

Review

Triboelectric Nanogenerators in Sustainable Chemical Sensors

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Abstract: The rapid development of sensing technology has created an urgent need for chemical sensor systems that can be rationally integrated into efficient, sustainable, and wearable electronic systems. In this case, the triboelectric nanogenerator (TENG) is expected to be a major impetus to such innovation because it can not only power the sensor by scavenging mechanical energies and transforming them into electricity but also act as the chemical sensor itself due to its intrinsic sensitivity towards the chemical reaction that occurs at the triboelectric interface. In this review, recent research achievements of chemical sensors that are based on TENGs are comprehensively reviewed according to the role of TENGs in the system, that is, pure power supplies or self-powered active chemical sensors. Focus is put on discussing the design criteria and practical applications of the TENG-based active sensors in different fields, which is unfolded with a classification that includes biosensors, gas sensors, and ion sensors. The materials selection, working mechanism, and design strategies of TENG-based active chemical sensor systems (CSSs) are also discussed, ending with a concise illustration of the key challenges and possible corresponding solutions. We hope this review will bring inspiration for the creation and development of TENG-based chemical sensors with higher sensitivity, simpler structure, and enhanced reliability.

Keywords: triboelectric nanogenerator; chemical sensor; self-powered; sustainability



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1. Introduction

Over the past decades, chemical sensors have played a significant role in clinical, industrial, and biomedical analyses because of their remarkable detection capability, simplicity, and low cost [1–6]. Meanwhile, in keeping with the trend of microminiaturization, networking, and intellectualization [7–9], chemical sensors are finding wider applications in flexible electronic equipment and wearable intellectual devices [10–14]. Nevertheless, due to the intrinsic drawbacks of traditional chemical batteries, such as insufficient capacity and limited-service life, the development of efficient, sustainable, and autonomous wearable chemical sensing systems still faces severe challenges [15–18]. Energy harvesting strategies that can bridge the integration of chemical sensors with energy storage units and promote the design of reliable and sustainable autonomous chemical sensing systems are urgently needed [19,20].

Among the various renewable energy harvesting technologies, such as triboelectric, thermoelectric, and photochemical generators [21–27], triboelectric nanogenerators (TENGs) are receiving tremendous focus due to their ubiquitous advantages in self-powered facilities, where they can act as both power source and smart sensor, including dynamic force sensors and chemical sensors, due to their intrinsic sensitivity toward chemical reactions at the triboelectric interface [28,29]. Theoretically, TENGs collect mechanical energies from the surroundings by interfacial contact electrification and electrostatic induction, and

the magnitude of the electrical signal is highly related to the charge density in the friction electrode surface [30–32]. In recent years, TENG-based chemical sensors have been advancing significantly, which allows reliable, practical, and energy-efficient chemical sensor systems (CSSs) to be established.

Herein, the recent development of chemical sensors on the base of TENGs is reviewed and summarized. As presented in Figure 1, TENG-based CSSs are classified according to the functional role of TENGs: either as a power supply or as an active chemical sensor itself. Accordingly, the design criteria, material selections, and basic principles of the TENG-based chemical sensor are discussed in light of increased stability, enhanced output, and improved reliability in harsh environments, thus satisfying the requirements of its application. For convenience, TENG-based chemical sensors are divided into three main categories in line with their practical applications: biosensors, gas sensors, and ion sensors. At the end of this paper, challenges and prospects for the development of TENG-based chemical sensors are concisely discussed. We hope this review will provide insight into the operation and design of continuous, simple, and reliable CSSs.

