A Review of Triboelectric Nanogenerators in Wind Energy Harvesting and Environmental Monitoring

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Abstract. With the growing demand for renewable energy and the development of portable electronic devices, there is an increasing need for self-powered systems. This paper reviews recent advancements in wind energy harvesting and environmental monitoring, with a particular focus on triboelectric nanogenerators (TENGs). TENG technology efficiently converts wind energy into electrical energy through the coupling of triboelectric effects and electrostatic induction, offering advantages such as simplicity, low cost, and high efficiency. The paper details the fundamental working principles of TENGs, their various operational modes, and the design of hybrid electromagnetic generators (TENG-EMG) that integrate TENGs with electromagnetic generators. It also discusses innovative devices such as the calliopsis biomimetic triboelectric nanogenerator (C-TENG), the polymer wind bead rolling triboelectric nanogenerator (WB-TENG), and the self-sustaining wind speed sensor system (SSWSSS). These devices not only enhance the efficiency of wind energy harvesting but also broaden the scope of wind speed and direction monitoring. Finally, the paper explores future research directions for TENG technology, including multifunctional integration, material innovation, intelligent management, and environmental impact assessment, aiming to further advance sustainable energy and environmental monitoring.

Keywords: Self-powered, Triboelectric Nanogenerator, Wind Energy, Environmental Monitoring, Renewable Energy.

1. Introduction

With the increasing emphasis on sustainable energy and environmental protection, the development and utilization of renewable energy have become crucial to modern society. Wind energy, as a clean and renewable resource, is a significant focus for new energy development due to its wide distribution and accessibility. While wind can cause significant damage during natural disasters, it also plays a vital role in meteorology, agriculture, navigation, and disaster relief by providing direction recognition, energy supply, and seed propagation. Concurrently, the rapid advancement of portable and miniaturized electronic devices has heightened the demand for energy. Traditionally, these devices have relied on batteries, which require regular replacement and contribute to environmental pollution, thereby limiting their range of applications and service life.

The creation of self-powered devices and sustainable power technologies has grown in significance in response to these difficulties. By effectively converting mechanical energy into electrical energy using friction initiation [1] and the electrostatic induction effect between two media [2], triboelectric nanogenerator (TENG), an emerging energy harvesting technology, have opened new possibilities for the harvesting and utilization of breeze energy in recent years. With its benefits of cheap cost, high conversion efficiency, and a simple construction, TENG technology offers novel approaches to environmental monitoring and wind energy harvesting. It offers cutting-edge solutions to the environmental monitoring and wind energy harvesting fields.

This article provides an overview of recent developments in environmental monitoring and wind energy harvesting, with an emphasis on the use and advancement of TENG technology. It aims to give readers a comprehensive understanding of TENG technology by examining its basic principles, various modes of operation, and integration with other energy harvesting technologies. Additionally, the paper explores the potential applications of TENG technology in environmental monitoring and renewable energy. To further promote the use of TENG technology in advancing environmental protection and sustainable development, the paper also discusses future directions, including multifunctional integration, material innovation, intelligent management, and environmental impact assessment.

2. System Principle

2.1. Development of Nano Energy and Triboelectric Nanogenerators

The development of nano energy technology and the emergence of triboelectric nanogenerators (TENGs) are closely related [3]. Nano energy technology aims to provide self-sufficient, long-lasting energy for nano systems, driven by advancements in science, technology, and microelectronics. Unlike conventional large-scale energy systems, nano energy places greater emphasis on energy availability, efficiency, and stability. TENG technology, as an innovative application of nanotechnology and nanomaterials in energy harvesting, gathers minute amounts of energy from the surrounding environment. It offers an autonomous energy supply pathway to power small electronic devices, serving as an alternative to conventional batteries.

