



# Research on the Principle and Application of Triboelectric Nanogenerator

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**Abstract.** Triboelectric Nanogenerator (TENG) is a cutting-edge micro-nano energy harvesting technology. It mainly achieves charge transfer and energy conversion through micro-scale material friction. This paper explores the working principle of this technology in detail and examples of multi-field applications. The research shows that the efficiency and stability of TENG depend largely on its material selection and structural design. By optimizing these factors, scientists can improve the energy conversion rate of these devices. Triboelectric nanogenerators have shown great potential in many application fields. Continuous research has also revealed that the power generation performance can be effectively enhanced by increasing the structural level, using specific functional materials and adjusting the vibration frequency. These research progress not only improves the efficiency of TENG, but also helps to promote sustainable development and environmental protection. Future research directions include improving the adaptability of equipment to the environment, developing new materials that integrate environmental protection and high efficiency, and using machine learning to improve the adaptive ability of the system to meet more complex needs.

**Keywords:** Triboelectric Nanogenerator (TENG); electrostatic induction effect; nanotechnology

## 1 Introduction

The scientific community has shown great interest in a new type of energy conversion device-triboelectric nanogenerator, which uses micro-level friction effects to convert mechanical kinetic energy into electrical energy. Triboelectric nanogenerators are considered to be a promising future energy technology due to their small size, light weight, low cost, and great energy capture and conversion possibilities.

With the continuous expansion of global energy demand and the improvement of environmental protection awareness, as an innovative energy harvesting technology, triboelectric nanogenerator has attracted great attention from the scientific community. This technology shows great development prospects in energy conversion and nanotechnology. This paper aims to deeply understand the operation principle of TENG and

its practical utility in various application scenarios. This paper hopes to promote the innovation and application of TENG technology, and provide theoretical basis and prospect for the future research direction and practical application.

## 2 The Basic Principle of TENG

### 2.1 Triboelectric Effect

TENG is a device that converts mechanical energy into electrical energy by using triboelectric effect and electrostatic induction effect. The basic principle is that when two different electronegative materials are in contact with each other, the charge will be transferred from the material with strong electrical properties to the weaker material. After the separation of the two materials, the potential difference between the materials is caused, resulting in current generation<sup>[3][4]</sup>. For example, the TENG device is mainly composed of a friction material layer, an electrode layer and a connected wire. In the process of contact and separation of these materials, the charge transfer and the resulting potential difference, mechanical energy is converted into electrical energy, and this conversion process is used. We can convert the mechanical power generated in daily activities into practical electrical energy<sup>[1]</sup>, such as specific TENG equipment can work in human activities, mechanical vibration and natural wind or water flow<sup>[5][13]</sup> environment, through these power sources to capture mechanical energy and efficiently convert energy.

In the field of TENG, some research groups have used high-tech composite materials and nanotechnology to optimize the structure of these generators and significantly improve their efficiency. On this basis, some teams have also integrated machine learning technology to improve energy conversion efficiency and improve the energy efficiency and stability of generators<sup>[15][18]</sup>. Further research and improvement of the two key energy conversion methods of triboelectricity and electrostatic induction are of great significance to promote the progress of this technology and the expansion of practical applications. Through these multi-angle strategies, we can look forward to continuous innovation and wider technical applications in this field in the future.

### 2.2 Electrostatic Induction Effect

TENG mainly relies on electrostatic induction : when two materials with different electron affinities contact and rub with each other, they will exchange electrons on the contact surface to generate opposite charges. Subsequently, when the two materials are separated, the charges they carry cause voltage changes in the external circuit through electrostatic induction, which drives the flow of electrons<sup>[2]</sup>, thereby converting mechanical energy into electrical energy<sup>[1]</sup>.

Specifically, when the device relies on the contact of two materials with significant electrical differences, the material with less electronegativity will transfer electrons to the material with larger electronegativity, thus forming static electricity. When the two materials are separated, these static electricity will generate a potential difference in the

connected circuit. This potential difference forces electrons to flow and thus converts into electrical energy<sup>[6]</sup>.

### 3 Material And Structure Design of TENG

#### 3.1 Materials Selection

Material selection has become an important part of TENG power output and its overall performance. The choice of materials and their matching methods will not only affect the power efficiency of TENG, but also affect the adaptability of the equipment under various environmental conditions and the mechanical stability during long-term operation<sup>[1]</sup>.

