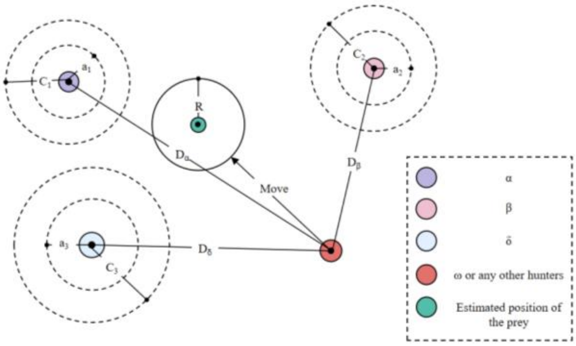


Figure. 11. The Gray Wolf Algorithm's Approach to Position Updates.

In addition to the novel approach derived in conjunction with the generator excitation system, researchers from Flinders University, Australia, and the University of Technology, Sydney, collaborated with the Gray Wolf algorithm to propose a performance model for rotating friction nanogenerators (TENGs). This model can be used for performance optimization and to reduce the number of repetitive experiments. By analyzing the effects of geometry and motion on the power generation energy of rotating friction nanogenerators, the researchers found that the power generation capacity is related to sector spacing, an-gular velocity, friction area, and external resistance. The performance of the rotary friction nanogenerator with different shapes and working conditions was analyzed using the Gray Wolf algorithm, which optimized its design. This resulted in an optimized rotary friction nanogenerator that can generate up to 0.369 mJ of electricity in a single cycle.

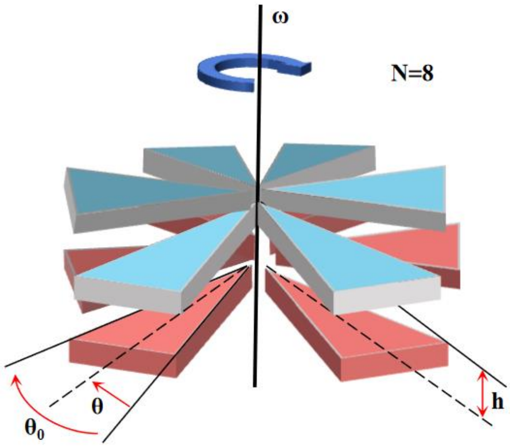


Figure. 12. Rotary TENG Performance Model.

A system that combines the Gray Wolf algorithm with friction nanogenerators may be more efficient in wave energy harvesting. By optimizing the design of the friction nanogenerator, its ability to capture wave energy can be enhanced, particularly under irregular wave conditions. Furthermore, the Gray Wolf algorithm can be employed to optimize the array layout of the wave energy converter, thereby improving the energy harvesting efficiency of the entire system [115].

In conclusion, the combination of the Gray Wolf algorithm and the friction nanogenerator has the potential to optimize wave energy harvesting, which can improve the efficiency of energy conversion and facilitate the applications in wearable devices, implantable devices, and environmental energy recovery. However, there is a paucity of specific cases and detailed data on this combination application. It is hoped that future research will further explore and validate the practical effects of this combination.

6.2 Artificial Intelligence Enhanced Mathematical Model

The application of artificial intelligence-enhanced mathematical model can assist researchers in comprehending the output characteristics of TENG under diverse kinematic and geometric conditions. By developing precise mathematical model in conjunction with AI algorithms for sensitivity analysis, intricate relationships between energy generation and matching resistance and structural parameters can be elucidated. Such model can inform the experimental design, reduce the number of superfluous tests, and expedite the optimization process.

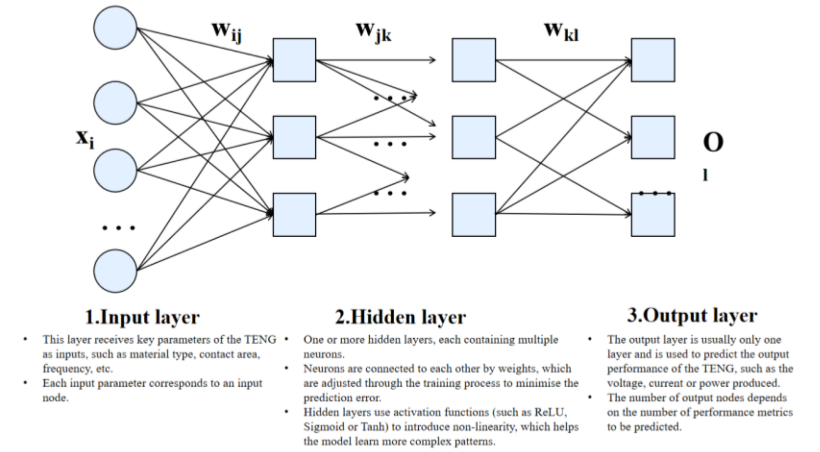


Figure. 13. Flowchart of mathematical model algorithm.