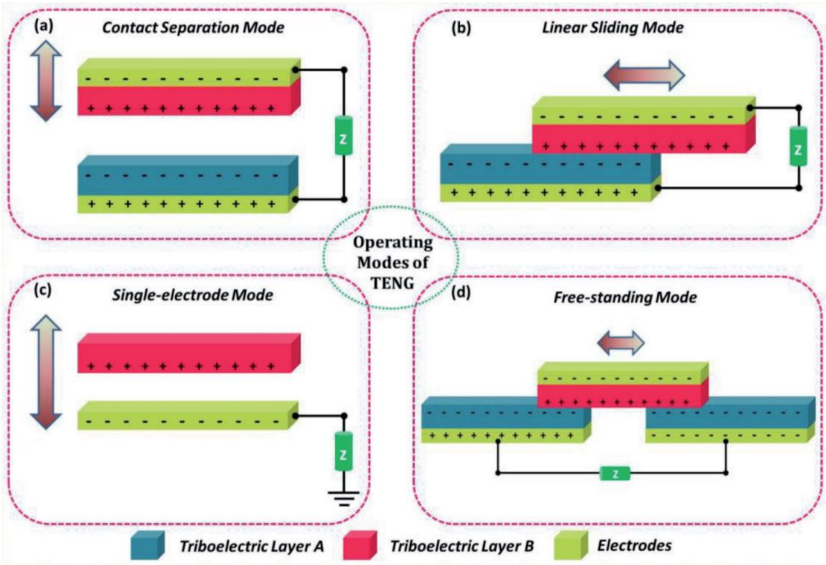
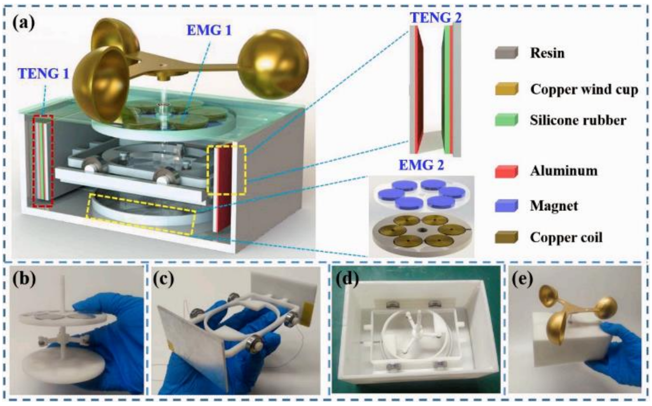


Figure 1. The four methods that TENG works: (a) Contact Separation Model; (b) Linear Sliding Model; (c) Single-electrode Model; (d) Free-standing Model

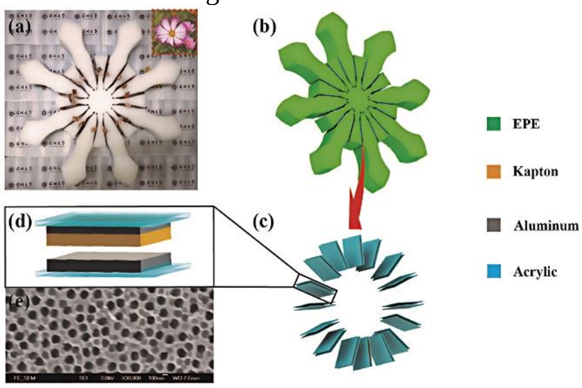
Nano energy is integrated into various technologies, including photovoltaic solar cells, electromagnetic generators based on electromagnetic induction, and piezoelectric nanogenerators utilizing the piezoelectric effect. Despite their innovations and advancements, these technologies face constraints related to conversion efficiency, material selection, and cost.

Up until the discovery of triboelectric nanogenerator [4], researchers kept looking for solutions to these problems. Because of its low cost, light weight, and variety of material sources, TENG has attracted the attention of researchers quite quickly.

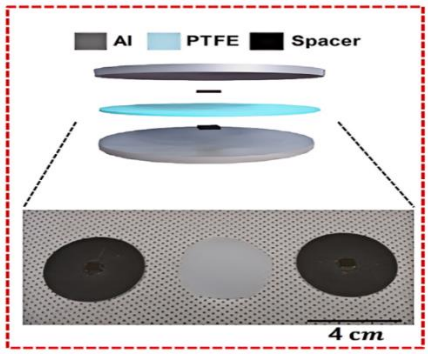
The synergistic effect of electrostatic induction and friction initiation, where charge movement is achieved through the contact and separation of two friction materials, forms the basis of TENG's power production principle. TENGs operate primarily in four modes: vertical contact-separation, horizontal sliding, single-electrode, and independent-layer modes. Each mode relies on the relative motion between the materials [5] (Figure 1).