Researchers have developed a variety of efficiency improvement techniques, including the use of ion implantation methods to enhance the charge adsorption capacity of the dielectric layer, and the use of micro-nano technology and fine surface structure to improve its triboelectric properties. These advances have been widely used and recognized in the technical field.

The design of TENG is particularly important for the material selection of the dielectric layer. Some commonly used materials such as stainless steel fibers, copper fibers and aluminum fibers, as well as a variety of plastic materials, such as polyurethane, polyester and polytetrafluoroethylene PTFE, often play a crucial role due to their excellent electronegativity and good mechanical stability.

Polydimethylsiloxane PDMS has been widely used in many fields due to its excellent elastic and dielectric properties. The use of lithography and replication methods to create a pyramid-shaped structure on the surface of PDMS can significantly optimize its function<sup>[4]</sup>. In the development of another part, in response to the material requirements of TENG, bio-based materials-based elastomers have begun to attract widespread attention due to their excellent biodegradability and reusability. These materials use salt-containing particles for three-dimensional printing to design multi-layer pore structures, which can enhance their mechanical stability and energy conversion efficiency<sup>[5]</sup>.

In exploring how to enhance the efficiency of TENG, the use of metal and polymer composites has become particularly important. Recent studies have shown that surface modification or addition of nanoparticles for certain polymer materials, such as polyimide and polymethyl methacrylate, can effectively increase the dielectric constant of these materials. This improvement significantly improves the power generation efficiency of TENG.

By using suitable materials and cutting-edge manufacturing processes, the energy harvesting and conversion efficiency of TENG has been significantly enhanced. Looking forward to the future, we can continue to explore more efficient material matching and design innovative structures, so as to release the greater potential of TENG technology and promote it to a wider range of applications.

### 3.2 Structural Optimization

In recent years, TENG has made significant progress in structural design. Researchers have continuously optimized design strategies in order to improve the energy output and stability of TENG. These changes are crucial to improve the overall performance of TENG.

In the research and development of TENG in the textile field, the adoption of multi-layer packaging and spiral winding structure can greatly enhance the stability and power output of the generator. This special structural design greatly improves the overall performance of the generator<sup>[1]</sup>. In addition, the use of a variety of different materials such as stainless steel, copper, aluminum fiber and some synthetic materials not only enriches the design scheme, but also significantly expands the possibility of performance optimization. The introduction of these new materials provides a broader space for the performance enhancement of the generator.

In recent research progress, nanogenerators using superelastic PDMS have shown significant efficiency improvement. The research team used lithography and replication technology to produce pyramid-shaped surface textures, which significantly enhanced the energy output performance of TENG. In addition, another study led by Shuo Chen in 2023<sup>[5]</sup> developed a new bio-based polymer elastomer, which uses three-dimensional printing technology to integrate salt particles to form a multi-level pore structure. This structure not only improves mechanical strength, but also greatly improves its power output efficiency. These research results have promoted the development of TENG.

TENG relies on its unique structural design, which includes a conductive layer placed at the top and bottom, and a dielectric layer embedded between them. It is critical to optimize the efficiency of TENG by the difference in material properties. For example, adding an air layer or enhancing the roughness of the surface can effectively improve the energy output, while the contact-separated structure and the design using spring nails have been shown to significantly improve the efficiency of energy conversion. These technical means are essential to improve the practicality and efficiency of TENG equipment.

An innovative electrospinning thin film TENG device is characterized by the introduction of a vibrating structure and multi-layer contact to enhance the efficiency of triboelectric phenomena, resulting in a significant improvement in power generation performance<sup>[8]</sup>. At the same time, polymer aerogels also show excellent performance in stacked TENG systems due to their lightweight and efficient characteristics<sup>[9]</sup>. These two research results have promoted the progress of TENG technology in the field of material application and design optimization.

In general, the TENG research process has taken such as single electrode, contact-separation and horizontal sliding mode operations<sup>[10][11][13]</sup>. In addition, by adding inorganic fillers to the composite film and using microstructure morphology control technology, the surface charge energy storage and electrical performance of TENG equipment can be enhanced<sup>[15][17]</sup>, which is of great significance.

## 4 Application of TENG

### 4.1 Energy Harvesting

TENG has a wide range of applications. This technology has successfully demonstrated its wide applicability and potential diversity in energy collection in the fields of smart wearables, environmental monitoring, and self-energy sensors.