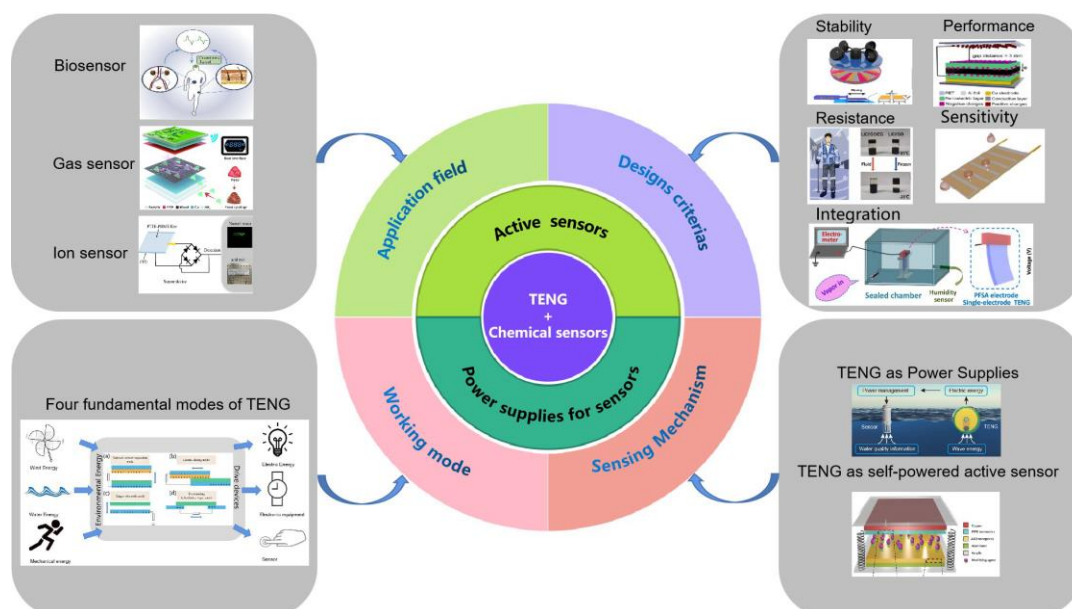


Figure 1. Recent progress of TENG-based CSSs.

2. Basic Principle of TENGs

2.1. Working Mode of TENGs

By varying the relative motion of the contact initiation layer, TENGs are generally classified into four basic operating modes: the vertical contact separation mode, the sliding mode, the single-electrode mode, and the free-standing friction layer mode [33,34].

The most typical device structure in TENGs is the vertical contact separation mode (Figure 2a), which has two electrodes—one attached to the top of the dielectric membrane and the other on the back. These two electrodes move towards each other in the vertical direction of the device, generating an electrical charge as a result of an externally applied force. The potential between the electrodes will change during contact or separation, resulting in a current output from the external circuit [35].

Next is the sliding mode (Figure 2b), which operates similarly to the vertical contact separation mode. The device is driven by an external force parallel to the interface, resulting in a relative displacement between the electrode material surfaces, which generates a dense frictional charge. The magnitude of the frictional charge varies periodically with the increase or decrease of the contact surface area. The potential difference between the electrodes changes, resulting in an external current to balance the potential difference. Both modes of operation require moving the object with electrodes [36].

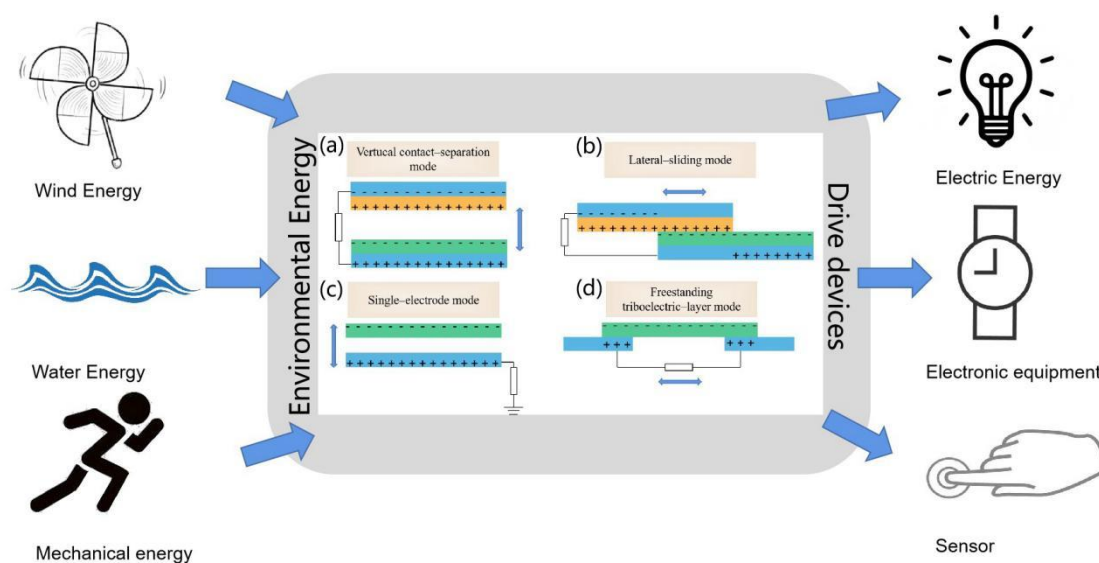


Figure 2. Four modes of TENGs: (a) vertical contact separation mode; (b) lateral sliding mode; (c) single-electrode mode; (d) free-standing triboelectric layer mode.