(a) Electric-electromagnetic dual transistors with contact [6]



(b) Bionic triboelectric nanogenerator advancement [7]



(c) Generator for polymer bead rolling [8] (d) Self-sufficient wind detection system [9]

Figure 2. Nanogenerator of multiform friction

In the vertical contact-separation mode of TENG, periodic contact and separation occur between two dielectric materials, or a friction layer composed of metal and dielectric when exposed to external forces. The horizontal sliding mode generates charge transfer in the transverse direction through sliding separation in the horizontal plane. In the single-electrode mode, the friction layer above the stationary electrode moves, but the shielding effect reduces energy conversion efficiency. To harvest energy from freely moving objects, such as human walking or automotive movement, the independent layer mode avoids the shielding effect and decreases friction loss by using symmetrical fixed electrodes and independent friction layers in alternating contact.

The vertical contact-separation mode is the most widely used due to its efficiency and simplicity. In this mode, the initial state and the voltage difference between the two electrodes are zero. An external force causes the upper and lower material surfaces to come into contact, leading to frictional electrification. As the surfaces separate, electrostatic induction occurs, creating a potential difference and generating a current through the external load. Mechanical energy is converted to electrical energy when this process is repeated, producing a periodic alternating current in the external circuit.

Although the remaining three modes operate differently from the vertical contact-separation mode, they are equally effective. For instance, the single-electrode mode and the independent layer mode are specifically designed for various application scenarios to maximize energy conversion efficiency and reduce losses, respectively. Meanwhile, the horizontal sliding mode generates an electrical signal by horizontal sliding separation.

2.2. Wind Energy-Based Triboelectric and Electromagnetic Hybrid Energy Harvesting

The electromagnetic generator with triboelectric nanogenerator (TENG-EMG) is a novel hybrid energy harvesting device presented by Xue Ming Fan et al. [6] to address the issue of chemical battery replacement for IoT devices in remote places on a regular basis. Combining the benefits of an electromagnetic generator (EMG) powered by wind energy with triboelectric nanogenerator (TENG) yields an efficient energy conversion system.

The TENG-EMG configuration comprises two sets of TENGs and two sets of EMGs, both operating in contact-separation mode. The device's main frame includes sliding and rotating components. These components work synergistically to convert rotational motion from the environment into linear motion and electrical energy. This design allows two distinct frictionally charged materials to be continuously and periodically separated, effectively utilizing the synergistic effects of electrostatic induction and frictional electrification (Figure 2(a)).

During the TENG phase, the surfaces of the aluminum and silicone rubber layers acquire opposing charges due to the friction-charging effect. The contact and separation of these materials, driven by external factors, result in electric current generation and charge transfer. Simultaneously, the EMG section induces a current in the coil due to the relative motion of the coil and the Faraday theory of electromagnetic induction. This dual energy harvesting mechanism ensures the device operates efficiently in various environments.

In addition to efficiently converting wind energy to electrical energy, the TENG-EMG is also a valuable tool for monitoring wind speed based on voltage variations. At a wind speed of 9m/s, the maximum output power of the TENG and EMG is 0.36mW and 18.6mW, respectively. With its innovative design, the TENG-EMG demonstrates significant potential in wind energy harvesting and environmental monitoring.

2.3. Biomimetic Triboelectric Nanogenerator for Multidirectional Wind Energy Harvesting

Cheng Han Zhao et al. created a novel calliopsis biomimetic triboelectric nanogenerator [7] (C-TENG) to address the issues of old triboelectric nanogenerators' low energy conversion efficiency, severe device wear and tear, and short working lives. Inspired by the motion of flower petals in the wind, the design can sense wind direction and speed on its own and gather multidirectional wind energy.

The combination of electrostatic induction and friction electric effect forms the basis of C-TENG's working principle. Its primary parts are a series of TENG modules, and a flowery frame construction made of commercial EPE. The C-TENG is tested using a commercial pneumatic pistol coupled to an air compressor, simulating various wind speeds under various wind directions. A commercial anemometer is used to measure the wind speed. The linear motor powers the device.