A study conducted by Khorsand, Mohammad, et al [116]. investigated the potential of artificial intelligence-enhanced mathematical model of rotating friction nanogenerators under various kinematic and geometrical conditions. The findings revealed that the power generated by TENG is a function of the number of segments, rotational speed, and friction surface spacing. To further enhance the understanding of TENG output, the mathematical model was combined with artificial intelligence. A sensitivity analysis demonstrated that the energy produced and the matching resistance were highly dependent on the segment and angular velocity rates. The results indicate that the optimal harvested energy per cycle is 0.369 mJ. This study contributes to the understanding of rotationally induced periodic friction nanogenerators and reveals the optimized characteristics of a disc-shaped friction nanogenerator energy harvester.

The AI-enhanced mathematical model facilitates the observation of the output characteristics of TENG under varying kinematic and geometrical conditions, thereby streamlining the experimentation process for TENG-based wave energy harvesting for power generation in the ocean. This approach reduces the number of unnecessary trials and accelerates the optimization process. The combination of the two allows researchers to optimize the characteristics of TENG itself and to discover the development direction of combining other AIs with TENG. This enables the efficiency and stability of TENG in wave energy collection to be effectively improved.

6.3 Combining TENG and Machine Learning

Machine learning is an artificial intelligence technique that allows computer systems to learn through experience and improve performance without explicit programming. Machine learning algorithms can process large amounts of data, extract useful information from it, and make predictions or decisions. When friction nanogenerator arrays are combined with machine learning, a variety of innovative applications can be realized. For instance, friction nanogenerator arrays can be employed to harvest mechanical energy from the surrounding environment and transform it into electrical energy. The collected data can then be processed and analyzed by machine learning algorithms to perform specific functions, such as speech recognition, gesture recognition, environmental monitoring [117] and numerical simulation [118].

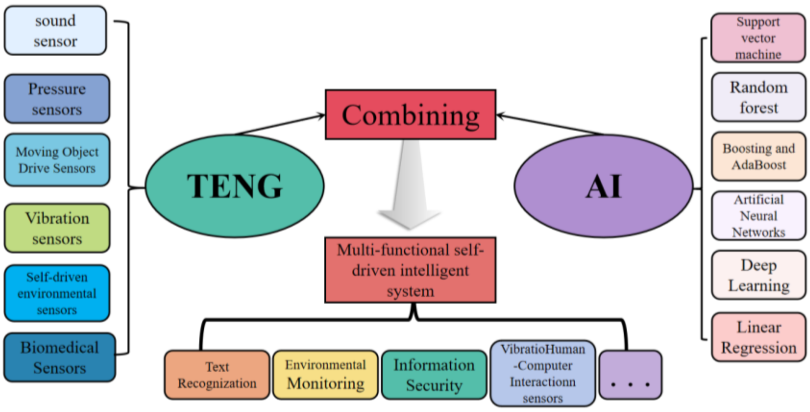


Figure. 14. Structure diagram of the multifunctional intelligent sensor system based on TENG and its main function display.

In conclusion, the integration of friction nanogenerators and machine learning is becoming a burgeoning and active research area. The combination of these two technologies is anticipated to address the limitations of traditional TENGs, including enhanced performance and expanded application scope. This research direction is expected to facilitate the advancement of friction nanogenerators in wave energy harvesting and to contribute to the development of wearables, AI, smart sensor networks, and the Internet of Things. Moreover, this research is poised to play a pivotal role in numerous industries.

7. Summary and Prospects

Friction nanogenerators, as a novel energy conversion technology, have achieved many important research successes in mechanical energy conversion and collecting in recent years, showing great potential. These research results not only help to promote the development of TENG field, but also provide the theoretical basis and technical support for the collecting of wave energy by TENG. However, the current application of TENG for wave energy collecting still faces some challenges, although important progress has been made.

7.1 Disadvantage

- Technological maturity: While TENG has proven to be an effective energy converter in lab settings, its performance might suffer in practical situations. Particularly in marine conditions.
- Durability: The stability and long-term durability of TENG may be put to the test by the harsh, corrosive, and temperature fluctuations of the maritime environment.
- Efficiency: Although TENG is capable of operating effectively at low frequencies, further work needs to be done to increase its energy conversion efficiency in order to effectively gather wave energy.
- Maintenance costs: The cost of TENG may rise due to its dependency on specialist materials and long-term operations and maintenance expenses, even with its benefits in material and production prices.

