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Review

Applied Research and Prospects of Triboelectric Nanogenerators Based on Waste Plastic Bags

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The increasing production of plastic products and insufficient recycling have caused the problem of white pollution to plague the world, which has severely impacted the ecological environment, marine life, and drainage systems. Moreover, the widespread application of low-consumption electronic devices makes power consumption a non-negligible factor. Therefore, recycling discarded plastic bags as the friction material of triboelectric nanogenerators (TENGs), collecting mechanical energy in daily life and converting it into continuous and stable electricity, can alleviate the two major problems of white pollution and energy consumption simultaneously. Furthermore, self-powered systems constructed using TENGs have enormous potential for driving low-consumption electronics, environmental monitoring, and wearable devices. Accordingly, this paper summarizes the general situation of white pollution, the theoretical origin, working principle, and theoretical model of TENGs, analyzes the feasibility of using waste plastic bags for TENGs, with the application progress of this self-powered sensing system, and looks forward to the future.

Keywords: Triboelectric nanogenerators; Self-powered systems; Waste plastic bags; TENGs

1. INTRODUCTION

Currently, the world is facing various environmental problems. The plastic waste generated by human is one of the leading causes of water and soil pollution [1]. Plastic products have increased sharply with the need for production and life. Global plastic production surged quickly, and the output in 2015 was 190 times of that in 1950, reaching 380 million tons. Over the past 65 years, plastic output has far exceeded that of other manufactured materials, and only 9% of discarded plastic products have been recycled [2]. China produces and consumes nearly 100 million tons of plastic waste every year, which causes massive waste of resources and negatively impacts environmental pollution [3]. In particular, while the COVID-19 pandemic swept the world, takeaway packaging and medical waste have exacerbated white pollution to a certain extent. In terms of medical use, at the pandemic's peak, Wuhan's hospitals' disposable plastic medical rubbish exceeded 240 tons daily, far exceeding the use before the pandemic [4]. Regarding takeaway packaging, takeaway food and groceries generated 1,400 tons of plastic waste during an eight-week lockdown in Singapore [5]. People's lives are inseparable from plastics, particularly during the pandemics. Plastic products are widely used because of their light weight, good performance, and stability. However, the disposal of plastic waste requires substantial financial and human resources [6]; therefore, recycling plastic waste is a crucial way to address the white pollution problem.

Simultaneously, the use of microelectronic devices such as electronic watches and sports bracelets is also increasing. Although a single electronic device consumes very little power, the power consumption occupied by these devices collectively, owing to their popularity and widespread use, cannot be ignored [7,8]. The increase in power generation raises the amount of greenhouse gases produced by power generation fuels [9], thereby affecting the balance of the global carbon cycle system. Relying only on the existing traditional energy supplies cannot meet the current demand, and the development of renewable energy guides to solve this problem [10]. All humans are looking for suitable new energy sources to alleviate the energy crisis and environmental pollution [11]. However, there are many forms of energy in the surrounding environment, particularly mechanical energy, which is the most extensive, occupying a large part [12-16]. Against this background, in 2012, the birth of triboelectric nanogenerators (TENGs), to a certain extent, helped to alleviate the problem of energy shortage. It uses the theory of triboelectrification and electrostatic coupling effects to transform the surrounding low-frequency energy into electrical energy. As a result, energy-to-electricity conversion is realized, and is devoted to various types of self-powered systems and triboelectric devices [17-19]. The TENG is a novel, environmentally friendly, and an efficient energy harvester and has become a research hotspot in nanotechnology. It has a high output performance, good stability, and high sensitivity. It can be used in various structures to provide low-maintenance, long-running, and self-powered energy for microelectronic systems [20-22].

Based on this, abandoned plastic bags can be recycled and used as friction materials to prepare TENGs, which can alleviate white pollution, protect the environment to a certain extent, and realize the conversion of old and new kinetic energy and alleviate the energy crisis. Moreover, sensor applications are becoming increasingly extensive, and they have been extended to the fields of environmental detection, biological engineering, ocean detection, and health monitoring, almost throughout various modern engineering application [23, 24]. Based on plastic TENGs, this micromechanical sensor has multi-functional sensing characteristics, can adapt to the environment, has strong stability, and can be used in body motion detection, electronic skin, touch screens, and other fields [17].

This study summarizes the general situation of white pollution, the theoretical origin, working principle, and theoretical model of TENGs. It also analyzes the feasibility of using waste plastic bags for TENGs and application research of this self-powered sensing system, and makes a prospect for the future.

2. OVERVIEW OF WHITE POLLUTION

"White pollution" is an intuitive description of waste plastics that pollute the environment. It means the discarding of plastic products such as packaging bags, agricultural mulching films, disposable tableware, plastic bottles, and other polymer compounds made of polystyrene, polypropylene, and polyvinyl chloride, which can pollute the ecological environment. Discarded waste plastics are difficult to degrade, and their harmful components persist in the environment for a long time, causing pollution of water and soil resources. Moreover, casually discarded plastics affect the appearance of cities and cause visual pollution.

Plastic pollution is a widespread phenomenon worldwide. If global plastic production and waste recycling do not change, the production of mishandled waste is expected to more than double of the current wastage by 2050 [25,26]. The adverse effects of plastic pollution are often irreversible [27]. Plastic pollution has harmed human production and life. Disposal of waste plastics might block drainage or sewage systems [28]. Dumping waste plastic products into the sea pollutes the marine environment and threatens the survival of marine organisms on consumption. Waste plastics also threaten to destroy soil and its structure.