In actual operation, the bionic design of C-TENG enables its petals to periodically contact and separate between the stators under the action of wind. As the wind speed changes, different units of the C-TENG produce different power outputs. Based on the amplitude of the electrical signal output from the C-TENG, the wind speed and direction can be accurately measured (Figure. 2(b)).

With its EPE frame structure and petals that expand in all directions, C-TENG's flexible blocks can react to wind coming from many directions at any given position. Along with increasing wind energy collecting efficiency, this bionic structure's electrical signal output allows it to function as a self-sustaining wind sensor. A single C-TENG can reach an open-circuit voltage of $61.7V$, a short-circuit current of $0.341\,A$, and a peak output power of $11.57\,mW/m^2$ at a load resistance of $100\,M\Omega$ at a wind speed of $15\,m/s$ and a frequency of $5\,Hz$.

In addition to increasing wind energy harvesting efficiency, the C-TENG's creative design offers fresh approaches to weather monitoring, agricultural productivity, and maritime sector needs, indicating a bright future with many potential uses.

2.4. Wind Energy Harvesting and Monitoring with Polymer Bead Rolling Triboelectric Nanogenerator

Conventional wind energy harvesting systems have limited applications due to their complex design, large size, scarcity of suitable construction sites, and inability to operate in low wind conditions. To address these issues, Daewon Kim and colleagues developed the polymer wind bead rolling triboelectric nanogenerator (WB-TENG) [8], which utilizes the rolling motion of polymer beads to generate electricity.

The WB-TENG features a circular frame containing polymer beads between its inner and outer walls. The device's flat design ensures that the wall height barely exceeds the diameter of the beads. When wind flows through, the beads roll due to eight diagonal perforations in each direction on the outer wall. This precise generating mechanism enables the beads to rotate in a circular motion within the container as air passes through the exterior wall's holes. The beads roll along the inner and outer walls, periodically contacting and separating from the electrodes. As the wind blows, the beads roll along the inner wall, creating a frictional electric effect that results in the beads becoming negatively charged and the electrode becoming positively charged (Figure 2(c)). When at rest, the beads are in contact with the upper electrode.

Driving current travels from the upper electrode to the lower electrode via the external circuit when the beads detach from the higher electrode and roll downhill, creating a potential difference. Upon passing the bottom electrode, the rolling beads disrupt the electrostatic balance and produce an inverse current flow. This procedure keeps going until the wind dies down.

Thanks to its unique design and methodology, WB-TENG effectively captures wind-driven mechanical energy. A short-circuit current of $2.3\mu A$ and an open-circuit voltage of $18.5V$ are produced at a wind speed of $10m/s$; at $20m/s$, the peak power density is $1.36mW/cm^2$. The WB-TENG is also appropriate for use as a portable power source for personal devices since it has a flat, lightweight structure and can be built to an arbitrary tiny size. Furthermore, the apparatus functions effectively at low wind velocities, rendering it appropriate for small-scale wind energy harvesting in the vicinity of residences or structures. Due to its ability to instantly adapt its output performance to variations in wind speed, the WB-TENG also has potential uses as a self-powered wind speed sensor.

To sum up, the WB-TENG's novel design shows that wind energy collection may be applied widely for portable power and wind speed monitoring, while also increasing its efficiency and adaptability.

2.5. Design and Application of an Omni-Directional Wind-Powered Self-Sustaining Wind Speed Sensor System

Conventional sensor networks used in the field for outdoor monitoring frequently encounter problems because of data transmission faults and battery depletion. An omni-directional wind triboelectric generator (OW-TEG) is integrated into the novel self-sustaining wind speed sensor system [9] (SSWSSS) that Sang-Jae Park et al. designed to effectively gather wind energy from numerous directions.

The SSWSSS system consists of two primary components: the OW-TEG and an advanced control circuit. The OW-TEG harnesses wind energy to drive a flat frictional electricity membrane between two electrodes. This membrane oscillates up and down regularly, converting mechanical energy into electrical energy. The circular design maximizes energy collection efficiency by capturing wind energy from all directions. The system's frictional electric membrane, made of polytetrafluoroethylene (PTFE) and positioned between the top and bottom aluminum electrodes, generates alternating current (AC) through periodic contact and separation, creating an electric charge via wind-induced oscillations (Figure 2(d)).