In the field of smart wearable devices, TENG is made by using special textile materials, so that the device can not only monitor the health status of users in real time, such as heart rate and respiratory rate, but also capture various data related to motion, which increases the practicability of TENG.<sup>[1]</sup>

In the field of ecological monitoring and energy collection, as well as in the medical technology industry, TENG has great potential, especially in the application level of water wave research and environmental data collection. This technology and equipment can effectively convert various mechanical energy into electrical energy, thus providing a new way for the sustainable development of the environment and the use of clean energy. And using this biomechanical-based technology, it can power implantable devices and continuously monitor diseases and collect key information in real time.

In today's scientific and technological fields, especially the development of smart devices and wireless sensor networks, TENG is mainly used for various self-powered sensors and actuators, especially in vehicle anti-collision systems and intelligent pneumatic control systems<sup>[3]</sup>. In addition, TENG technology has made breakthroughs in improving the efficiency of self-powered sensors, and has been widely used not only in traffic safety, but also in data protection and health monitoring.<sup>[10]</sup>

TENG has shown great application prospects in the field of energy harvesting. This technology has become the core driving force for innovation in smart wearable devices, environmental monitoring systems, self-powered sensors, and Internet of Things and photoelectrocatalysis.

### 4.2 Sensor Development

TENG has shown great potential in the field of sensors. By converting the mechanical energy of the environment into electrical energy, the technology allows the sensor to achieve self-sufficient power, greatly broadening the sensor's ability to adapt to a variety of environments.<sup>[12]</sup>

TENG biomedical sensors have been widely used in the field of health monitoring. Yang's team<sup>[1]</sup> developed a TENG device using textile materials. The device can track and record basic physiological indicators such as the heartbeat and respiratory rate of the human body, which greatly facilitates daily health monitoring. The advantage of these devices is that they reduce the demand for traditional energy and can continue to power the monitoring system. TENG technology is also suitable for the field of chemical sensing. It can identify and detect specific chemical substances in air or liquid, which helps to reduce the overall energy consumption<sup>[11]</sup>. These advances mark the dual advantages of TENG technology in scientific research and practicality.

TENG has shown great application prospects in the field of environmental monitoring. As mentioned in the research of Zhou Long and other scholars<sup>[2]</sup>, TENG has shown remarkable functionality on sensors with automatic power supply, especially in monitoring ocean fluctuations and other environmental factors. Furthermore, Bi Chen 's team pointed out in 2020<sup>[9]</sup> that TENG is not only suitable for mobile electronic devices, but also can continuously track environmental changes by absorbing energy. These devices use the combination of TENG and modern sensing technology to stably provide energy in outdoor environments, thus supporting continuous collection and analysis of environmental data.

With the progress of science and technology, TENG is applied in intelligent devices and transportation systems. According to the research of Zhang Chi 's team in 2019<sup>[3]</sup>, TENG plays a key role in intelligent vehicles, especially in the neighborhood of anti-collision and air flow regulation systems. Such devices can convert mechanical motion into electrical signals to achieve the accuracy of automatic control and operation. In addition, Zhang Jiawei 's team pointed out in 2022<sup>[10]</sup> that TENG combined with the application of machine learning can provide self-driven sensing functions in intelligent monitoring and transportation systems, demonstrating its potential in technology integration.

In the field of self-generated power technology and energy acquisition, Wang Xiaoli 's team conducted innovative research in 2020<sup>[4]</sup> and developed a TENG made of PDMS, demonstrating the device 's ability to provide power to small electronic products in a variety of environments. In 2023, Chen's team proposed a new type of TENG<sup>[5]</sup> based on bio-vitelli elastomer materials. This innovation not only promotes the development of sustainable technology, but also provides new possibilities for collecting environmentally friendly energy and supporting the progress of wearable electronic devices.

In view of the application of TENG in self-powered systems and energy harvesting, many scholars have proposed a series of innovative studies. Rui 's team pointed out in the study of 2023<sup>[6]</sup> that TENG is suitable for the capture of low-frequency mechanical energy. In addition, Liu 's team 's research in 2019 further emphasized the high efficiency of TENG technology in obtaining low-frequency vibration energy in the environment<sup>[7]</sup>, which is very important for the development of self-powered vibration sensors, especially in portable electronic devices. The above research results provide important scientific basis and technical support for the practical application of TENG technology, especially in improving energy efficiency and promoting sustainable energy development.