Figure 1. The waste plastic bags float in the sea

3. BASIC THEORY AND WORKING PRINCIPLE OF TENG

3.1. Theoretical Origins of TENG

Nano-energy uses nanomaterials and emerging technologies to collect and store energy dispersed in the environment. This new research field has a broad scope of development. The emergence of TENG further promotes the development of nano-energy [29,30]. As a novel energy technology and a basic unit to construct a self-powered system or autonomous sensor, the TENG can realize the continuous operation of the system. Although nanogenerator is an emerging technology under development, they have shown great potential in energy collection, power generation, energy storage, and sensing. Their theoretical origin is Maxwell's displacement current [31-34].

The basis for the rapid advancement of human society in the past 100 years, such as, the beginning, development, and mature applications of communication technology, radio, television, and microelectronics technology, was derived from Maxwell’s equations. The relevant theoretical pillars of these technologies are inseparable from Maxwell’s equations [35-38].

The expressions for Maxwell's equations are as follows:

$$\nabla \cdot D = \rho_f \quad (1\text{-}1)$$

$$\nabla \cdot B = 0 \quad (1\text{-}2)$$

$$\nabla \times E = -\frac{\partial B}{\partial t} \quad (1\text{-}3)$$

$$\nabla \times H = J_f + \frac{\partial D}{\partial t} \quad (1\text{-}4)$$

where D represents the displacement field, ρ_f is the free charge density, B represents the magnetic field, E refers to the electric field, H is the magnetizing field, J_f represents the free current density, and

$$D = \varepsilon_0 E + P \quad (1\text{-}5)$$

where ε_0 represents the vacuum dielectric constant, and P represents the polarization field density.

When deriving these formulae, the continuity equation for the electric charge cannot be initially satisfied using existing laws. On this basis, Maxwell innovatively introduced the concept of the displacement current, and conceived this theory-based "displacement current". He also proposed the existence of electromagnetic waves.

Nanogenerators are newly generated technologies for energy harvesting in terms of energy conversion, and their essential source is the Maxwell displacement current [39]. Application research based on the Maxwell displacement current, including broadcasting, communication, sensing, and the Internet of Things, has laid a good foundation for society to enter the age of connected communication. In a medium with a polarized surface charge, such as a material, the electricity is generated by friction, the displacement current includes the contribution of the surface polarized charge, and some characteristics of nanogenerators go hand-in-hand with it.

For isotropic media, $P = (\varepsilon - \varepsilon_0)E$, $D = \varepsilon E$, of which ε represents the dielectric constant of the dielectric. In type (1-4), the displacement current is

$$J_D = \frac{\partial D}{\partial t} = \varepsilon_0 \frac{\partial E}{\partial t} + \frac{\partial P_s}{\partial t} \quad (1\text{-}6)$$

In this equation, the displacement current is referred to as J_D, the displacement field is denoted by D, E refers to the electric field, P_s represents the polarization field density produced by surface polarons, and ε represents the dielectric properties. This equation has some implications for the growth of new energy [40, 41].

3.2. The Working Principle of TENG

In 2006, Professor Zhonglin Wang first proposed the concept of a nanogenerator, the smallest generator in the world at the present stage [42]. The working theory of TENG is that triboelectric charging interrelationships and charge redistribution. The TENG effectively converts low-frequency kinetic energy into electrical energy. Many triboelectric equipment and self-service systems have been designed based on this. This type of nanogenerator was first fabricated by Wang Zhonglin's team in 2012. Its composition is relatively unsophisticated, primarily comprising two friction electrode pairs [31]. The friction parts include a positive and a negative layer. Generally, materials with significant differences in electronegativity are selected, as shown in Figure 2. During triboelectrification, the positive material can easily give electrons, the negative material can easily obtain electrons, and free electrons accumulate in the $\sigma_{\mathrm{I}}(z,t)$. The number of charges per unit area of the medium is positively related to the number of contact separations and eventually reaches saturation after a specific time. TENGs can harvest a wide range of energies, such as wind energy, ocean water wave energy, sound energy, and even the energy of falling raindrops or the mechanical energy of human walking [43-47]. Such nanogenerators are extremely efficient and are now mainstream in various nanogenerators.

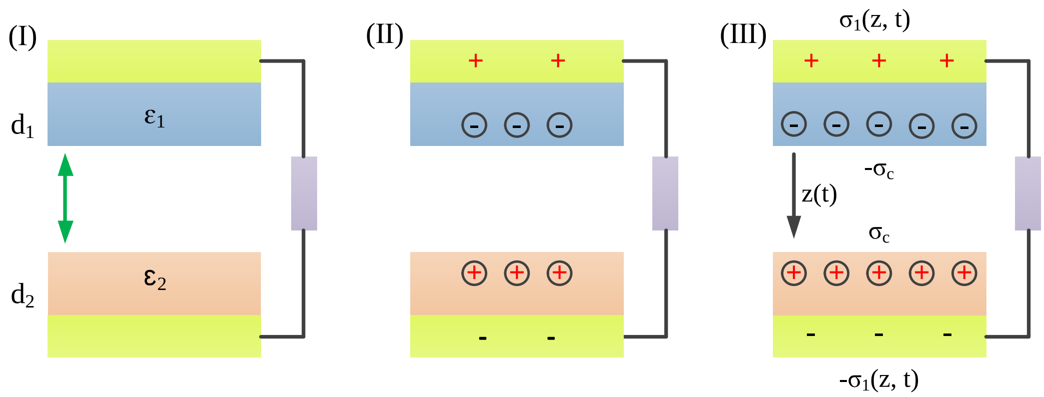

Figure 2. Principle of TENGs

3.3. Working Mode of TENG

Although the principles of TENGs are similar, because of the different interactions between various friction materials, four basic working modes have emerged after development, as indicated in Figure 3.

The vertical contact-separation mode (Figure. 3(a)) is the most widely used class [48, 49]. In this mode structure, films of two disparate materials are vertically opposed, the back of them are coated with metal as electrodes, and the two layers are contacted by applying an external force. Because the two materials hold electrons differently, charges of opposite signs are created in the two layers. After the force disappears, they move away from each other and sense the voltage deviation between themselves. A current is generated in an external circuit, and when an external force is applied again, it flows in the opposite direction. This mode of TENG has a simple fabrication process and high instantaneous output power. Its classic application is to install it on daily wear, such as on shoe soles. When a person walks, it generates energy to power electronic devices [50].