The control circuit, which manages and stores the energy collected by the OW-TEG, is crucial for the system's operation, including wind speed detection. The energy-saving module adjusts the rectifier's voltage to optimize energy collection and utilization, ensuring efficient storage and readiness for system use. The data counting module uses the frequency resolution of the power signals generated by the OW-TEG to accurately measure wind speed.

It was shown that the system could provide 26 μW of average maximum power at a crt voltage of 16V. This self-powered setup shows that it can run continuously without an external power supply, indicating that it may be used for extended periods of time in an unattended setting. By using this architecture, the SSWSSS not only addresses the issue of regular maintenance for conventional sensors, but it also considerably lowers the running expenses of environmental monitoring initiatives.

In summary, the SSWSSS presents a novel approach to environmental monitoring, significantly enhancing the reliability and efficiency of data collection through its all-around energy capture design and unique energy self-sufficiency feature. Its self-sustaining wind speed sensor system enables the development of sustainable environmental monitoring systems and provides valuable environmental data for scientific research.

3. System Expansion

As technology has advanced, the conventional triboelectric nanogenerator (TENG) has evolved into a versatile and user-friendly tool that meets the demands of contemporary living. The civilian applications of TENG devices have expanded beyond monitoring wind direction and speed to include airborne chemical level monitoring in residential settings. These advancements have made TENG technology more widespread and practical, offering renewable energy solutions and improving environmental monitoring and indoor air quality.

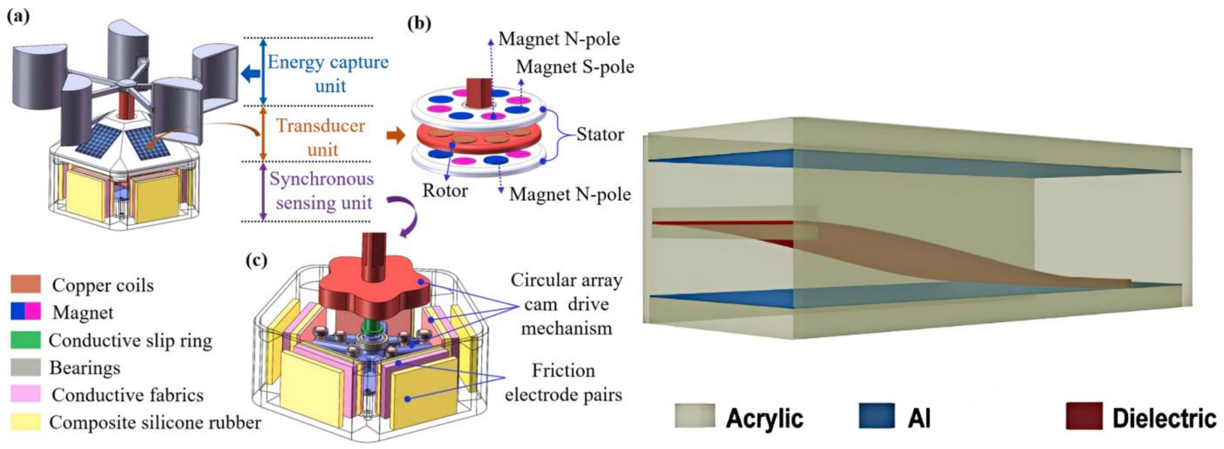
3.1. Application of Self-Powered Wind Speed Sensing System in Grassland Monitoring

Variations in wind speed in specific locations can significantly impact plant development, surface microclimate, and ecosystem patterns in wind-eroded grasslands. Therefore, monitoring wind speed is crucial for assessing the state of prairie ecosystems and implementing strategies to support their sustainable growth. However, conventional wind speed monitoring techniques face several challenges in remote and energy-poor areas. Commercial sensors powered by lithium-ion batteries are commonly used in these areas, but these batteries have a limited lifespan and rely on conventional energy sources, which can lead to environmental pollution.