Given that most movements in real-world scenes are irregular, researchers recommend the single-electrode mode (Figure 2c), in which the object can move freely without being constrained by electrodes. In this mode, the device only requires one electrode to be grounded, which acts as a reference electrode. After contact with a free-moving object, an electrical charge is generated at the interface. During the motion, the potential distribution caused by the charged surface will change, resulting in the flow of external circuit current [37].

The free-standing triboelectric layer mode requires only one free-moving part (Figure 2d). In this case, the device consists of a dielectric layer and a pair of symmetrical electrodes, and the free-moving part generates an asymmetric potential distribution by changing its position. Subsequently, electrons move continuously between the two electrode materials, which results in electrical output [38].

2.2. Working Principle

Triboelectrification is a common phenomenon that we encounter daily. While its origin is still unclear, it is widely believed that frictional electricity is caused by the overlap of electron clouds inside the material when the electrode surfaces are in contact. In this case, the energy barrier in the interior of the atom is lowered [39]. From a theoretical point of view, the charges of the two friction electrodes are equal. When no external force is applied, the two friction electrode surfaces are separated from each other, leading to the establishment of an internal potential in the device [40,41]. Additionally, in this process, the internal potential can induce the flow of carriers in the material from one electrode to the other, thus counteracting the change in electric potential caused by electrostatic induction and, finally, generating a positive current [42]. When there is an external force, the two electrodes of the TENG move toward each other, which can cause the carriers in the material to flow in opposite directions, resulting in a change in the polarity of the electric potential as well [43]. In addition, when the two friction electrodes are in contact again, this process will cycle, resulting in a periodic output with positive and negative properties [44].

3. Recent Progress of TENG-Based Chemical Sensor Systems

3.1. Chemical Sensor Powered by TENG

As a renewable energy harvesting technology, TENGs have promoted the development of self-powered sensors and portable electronic equipment to meet the growing demand

for autonomy and sustainability [45]. Here, the basic principle, design strategy, and recent progress of TENGs acting as a power source in chemical sensors are illustrated.

3.1.1. Basic Principle

As shown in Figure 3, the TENG serves as a power source that can directly drive a chemical sensor system (CSS). In this process, the output of the TENG is processed by a power management device in the system, which typically consists of a rectifier and various types of energy storage devices. In this case, the stability of the TENG output can only affect the charging efficiency of the energy storage devices in the system and has no effect on the detection abilities of the sensor.

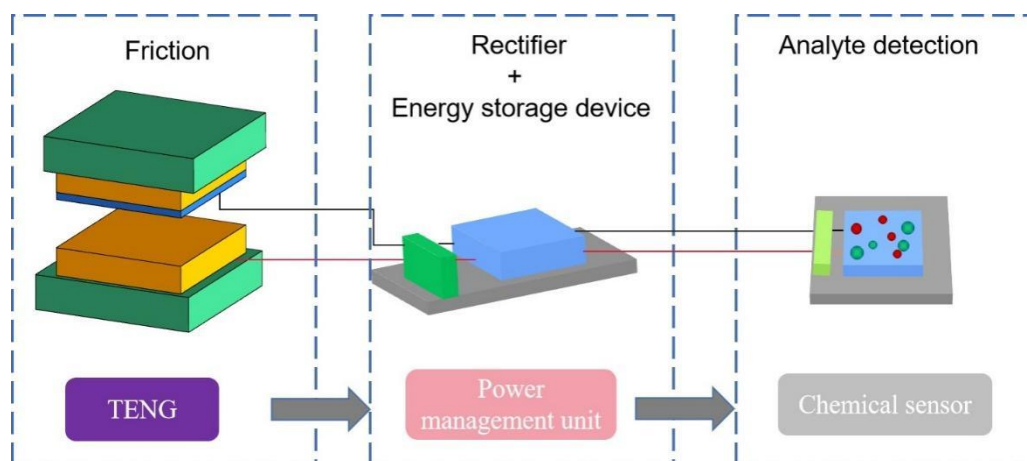


Figure 3. TENG serves as a power source in the TENG-based chemical sensor system.

3.1.2. Design Criteria of TENG-Based Power Source

To be used as a power supply, the design of TENGs needs to consider the following aspects. First, a direct and stable output TENG should be designed to continuously drive the sensor. Second, it is essential to increase the maximum output power and energy conversion efficiency of the device and, finally, improve the reliability performance of the device in harsh operating conditions.