The horizontal sliding mode (Figure 3(b)) is similar to that shown in Figure 3(a). Similarly, the back of the films on both sides was plated with a layer of conductive medium, but there was no space between them. The two contact surfaces slide relative to each other horizontally so that the polarization will force electrons to change position, and the continuous and repeated sliding will form an AC output. In addition to horizontal sliding, it also has multiple motion modes, and the touch-type screen of a smartphone is an excellent application example [51].

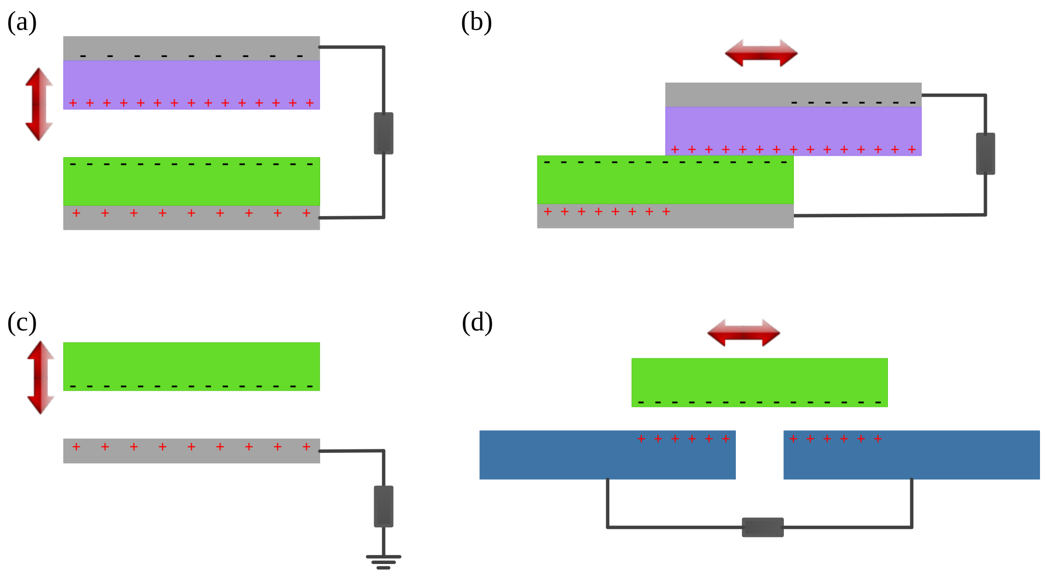

Figure 3. Structure diagram of four basic modes (a) Vertical contact-separation mode (b) Horizontal sliding mode (c) Single electrode mode (d) Independent layer mode

Single-electrode mode (Figure 3(c)) has only one electrode. In some environments, some parts of the nanogenerator are unsuitable for connection wires and electrodes, so only the grounding electrode at the bottom is convenient for collecting mechanical energy. The other electrode is only used as a reference electrode, and its upward and downward movements will affect the local electric field distribution. The TENG in single-motor mode is suitable for installation on the ground to collect the energy released by pedestrians and cars passing by or to collect the energy of falling raindrops on rainy days [52, 53].

The independent-layer mode (Figure 3(d)) includes two symmetrical and disconnected electrodes, the size of which is consistent with the moving friction layer above. A potential difference occurs when the friction layer reciprocates between the electrodes. It should be noted that the friction layer moving above is not necessarily in direct contact with the electrode surface below, which can prevent friction loss to the greatest extent and improve the service life of the TENG.

3.4. Theoretical Model of TENGs

3.4.1. Inherent Capacitive Properties of TENGs

The role of triboelectricity is to provide static polarization charges, electrostatic induction is energy-to-electricity conversion, and capacitance is the basic electronic device. Electrostatic induction is its principle; in other words, the friction nanogenerator has the original capacitance property. The two friction layers had opposite polarities after contact and friction. The good insulation effect between the electrodes eliminates other possibilities for electron flow and can only flow through the artificially constructed channel between the electrodes. The two electrodes transfer the same number of charges, respectively, $+Q$ and $-Q$; its effect on the potential difference is $-Q / C(x)$; $V_{OC}(x)$ represents the potential difference because of polarized triboelectric charges and has a certain functional relationship with the distance x. Using the principle of potential superposition, the total electromotive force between the electrodes can be expressed as follows:

$$V = -\frac{1}{C(x)}Q + V_{OC}(x) \qquad (2\text{-}1)$$

This equation represents the governing equation of an arbitrary TENG and accounts for its inherent capacitive properties. In the case of short circuits, we obtain the equation as follows:

$$0 = -\frac{1}{C(x)}Q + V_{OC}(x) \qquad (2\text{-}2)$$

Hence, the fundamental relationship between transfer charges Q_{SC}, C, and V_{OC} can be represented as:

$$Q_{SC}(x) = C(x)V_{OC}(x) \qquad (2\text{-}3)$$

3.4.2. Capacitance Models for Nanogenerators

The displacement current theory is used to deduce the output characteristics of the nanogenerator from the inside of the material, and the capacitance model is generally preferred when deriving its power generation principle. The existence of a potential difference causes the electrons to move repeatedly. At this time, the nanogenerator can be regarded as a capacitor. The effects are similar, and the corresponding output characteristics can be deduced. The current forms in the internal and external circuits are different, that is, displacement current and conduction current, respectively. Once the upper and lower electrodes are in contact, the electronic transmissions of the internal and external circuits are unified. Voltage is applied to the top and bottom plates of the capacitor. With the change in time, the amount of charge on the plates of the capacitor will also change accordingly, thus causing the current to flow in the external circuit, and its magnitude is expressed as:

$$I = \frac{dQ}{dt} = C\frac{dV}{dt} + V\frac{dC}{dt} \qquad (2\text{-}4)$$

For piezoelectric nanogenerators, the effect of pressure does not cause significant changes in the plate spacing; therefore, the change in capacitance in the system can be ignored. However, for the