A self-powered wind speed sensing system [10] (SWSS) has been suggested as a solution to these issues. By using wireless communication technology, this system creates an effective wireless wind speed gauge by combining a stereoscopically increased electromagnetic nanogenerator and a polygonal cam-driven stress electric nanogenerator (TENG). Multi-walled carbon nanotube (MWCNT) doped silicone rubber substrate greatly enhances the TENG's output performance. Utilizing a polygonal cam drive structure, the apparatus transforms wind excitation's rotational motion into reciprocating motion. By refining the cam design, the TENG produces five signals in a single rotation, increasing data sensitivity and lowering memory requirements (Figure. 3(a)).

By integrating energy collection, sensor, and wireless transmission components, the SWSS system offers a comprehensive ecological monitoring solution for wind-damaged grasslands. In addition to safeguarding herders' livelihoods and maintaining the ecological balance of the grassland, the system provides researchers with vital monitoring data that can be used to support sustainable and effective management practices.

The SWSS system provides a comprehensive monitoring solution for wind-damaged grasslands by integrating energy collection, sensor, and wireless transmission components. In addition to safeguarding the livelihoods of herders and maintaining the ecological balance of the grassland, the system provides essential monitoring data to researchers, which they can use to support sustainable and effective management practices.



(a) Self-contained wind meter [10] (b) Wired sensor network with self-power [11]

Figure 3. Application map for TENG

3.2. Design and Application of a TENG-Based Self-Powered Wireless Environmental Sensing System

In today's technological world, billions of wireless nodes demand a significant amount of electricity due to the Internet of Things' (IoT) fast proliferation. Sustaining these devices is a significant task, particularly in isolated or challenging-to-reach locations. By converting ambient energy, triboelectric nanogenerator (TENG) technology offers a novel approach to designing wireless environmental sensing systems that run on their own [11]. This greatly increases the energy independence of smart devices.

The Contact Separation Mode (CSM), particularly effective in absorbing mechanical energy and converting it into power in dynamic situations, is utilized by TENG technology to harvest energy from the environment. The developed TENG device can efficiently charge capacitors that power a wireless environmental sensing system. This system employs a highly efficient power control module (PMM) that optimizes energy collection, storage, and conversion processes (Figure 3(b)).

The system can monitor temperature and humidity in specific applications by broadcasting MAC addresses to receivers, ensuring efficient processing and real-time data transfer. Receivers are placed in residents' homes to provide access to real-time data, while the sensing system is typically installed in public locations such as street lampposts. Additionally, the TENG system uses a 433MHz radio frequency to monitor carbon monoxide (CO) levels, sending out an alarm every 18 minutes from 1.5 kilometers. Similarly, its temperature and humidity sensors use Bluetooth technology operating at 2.4 GHz to transmit data every nine minutes from fifty meters away. By integrating these technologies, the monitoring becomes more precise and timelier, enhancing the system's utility and convenience.

Developed with TENG technology, the wind-powered, self-sustaining system offers a maintenance-free and eco-friendly solution for wireless remote environmental sensing. It can be widely applied in various monitoring scenarios, promoting the advancement of IoT technology and environmental protection, and is suitable not only for monitoring weather conditions but also for assessing environmental quality.

4. Future Research Perspectives

Triboelectric nanogenerator (TENG) technology, still in its developmental stages, holds significant potential for applications in environmental monitoring and energy harvesting. This study explores potential research directions to further the development and application of TENG technology.

4.1. Trends in future research

Triboelectric nanogenerator (TENG) technology holds significant promise for application and development. Future research should prioritize the following areas:

(1) Multimodal Self-Sensing Technology: To achieve simultaneous wind direction and speed monitoring and multidirectional wind energy collection, bionic design and advanced TENG technology should be integrated. For instance, the petal-shaped design of the C-TENG enhances the device's functionality and applicability across various sectors, including nautical, agricultural, and meteorological monitoring.

(2) Material Innovation and Structural Design Optimization: Enhanced energy harvesting efficiency and TENG sensitivity can be achieved through material and structural innovation. For example, WB-TENG demonstrates the potential for creating lightweight and efficient energy conversion devices by using plastic beads and optimizing structural design to adapt to low-wind environments.