TENG has shown great application prospects in the application of sensor technology. This technology has been successfully applied in many scenarios such as health monitoring, intelligent transportation, environmental detection and mobile electronic devices. The use of TENG not only improves the autonomous operation ability of sensors, but also expands their functions and applicable environment, and opens up a new path for sensor technology. On the whole, the innovative application of TENG indicates a wide range of development and innovation space in the sensor field in the future.

### 4.3 Other Domains

TENG shows its strong application prospects in various neighborhoods.

In the field of small systems and flexible electronics, TENG shows broad application prospects in the future. Through TENG technology, sensors and actuators that can be driven autonomously can be developed. These devices can be applied to vehicle system collision protection and advanced intelligent control neighborhood to enhance the intelligence and safety level of vehicle system safety.

TENG technology has outstanding capabilities in the field of energy acquisition. Research shows that TENG can extract energy from many mechanical actions, including human motion, mechanical vibration, wind and sound<sup>[14]</sup>. Its multi-functional characteristics are very suitable for portable electronic devices and small machinery energy supply. For example, there is a TENG based on cellulose paper, which can not only power small devices, but also effectively convert kinetic energy to electrical energy in the Internet of Things and wearable devices<sup>[16][18]</sup>. The future application potential of this technology is huge, showing its core importance in the field of modern technology.

TENG has excellent performance in energy conversion efficiency and versatility, which makes it occupy an important position in the field of nanotechnology. This kind of equipment is widely used in various fields, including smart wearable devices, self-sufficient sensing systems, and more extensive microsystems and flexible electronic technology. With the continuous recognition and expansion of TENG's application prospects and technical value, its role in modern science and technology has become increasingly prominent.

## 5 The Main Findings, Contributions and Limitations of TENG Research

### 5.1 TENG Improves Energy Conversion Efficiency

TENG has attracted great attention in the field of scientific research in improving energy conversion efficiency. Various strategies can be used to improve the energy efficiency of TENG.

By adopting a layered design architecture with an air layer, the ability to collect electrical energy can be significantly improved, which enhances power output. In addition, the use of specific high-efficiency materials and the optimization of the structure also play an important role in improving the energy conversion efficiency. For example, TENG made of ultra-high elastic PDMS material has a significant increase in the contact area and open circuit voltage when the external pressure increases<sup>[4]</sup>. This material optimizes the output of electrical energy and enhances the overall stability of the device.

The application of environmentally friendly materials can greatly improve energy efficiency. Shuo Chen and his team have developed a bioelastomer called polymeric vitamine<sup>[5]</sup>, which is used in TENG through its own degradation and the recycling of carbon nanotubes, showing excellent energy conversion performance.

In the field of intelligent sensing, self-powered sensors using TENG technology have become a research hotspot due to their low energy consumption and extremely high

adaptability. By integrating machine learning technology, these devices have significantly improved the accuracy of signal processing and recognition. In addition, with the help of the self-generating capacity of TENG technology, these sensors also show high sensitivity and excellent selectivity in applications such as gas monitoring.

In the technological evolution of TENG, the efficiency of energy conversion has been significantly improved by improving the design structure, selecting appropriate materials and adjusting environmental parameters. These technical optimizations have helped TENG solidify its position in modern technology applications and provide a valuable reference for the future innovation direction of energy harvesting technology.

## 5.2 TENG Stability and Durability

One of the important directions of TENG technology research is to improve its stability and durability in different use environments. To achieve this goal, it is necessary to select appropriate materials and carefully plan the design and structure to ensure that it can adapt to various environmental conditions.

Wang's team's research in 2020 shows that<sup>[4]</sup> using PDMS to make TENG can greatly improve its power output stability and durability under different pressure environments. This study shows that hyperelastic materials have better performance and closer to ideal working effects than traditional materials in a variety of practical application scenarios. This discovery opens up new possibilities and directions for further research and application of TENG.

In 2023, Chen and his team introduced a new type of biodegradable material mainly used to construct TENG<sup>[5]</sup>. After the material is used, it can be recycled by biodegradation, which not only maintains the ecological balance, but also reduces the environmental pollution by reusing carbon nanotubes, promotes the environmental protection characteristics of its products and prolongs its service cycle.