TENGs, the change in the pole plate spacing is relatively large, and both terms in equation (2-4) occupy an important position and cannot be ignored. Then, the current is expressed as:

$$I = \frac{\mathrm{d}Q}{\mathrm{dt}} = A\frac{d\sigma_I}{dt} \qquad (2\text{-}5)$$

where A represents the electrode area. This further indicates that the displacement current is a fundamental theory in the capacitive mode. In addition, the relationship between the transport in the external circuit and the open-circuit voltage is expressed as

$$RA\frac{d\sigma_I(z,t)}{dt} = V_{OC} - A\sigma_I(z,t)/C \qquad (2\text{-}6)$$

where V_{OC} represents the open-circuit output voltage of the TENG. This indicates that the displacement current is a physical representation of the effective operation of the nanogenerator, and its external output form is the capacitance model of the external circuit. Capacitance parameters have a critical impact on the service life of the system and the stability and safety of the entire energy storage system [54]; thus, the capacitance model of the nanogenerators significantly impacts its performance.

3.4.3. Equivalent Circuit Model of TENGs

The two parts to the right of the equal sign can be expressed by the voltage generated by the two equivalent model circuit elements using formula (2-1). Owing to its intrinsic capacitive properties, the inherent capacitance of the bipolar plate can be replaced by the capacitance C, and the open-circuit voltage is characterized by an ideal voltage source V_{OC} originating from the friction charge after the deviation. Thus, these two components constitute an alternative model of lumped circuits: an ideal voltage source in series with a capacitor.

The intrinsic characteristics of TENGs are capacitive, and their intrinsic capacitance primarily determines their internal impedance. Therefore, the insulation performance between the two electrodes was excellent owing to the reasonable design. Furthermore, owing to the small inherent capacitance, it has a very high internal impedance, which can be considered to approach infinity. Therefore, there is no equivalent resistance in its equivalent circuit; the TENG is distinguished from the traditional generator, which uses electromagnetic induction as a principle. Thus, its intrinsic performance is resistance, and its internal impedance is significantly smaller.

4. FEASIBILITY OF WASTE PLASTIC BAGS FOR TENGs

According to the working principle of TENGs, common silk, metals, and synthetic chemical materials can be used to produce TENGs. Waste plastic bags have a good triboelectric effect, and plastic bags have good stability; even waste plastic bags have no significant difference in material properties and performance. The polarity of friction material is closely related to its capacity to gain or lose electrons. Considering the polarity of the components of different plastic bags, plastic bags of different components can be matched. Table 1 compares the triboelectric sequences of common materials, starting from the material in the leftmost column; from top to bottom, the material below is more likely to obtain electrons, functioning as a negative friction layer in the friction course.

Table 1. Triboelectric sequence of common materials

	Receive the left column	**Receive the left column**	**Receive the left column**
polyformaldehyde	wood	polyisobutylene	polyvinylidene chloride
nylon	hard rubber	Flexible sponge	polystyrene
melamine	copper	polyethylene terephthalate	polyethylene
woven wool	sulphur	polyvinyl butyral	polypropylene
woven silk	silver	neoprene	polyimide
aluminum	artificial fiber	natural rubber	polyvinyl chloride
paper	Polymethylmethacrylate	polyacrylonitrile	Polydimethylsiloxane
Textile cotton	polyvinyl alcohol	modacrylic	teflon
steel	polyester	Polycarbonate bisphenol	
Turn the right column	**Turn the right column**	**Turn the right column**	

According to the above table, the friction materials can be reasonably selected to maximize the various indicators of the TENG's output in the optimal state as far as possible. Efficient output is significant for intelligent control systems [55].

5. APPLICATION OF SELF-POWER SENSING SYSTEM

The TENG was completely composed of plastic waste bags. It can gather mechanical energy from the surrounding environment. This portion of the energy is converted into electrical energy. Combined with sensors, this can eliminate the drawbacks of traditional power sources and power microelectronic devices. They can be creatively applied to drive electronic miniature equipment, environmental monitoring, and wearable devices that power themselves without extra energy.

5.1. TENGs Drives Electronics

Although the power consumption of a single tiny electronic device is low, with the popularization of these electronic devices, power consumption cannot be ignored. Therefore, energy conservation plays an essential role in industrial and sustainable development [56]. The TENG can directly supply power to energy storage devices and power equipment related to power electronics without requiring rectifiers. Liu et al. proposed a system without an external power supply. They regarded the direct-current triboelectric nanogenerator (DC-TENG) as an innovation that could concentrate some of the neglected energy in life and transform it into energy that can be utilized by electrical devices to drive some electronic devices. The DC-TENG in the rotating mode was used to charge the capacitor directly. This mode is relatively simple and does not require a complex conversion process, and the stability and efficiency of the output current can be guaranteed. In this mode, the voltage can reach 80 V, and the current density can reach 270 μA/m^2 [57]. The power supply is sufficient to satisfy the normal use of daily electronic loads. The charging rate is closely related to the rotation rate and capacity of the capacitor and exhibits a certain change law. Under the same capacitance, the charging rate was positively correlated with the rotation rate within a certain range. In the analysis of Figure 4(c), if the capacitor is charged to approximately 1.5 V, the DC-TENG needs 50 s at a rate of 600 rpm, nearly 100 s at a rate of 400 rpm, and more than 200 s at a rate of 200 rpm. For the same rotation rate, the charging rate decreases with an increase in the capacitance within a certain range.