Power Management Approach

We know that conventional TENGs produce a transient peak AC output when in operation, which is one of their most significant limitations; therefore, they cannot be directly used as a power source for sensors. Nowadays, there are two main methods of achieving conversion from AC power to DC power in a circuit. The first method is to connect a rectifier to the TENGs to obtain a stable, constant DC voltage, thus maintaining the daily operation of the sensor.

Zhang et al. combined a TENG with a humidity sensor. They prepared a flexible Teflon triboelectric nanogenerator (TENG) and used it as an energy harvester to drive a flexible humidity sensor [46]. The humidity sensor was made by screen-printing an SnS_2/RGO suspension with a pair of Au interdigital electrode (IDE) on a flexible PET substrate. During operation, the frictional charge of the TENG electrode material is triggered to produce a large alternating voltage, as in an electronic pump. To achieve the conversion of AC into a stable DC output, they integrated the TENG with a voltage rectifier and stabilizer circuit, thus providing a continuous and stable power supply for the humidity sensor (Figure 4a). The output performance of the frictional electric humidity sensor system was systematically investigated in different humidity environments, and it exhibited a highly stable output voltage (0–24 V), fast response/recovery time (Figure 4b,c), a wide sensing range, great stability, and ultra-low power consumption. This humidity sensing system allows stable and continuous monitoring of human breathing and coughing and has promising future applications in wearable devices and non-invasive medical monitoring, etc.