A study conducted by Wu Yesheng's team in 2019 focused on the influence of vibration frequency on the electrical performance of TENG equipment<sup>[7]</sup>. The results show that the output efficiency of voltage and current can be significantly enhanced under a certain frequency range adjustment. However, how to maintain this high-efficiency output still needs to be further explored in continuous operation. Bi's team found that<sup>[9]</sup>, the energy conversion efficiency and output power of TENG greatly depend on the roughness of the friction surface and the selected materials. Therefore, in order to ensure the stability of the equipment during long-term operation, it is necessary to accurately adjust the structure and materials of the equipment to adapt to the specific environment.

The research of Zheng Youbin's team in 2018 showed that<sup>[17]</sup>, the size of TENG nanowires used to construct has a significant impact on power generation efficiency. Through the fine design and optimization of these nanostructures, the performance of TENG equipment can be significantly improved, which provides a new idea for improving the working efficiency and durability of such equipment.

The exploration of TENG includes the innovative use of materials, the optimization and adjustment of structure and the adaptability to different environmental conditions. The next research work should focus on the selection of environmentally friendly and

sustainable materials, in-depth analysis of the fundamental mechanism of triboelectric effect, and the fine optimization of the contact surface design and material matching of the motor to ensure that TENG can maintain its efficiency and performance stability during long-term operation.

### 5.3 Main Contributions of TENG Research

The main advantage of TENG is that it can efficiently convert small mechanical power into electricity, which shows great potential in the field of micro-energy collection and renewable energy. Using TENG technology, we can more effectively develop and use environmentally friendly renewable energy. In addition, the application of TENG is a major progress in the research of environmentally friendly energy technology, which is expected to promote the integration of environmental protection and energy innovation in the future.

In terms of material selection, significant progress has been made in the field of TENG. For example, TENG made of PDMS material with high superelasticity shows superior performance in this application scenario<sup>[4]</sup>. In addition, the nano-scale film produced by electrospinning technology not only provides a new type of triboelectric material for the development of TENG, but also effectively improves the efficiency of energy collection<sup>[8]</sup>. The use of environmentally friendly materials such as cellulose also accelerates the transformation of electronic equipment to environmental protection<sup>[18]</sup>.

The research progress of TENG technology has benefited from the continuous deepening of its theoretical basis, including the further application of capacitance theory. Studies have shown that the use of inorganic fillers with high dielectric constant can greatly improve the output efficiency of these composite film TENGs with inorganic fillers. Although the current output level of this technology is still at the milliwatt level, the research of Guo Yinben 's team in 2021 believes that<sup>[15]</sup> this technology has great development potential.

Recent research trends have begun to focus on how to develop sustainable TENG, which has made significant progress in energy harvesting, material innovation, theoretical research and practical application.

### 5.4 Limitations of TENG Research

The application and performance of TENG in the industrial field still have problems such as high production cost, negative impact on the environment, high temperature resistance and cost-effectiveness. At the same time, the performance of TENG is easily affected by the surrounding environmental factors, because the wear of materials, the use of low frequency or the instability of natural environment may affect its performance, and the operation efficiency of TENG is still low. These problems need to be solved through technical improvement and innovation<sup>[3]</sup>.

The development of TENG faces significant challenges in design optimization and performance improvement. At the same time, the research focus also includes the selection of more suitable friction materials and the improvement of their efficiency to

ensure that this technology can be better applied to different actual operating environments<sup>[8]</sup>. These gaps need to be bridged by further improvements in future technology.

In terms of intelligent sensing and energy capture technology, TENG technology still needs to cope with the interference of external environment and the problem of low signal quality. In addition, in order to ensure the long-term use of equipment, the stability and sealing of materials are also very important. From the perspective of commercialization, chemical sensors using TENG technology should focus on material degradation and the accuracy of sensing. At the same time, when using these devices in outdoor environments, the durability of the devices must be improved. These challenges need to be solved through continuous technological innovation.

The application of TENG still faces problems including cost, energy efficiency, durability, and material stability.

## 6 Conclusion

The key to the development of TENG is the design and efficiency improvement of the generator. The next research should focus on improving the effectiveness of these systems in a variety of environments, developing more environmentally friendly materials, and studying how to better integrate machine learning technology into intelligent systems. Adopting these strategies will help greatly promote the application scope and technological innovation of TENG technology.

In the future, the development of TENG should focus on several key aspects : the performance of equipment and the ability to adapt to the environment, continuous growth, and the progress of intelligent system application. Through the system innovation and development in these key areas, TENG will show a broader prospect and possibility.

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