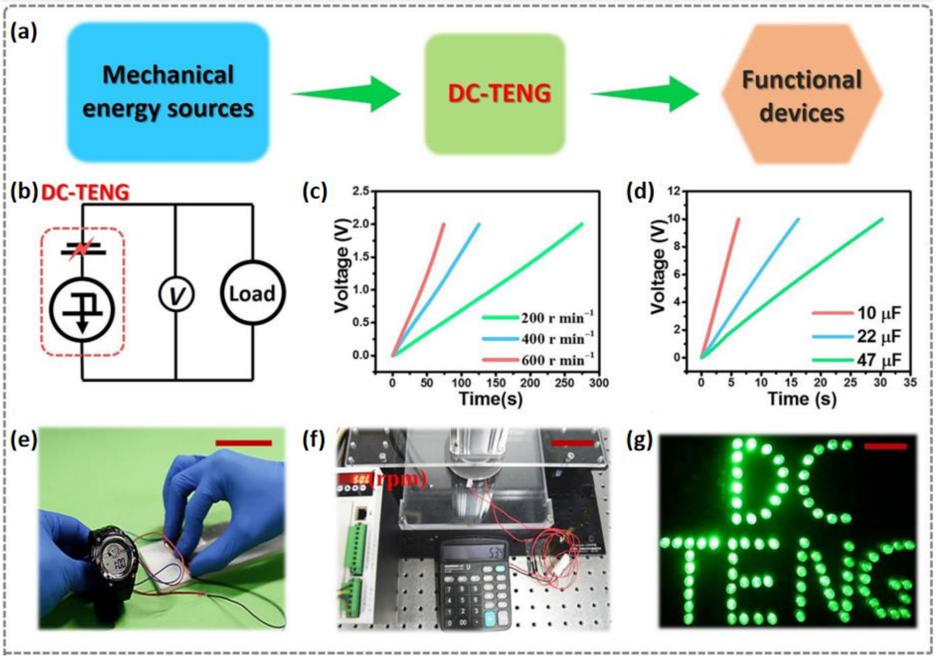

Figure 4. Operation analysis and power supply application of DC-TENG. (a) System action diagram (b) Circuit diagram of direct operation between load and DC-TENG (c) Image of the relationship between charging voltage and time of the capacitor (470μF) fed by DC-TENG at the rotation rate (d) Image of the relationship between charging voltage and time of the capacitor fed by DC-TENG at the fixed rotation rate (500rpm) (e) Physical picture of a DC-TENG driven wristwatch (f) Physical picture of a calculator powered by DC-TENG (g) Light display panel composed of light emitting diodes driven by DC-TENG Reproduced with permission. [58] Copyright 2019, Science Advances.

At a rate of 500 rpm, when charging to 8 V, the time required for the 22 μF capacitor is more than twice that of the 10 μF capacitor, while the time required for the 44 μF capacitor is nearly five times, which is more intuitively characterized in Figure 4(d). TENGs can be used to drive low-consumption electronic devices. For example, an electronic watch worn on the wrist can be connected to the device so that the electronic watch can operate normally. It has a particular contribution to alleviating the energy consumption problem in the world today and is a simple and feasible case for realizing the conversion of old and new kinetic energy. Similarly, a scientific calculator, such as a commercial calculator, can accurately calculate the required results at a rate of 500 rpm. The light display panel composed of light-emitting diodes can also be lit by a DC-TENG in the rotating mode [58].

5.2. TENGs for Environmental Monitoring

Wind speed is a vital weather forecasting indicator, as it affects traffic, agricultural production, and even safety. Therefore, accurate estimation of wind speed is also important. The electromotive force required by the general wind speed sensor is generated by the change in magnetic flux and is measured using the wind cup. Wind energy has the characteristics of stability and no pollution. In addition, wind energy can supply power to wind sensors, effectively overcoming the shortcomings and limitations of traditional sensors [59, 60]. Liu and Che et al. proposed a wind speed sensor with high accuracy that uses TENGs to provide power and consists of two identical sensors. Each TENG can detect wind speed and minimize measurement errors as much as possible. It uses the electrostatic inductive interaction between two tiers of parallel polytetrafluoroethylene (PTFE) membranes and Al/Kapton/Al films sputtered by a metal electrode layer to generate electricity.

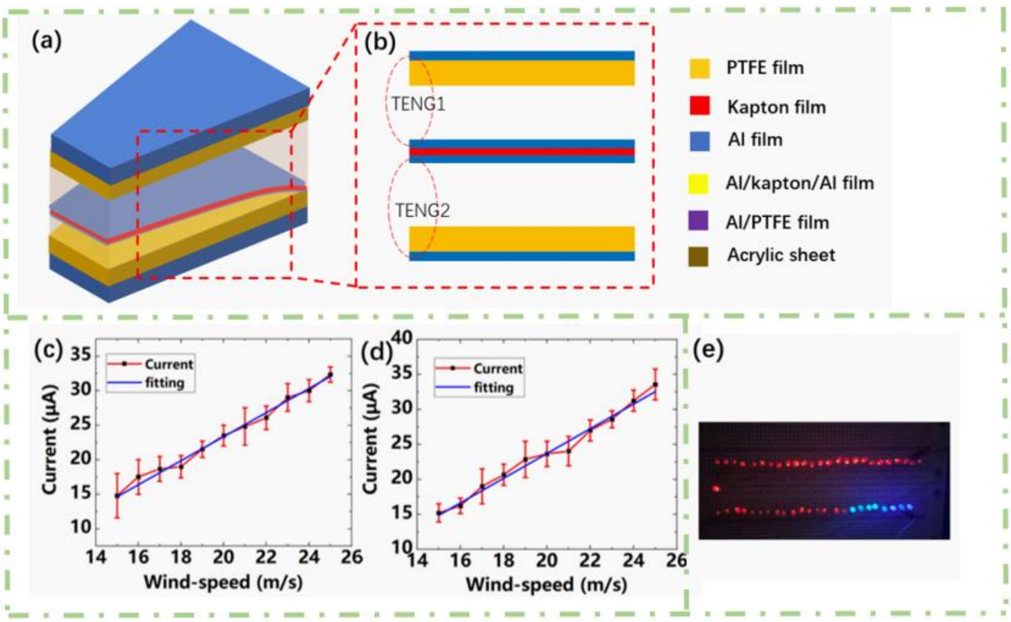

Figure 5. (a) Structural diagram of the wind speed sensor constructed by TENG (b) Internal concrete structure (c) Image of relation between rectification short-circuit current and wind speed of TENG1 (d) TENG2 image (e) Physical picture of LED lamps driven by this device [61] Copyright 2021, Sensors.