7.2 Challenge

- Environmental Adaptability: The variable nature of the marine environment necessitates that TENG possess exceptional environmental adaptability in order to effectively navigate diverse sea and climate conditions.
- Energy Management: The instability of wave energy necessitates the implementation of effective energy management and storage technologies for TENG in order to ensure a stable energy output.
- Integration: Incorporating TENG into existing energy collection and conversion systems may necessitate further research and development, potentially involving compatibility challenges with other technologies.
- Commercialization: Due to TENG's low power generation efficiency and low energy conversion efficiency, it is necessary to use large-scale sea regions to create electricity, which is too expensive, if it is to be used to supply electricity. Even though TENG has a low material cost, if it is effective, frequent equipment maintenance is required, which drives up the cost. Commercialization is challenging as a result.

Based on the issues raised in the review and discussion above, it can be concluded that the major obstacles to the advancement of friction nanogenerator technology in the field of wave energy harvesting are inefficiencies in the power generation by these devices, proper maintenance for equipment operating in marine environments, equipment optimization in various environments, and commercial applications. Therefore it is recommended:

7.2.1 Collecting more experimental data

- Scientifically and reasonably design the experimental equipment, measure the marine environment, and optimize the friction nanogenerator equipment according to the research, so as to ensure that the equipment can work under the marine environment for a long time and stably.
- Establish cooperation with domestic and international friction nanogenerator research groups to promote the sharing and exchange of experimental data.
- For the large amount of data generated by friction nanogenerators in marine environment experiments, data processing and analyzing techniques are carried out in order to extract key information and conduct in-depth analysis.

7.2.2 Expanding the coverage of data Sources

Data collecting should be expanded and not limited to just one source of field data. Qualitative changes are the result of quantitative changes. Collecting physical field data from a variety of sources requires collecting not only local wave information, but also factors that incorporate corrosive elements such as salt water, sea breezes, and ultraviolet light.

- Improve existing data collecting methods and processing systems to enhance the accuracy and reliability of data and expand the range of data sources.
- Strengthen interdisciplinary cooperation with marine chemistry, marine physics, marine science and other disciplines to explore and utilize data resources from all disciplines.
- Promote digital technology: use digital technology to collect and process data, create a digital data collecting and processing system, establish an all-process digital data

collecting and processing system, and improve data visualization and sharing capabilities.

7.2.3 Improving the quality of data

The work of friction nanogenerators requires accuracy. In addition to the large volume of data, it needs to be filtered and processed to ensure its accuracy and usability.

- Data can be analyzed in depth through statistical analysis, multi-scale analysis and other methods. For example, data can be processed through averaging methods to extract more accurate information about ocean wave energy as well as the environment.
- Research and development of artificial intelligence techniques and machine learning algorithms related to marine environment monitoring to improve the accuracy, stability and interpretability of model.
- Developing new model and methods to study the operating conditions of friction nanogenerators in different marine environments to accurately analyze the direction of improvement of equipment parts.

7.2.4 Durability and reliability

Friction nanogenerators require long-term exposure to harsh marine environments, which may result in material degradation, wear, or corrosion.

- Develop and test more durable materials and coatings, such as the use of stainless steel or special alloys, to enhance the friction nanogenerator's resistance to corrosion and weathering.
- Design modular structures, introduce regular inspections and preventive maintenance programs to monitor the condition of the equipment and repair possible damage in a timely manner.

7.2.5 Energy conversion efficiency:

Although TENG has demonstrated high energy conversion efficiencies under laboratory conditions, its efficiency may be reduced in the actual marine environment due to a number of factors.

- Continue to study and optimize the design of the friction nanogenerator, including adjusting the contact area and pressure, improving its responsiveness to the frequency of water waves, and increasing the energy storage capacity to better adapt to the frequency and intensity of ocean waves.
- Incorporate energy storage technologies, such as supercapacitors or small battery packs, to store the power generated by the TENG to ensure a continuous supply of energy.
- Consider combining friction nanogenerators with other energy conversion technologies, for example, with EMG-TENG, to achieve higher overall efficiency.

Through these efforts, the application of friction nanogenerators in wave energy collecting will be more promising. By overcoming these challenges, the research on friction nanogenerators will make a greater contribution to solving ecological problems and energy shortage. It is hoped that this literature review can somehow provide reference and help for researchers of friction nanogenerators in wave energy collecting.

Conflict of interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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