(3) Intelligence and Networking: The integration of TENG devices with networking and intelligence has become a crucial trend, driven by advancements in AIOT and artificial intelligence. For instance, the SSWSSS system integrates an omni-directional wind triboelectric generator (OW-TEG) with controlled wiring to achieve automatic wind speed monitoring. Additionally, the energy management module optimizes energy storage and usage, highlighting the potential for intelligent management and remote equipment control.

(4) Environmental Impact Assessment and Sustainability: Evaluating the sustainability and environmental impact of TENG technology is a primary research objective. This involves a comprehensive assessment of the resources used in the machinery, the manufacturing process, and the environmental effects throughout the life cycle to ensure long-term sustainability and ecological friendliness. These investigations are expected to enhance TENG technology's contributions to sustainable development and environmental protection, as well as to scientific and technological advancements and the creation of new materials.

4.2. Future Research Challenges

Despite its promising potential, triboelectric nanogenerator (TENG) technology still faces several challenges and obstacles in further research:

(1) Energy Conversion Efficiency and Cost Balance: One of the main challenges is striking a balance between enhancing TENG's energy conversion efficiency and managing costs. For example, WB-TENG uses a polymer bead rolling mechanism to increase energy conversion efficiency in low-wind conditions, but further work is needed to improve the material's affordability and design.

(2) Environmental Adaptability: TENG systems must operate reliably under harsh climatic conditions, such as fluctuating humidity, varying temperatures, and mechanical stress. Optimizing these systems for a wider range of climatic conditions remains a challenge. For instance, the C-TENG design, inspired by the petals of flowers, can function steadily in multi-directional winds.

(3) Scale-Up Production and Commercialization: The commercialization of lab-grade TENG technology requires addressing cost management, market acceptance, and the feasibility of scale-up manufacturing. This includes evaluating market demand, standardizing manufacturing procedures, and conducting cost-benefit analyses.

(4) International Standards and Safety Testing: Developing appropriate global standards and safety testing procedures is imperative for the advancement and application of TENG technology. Ensuring broad usage and user safety requires performance assessment and safety standards for TENG equipment. Standardized research on topics such as electromagnetic compatibility, long-term stability, and environmental impact will significantly influence the market promotion and deployment of TENG equipment.

5. Conclusion

As an innovative energy harvesting technology, triboelectric nanogenerators (TENGs) have made substantial progress in recent years across fields such as energy conversion, environmental monitoring, and wearable devices. By harnessing friction between different materials to generate electrostatic effects, TENGs efficiently convert mechanical energy into electrical energy. For example, C-TENGs, utilizing a biomimetic design, effectively collect wind energy from multiple directions while also functioning as wind speed and direction sensors. Similarly, WB-TENGs enhance the design of traditional TENGs by incorporating rolling polymer beads, achieving high energy conversion efficiency even at low wind speeds. Additionally, integrating TENG with electromagnetic generation technologies has led to structural optimizations that significantly improve energy harvesting performance, particularly in low-wind environments.

Despite these advancements, TENG technology still faces several challenges. Multifunctional integration and intelligence are critical for the next phase of development. Integrating more monitoring capabilities and intelligent control systems, particularly through the use of IoT technology for data collection and analysis, can enhance the adaptability and ease of operation of TENGs in complex environments. Furthermore, material innovation and structural optimization remain crucial for advancing TENG technology. The development of new materials and designs, especially those that improve energy conversion efficiency and device durability, will be instrumental in expanding the practical applications of TENGs. Another major challenge lies in scaling up and commercializing lab-level research. This involves addressing the feasibility of large-scale production, cost management, and market acceptance, as well as establishing international standards and safety testing protocols to ensure widespread adoption and user safety.

With continuous technological innovation and system optimization, TENG technology is expected to not only broaden its applications in energy harvesting and environmental monitoring but also play a pivotal role in achieving global sustainability goals. Triboelectric nanogenerators are poised to become a key technology for promoting environmental protection and energy transitions. Their ongoing research and development hold immense promise, and in the face of global energy and environmental challenges, TENG technology is set to contribute significantly to sustainable development objectives.

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