Liu et al. proposed the best geometric parameters of the sensor after many experiments and comparisons: the distance of the PTFE film was 12 mm, the length was 80 mm, and the top line of the trapezoid was 20 mm. In the velocity scope of 15–25 m/s, in the process of converting wind energy into electric energy, the average peak current increases sharply when the wind power changes; the sensitivity of the wind speed sensor can reach 1.79 μA/(m/s), as shown in Figure 5, and 50 LEDs can be lit at a wind speed of 15 m/s [61].

Currently, the power required by devices such as the Internet of Things needs to rely on traditional batteries. However, with the increase in power consumption and other factors, the batteries need to be replaced regularly.

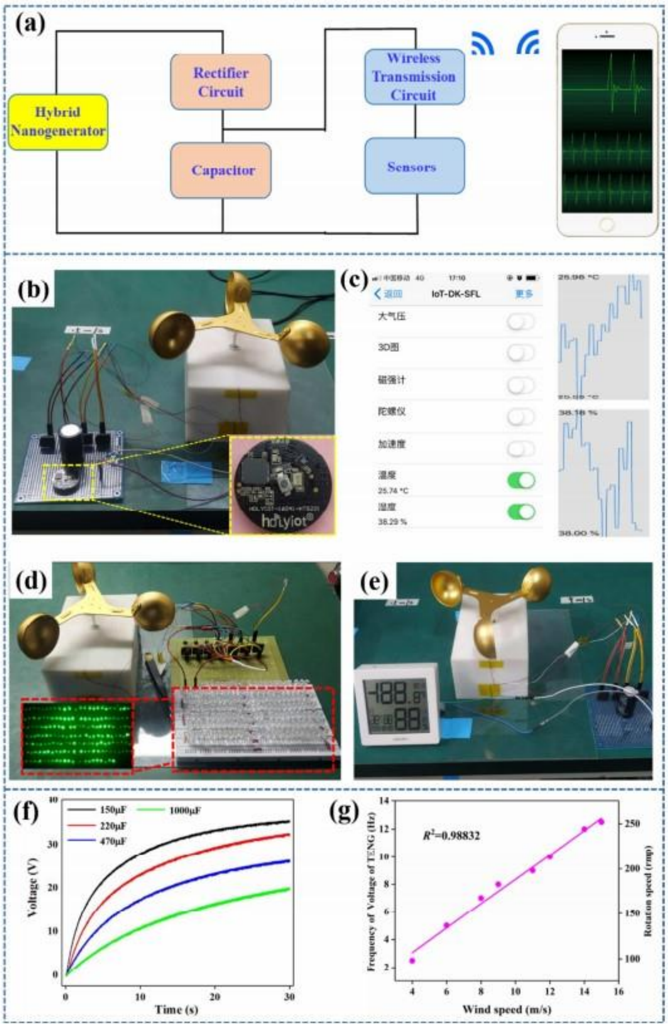

Figure 6. (a) Block diagram of combination of self power supply system and remote monitoring system (b) Physical diagram of self powered monitoring (c) Mobile phone reading monitoring data information interface (d) Supply more than one hundred LED lights to light normally (e) Physical diagram of driven hygrometer (f) Charging curve under different capacitor capacities (g) Function relation image of wind speed, rotation speed and voltage frequency [62] Copyright 2019, Nano Energy.

Fan and He et al. proposed a device for collecting mixed energy based on this status. The particularity of the device is that its core is divided into two parts, primarily focusing on the collection, transformation, and utilization of wind energy. The part characterized by rotation adopts an electromagnetic generator, and the other part is characterized by sliding using a TENG. The unit modules of the generator, which are the core parts of the device, were tightly sealed in the equipment box. With this innovative design, the designed power generation and energy storage equipment can be successfully protected from the interference of uncontrollable factors, such as natural weather. Therefore, they can be used in remote areas with harsh environments. Moreover, the complexity of the device was not high. This also presents a new solution to the power supply problem in the field or harsh environments. This study suggests that wind speed determines the efficiency of energy conversion. The output performance of the two generators increases with an increase in wind speed, and the premise of conversion is that the wind speed is greater than or equal to 4 m/s. The faster the wind speed, the greater the voltage output by the two generators and the higher the maximum output power. The charging speed of the device for external loads is also considerable. By analyzing the frequency of the TENG output voltage and connecting with smartphones through wireless transmission paths, real-time wind information and even local temperature and humidity information can be read on remote devices such as mobile phones [62].

5.3. TENGs for Wearable Electronics

In recent years, with the increase in people's income level and emphasis on their health, the demand for wearable electronic products such as electronic wristbands, pulse, and blood pressure monitors has increased, and the invention of electronic skin has also brought many benefits. Wearable electronic products based on TENGs can overcome some disadvantages that cannot be ignored while using common batteries and convert the low-frequency mechanical energy of body movement into electrical energy. These TENG-based products are lightweight, portable, and easy to carry. Moreover, the wearability of electronic products has high requirements for flexibility and fit with the human skin. Therefore, these factors should be considered when selecting electrode materials and designing the system structure. Chu et al. proposed a device that meets the above requirements using atomically thin graphene (<1 nm) as the electrode of the TENG, which not only achieves excellent electrical conductivity but also has the characteristics of high strength and toughness, and the electrode material is flexible. Polydimethylsiloxane (<1.5 μm) was used as its charged layer, which has good stability and shock absorption. With polyethylene terephthalate (<0.9 μm) as the substrate, its wear resistance and dimensional stability are good, and electrical insulation and folding resistance are compatible with the equipment's design requirements. Wearable electronic devices adopt a single-electrode structure design, which improves their reliability. The design can be directly implemented on human skin, which maximizes the tight fit and adaptability of the human skin and allows rechargeable devices to be operated without the need for a charging process, as shown in Figure 7. The conformal TENG generates current by rubbing the fitted human skin and clothing worn. Triboelectric properties depend on the valid friction contact area. This design can be applied to self-powered touch sensors to provide useful assistance to communication systems by transforming similar human motion messages into digital signals and can also be used to detect body motion [63].

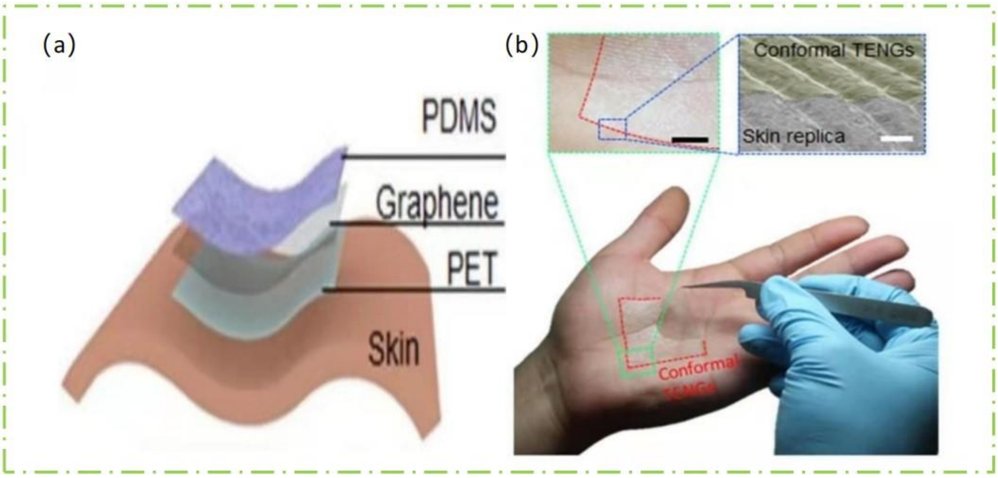

Figure 7. (a) Structural composition model diagram of conformal TENGs fitted to human skin, showing the main components of materials used in each part (b) Physical display effect drawing and detail enlarged display drawing of the device Reproduced with permission. [63] Copyright 2016, Nano Energy.

Presently, some diseases have no obvious symptoms and are not easily detected at the initial stage of onset; however, there are potential threats to people's lives and health. As an in vitro biomarker, sweat contains rich biochemical data, such as pH, and element content represents the state of the body, which can be collected using non-invasive technology to achieve dynamic monitoring. Song et al. proposed an independent wearable sweat-monitoring sensor system. The system uses low-power wireless sensor circuits and microfluidic sweat sensor patches driven by fibrous TENGs. The patch adopts flexible printed circuit technology, which has a high production efficiency and can be produced continuously and automatically. It is lightweight and can change shape elastically. It has high stability and avoids hard system failures when worn by the human body. To improve the efficiency of energy collection and utilization from the human skin, the system adopts a unique independent design and efficient power management, particularly suitable for powering wearable devices with skin interfaces. Moreover, to improve the energy utilization efficiency to the optimal state, the device was fixed to the trunk of the body's limbs with the help of waterproof medical tape. The integrated Bluetooth low power (BLE) module allows easy data transfer from sensors to the mobile interface to track health during movement, as shown in Figure 8 [64].

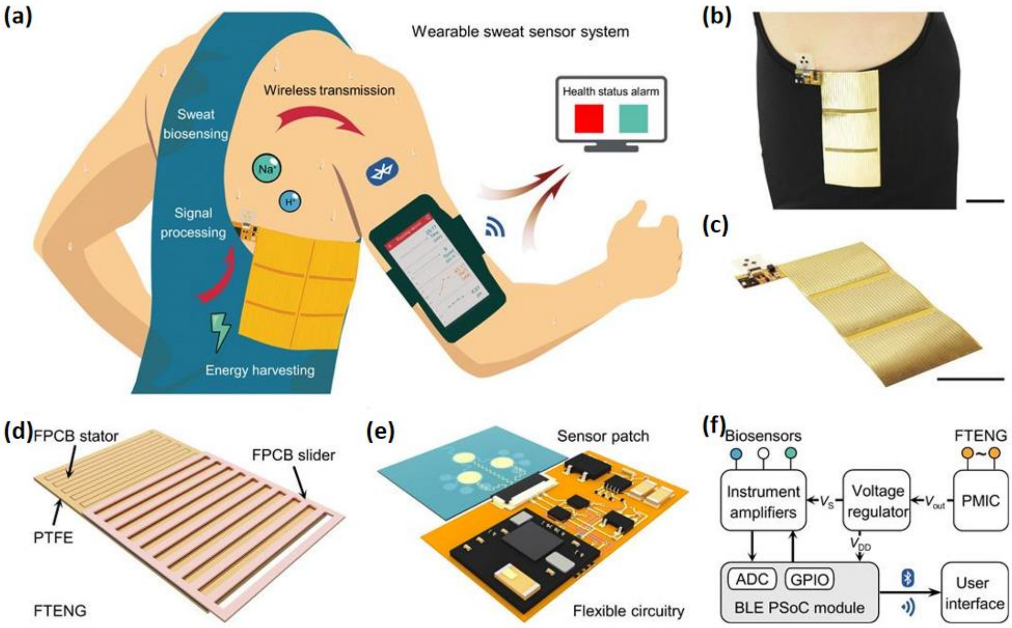

Figure 8. (A) Micro working principle diagram of wearable sweat monitoring sensor system (B) Simulation diagram of the device worn on the human torso (C) Optical image of the device (D) Micro schematic diagram of flexible printed circuit of fibrous friction nano generator (E) Schematic diagram of microfluidic sweat sensor patch with flexible circuit interface (F) Work flow block diagram of each part of the whole system Reproduced with permission. [64] Copyright 2020, Science advances.

The high infectivity of COVID-19 has posed a massive challenge to global medical protection and treatment work, particularly in the early stages of the outbreak, owing to the lack of medical personnel, resulting in patients' respiratory conditions not being comprehensively monitored. Wang et al. proposed a fiber-optic strain sensor with a spiral structure based on TENGs, which can be used to monitor the situation of the respiratory system. The design fully adopts the spiral structure, significantly improving its sensitivity; the device can detect even small tensile strain, the detection accuracy is less than 1%, and the power supply efficiency is also high. Furthermore, it does not need an additional battery supply and can work for a long time. The friction layer is also composed of commonly available materials such as Teflon (PTFE) and nylon [65]. The device is fixed to the lower part of the chest, according to the contraction and expansion of the chest movement, and can analyze breathing frequency, lung capacity, and other breathing conditions and then determine whether the respiratory system is abnormal. When the sensor data are connected, the monitoring station can send an alarm signal to the medical staff, indicating that the patient needs attention or even rescue. This reduces the working pressure of the medical staff and prevent missing the best treatment time by monitoring patient's real time breathing condition.

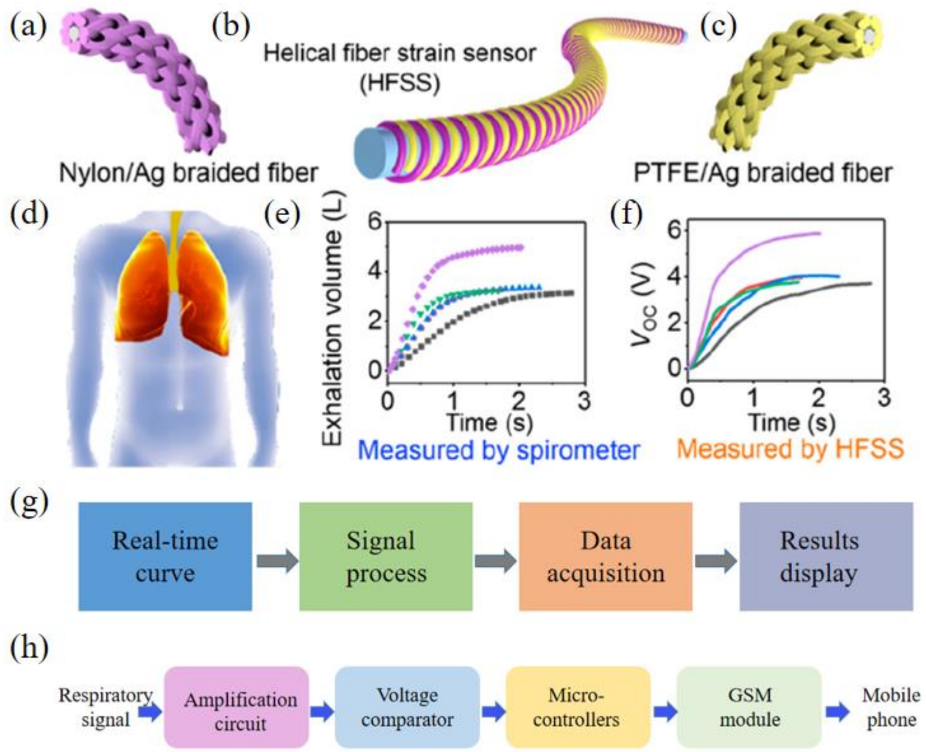

Figure 9. ((a), (b) and (c)) Micro schematic diagram of friction materials (d) Diagrammatic sketch of the human lungs showing the location of the device (e) Image of expiratory volume measurement (f) Corresponding voltage signal - time coordinate image (g) Flow chart of the system working (h) Complete module composition diagram of the system Reproduced with permission. [65] Copyright 2021, ACS.

6. CONCLUSIONS

In summary, TENGs convert overlooked mechanical energy into electrical energy, overcome the shortcomings of traditional batteries that are cumbersome and require regular charging and replacement, and have great significance and prospects in energy-to-electricity conversion and self-power supply. By analyzing the composition, structure, and polarity of discarded plastic bags, it was found that they have good triboelectric effects and stability. Even waste plastic bags do not vary significantly regarding material properties and performance. According to the principle of TENGs and triboelectric sequence, selecting appropriate waste plastic bags can achieve better output performance.

The self-powered sensing system constructed using TENGs can be applied to environmental monitoring, life and health monitoring, and other fields. For example, continuous wind energy can be used in environmental monitoring to detect wind speed, atmospheric temperature, and humidity. It also has very bright prospects in life and health monitoring; for example, electronic skin, wearable vital sign detectors, and biomarker detection devices have excellent prospects in health care. Furthermore, with the spread of COVID-19, monitoring the respiratory system, body temperature, and other biological characteristics have become routine. In future research, it is crucial to improve the environmental adaptability and stability of the self-powered system of TENGs, prolonging their service life, and improving product performance and promotion rate. In addition, they have excellent application prospects, particularly in remote areas with harsh environments and in the field of life and health monitoring.

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