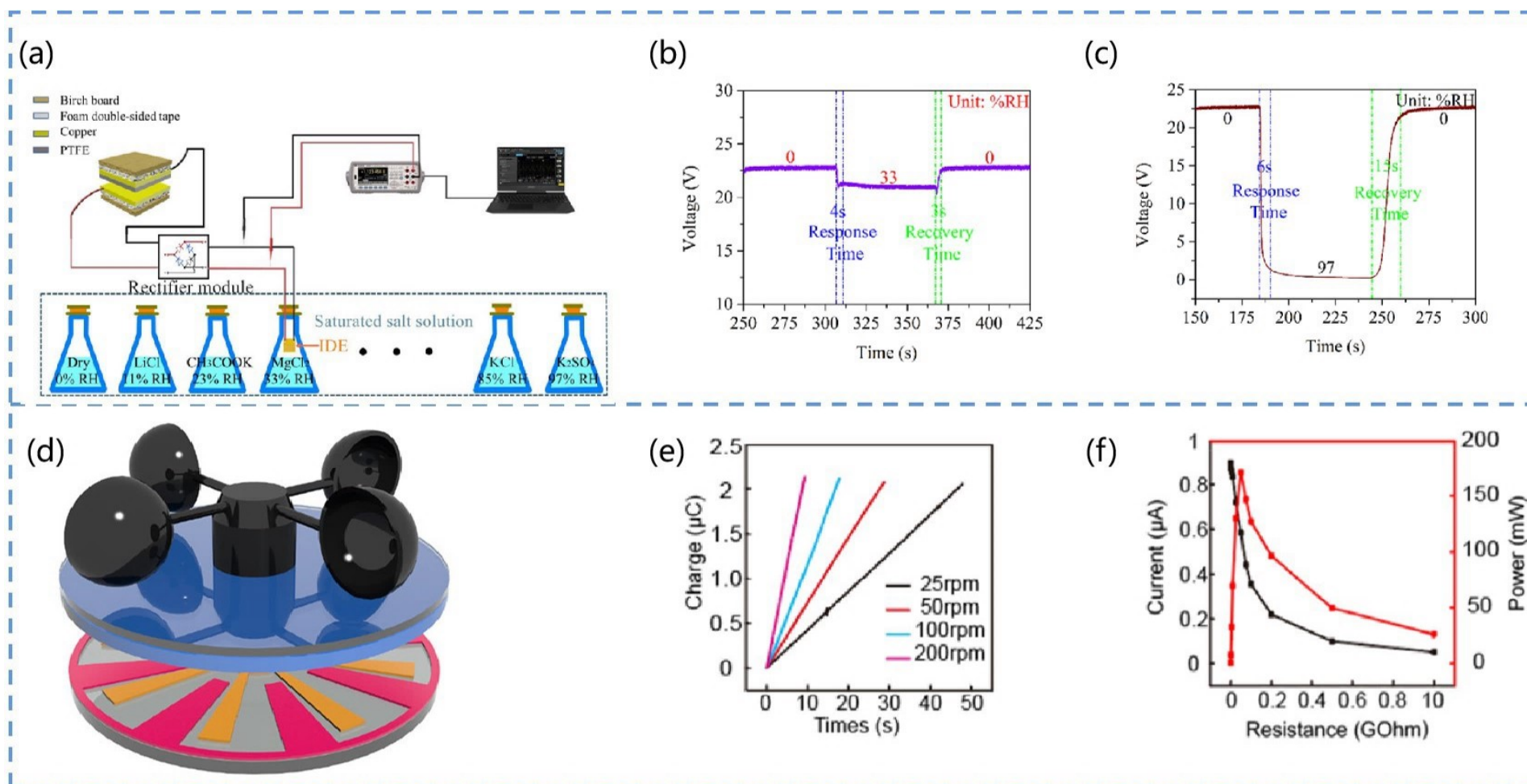


Figure 4. (a) Schematic diagram of the fabrication and operation of a TENG-based humidity sensing system. (b) Response of the device at 33% humidity conditions. (c) Response of the device at 97% humidity conditions. Reprinted from [46] with permission from Elsevier. (d) Schematic diagram of the structure of the coplanar electrode DC-TENG. (e) Output of the TENG for charging the capacitor at different rotational speeds. (f) Output of the TENG at 400 r/min rotation speed. Reprinted from [47] with permission from Wiley Online Library.

However, the method of using rectifiers is not conducive to the portability of the TENG, and its performance is susceptible to circuit failures or environmental impacts. As a result, some researchers tried alternative design methods to obtain a DC output from a TENG without any device to stabilize the voltage.

For example, Xu et al. developed a coplanar electrode DC (CDC-TENG) (Figure 4d) [47]. The device has two friction electrodes in the same plane, and the rotating CDC-TENG continuously draws energy from the environment to produce a large DC current output (Figure 4e,f). Theoretically, this is caused by the potential difference, where the charge is transferred from the front electrode to the back electrode through an external circuit and then released by discharge. The external circuit can produce a DC output under a continuous unidirectional external force. Compared with rectifiers, this CDC-TENG has the characteristics of portability and a simplified manufacturing process, which can open new channels for the further development of direct and simple energy harvesting systems.

Similarly, Luo et al. created a DC tribological nanogenerator (DC-TENG) using the air breakdown technique [48]. During device operation, the charge first moves from the bottom electrode to the top electrode and then returns through the ionized air channel formed by air breakdown, thus creating a closed loop that produces a continuous DC output without the required bridge rectifier.

Performance Enhancement Strategy

Although TENGs are a promising power source due to their ability to collect energy from the environment, the relatively low output power limits the broad application of TENGs. The following are several effective ways to increase the output of TENGs: firstly, increase the surface charge density of the material; subsequently, increase the area of electrode contact separation; in addition, optimizing the structural design is also a solution.

Generally, the energy conversion and output of TENGs depend on the charge transfer resulting from the contact separation of the friction electrode surfaces. Moreover, the charge density is highly important as it directly determines the power density, output voltage, and current density of the TENG device.

To increase output power, Chai et al. developed a high-output contact separation mode TENG (Figure 5a) [49]. They used conductive MWCNT/P(VDF-TrFE) interlayer ferroelectric BTO/P(VDF-TrFE) nanocomposites as negative frictional electric materials. Compared with previous versions, the optimized TENG improved the transferred charge density to $105.70 \mu\text{C m}^{-2}$ (Figure 5b) and the peak power density to 7.21 W m^{-2} (Figure 5c) in the test. These performance enhancements can be attributed to the presence of a conductive interlayer in the negative frictional electric material, which induces charge trapping, enhancing the ferroelectric polarization and charge density of the nanocomposite and improving the output performance of the TENG. This work shows strong potential in the design of high-output TENGs.

Another approach is to change the surface microstructure of the friction electrode material to obtain a larger contact area during operation, resulting in higher output power. Lee et al. prepared surface woven glass fiber-reinforced siloxane hybrid membranes (SGH membranes) with a layered structure using a gel method [50] and successfully fabricated a TENG with this film (Figure 5d). They replicated the film more than 100 times with one mold, which increased the stability of the film (Figure 5e). The membrane with a layered surface structure increased the surface area by 210% compared to a flat membrane (Figure 5f). The output of the layered surface TENG was several times higher than flat TENGs. This work shows that it is possible to develop TENGs with enhanced performance by optimizing the membrane surface structure.

Furthermore, advanced structural design can greatly increase the output power of the TENG. For instance, Kim et al. developed a contact separation mode TENG with serrated electrodes (SE-TENG) (Figure 5g) [51]. In principle, owing to the frictional initiation of electricity, a spark discharge occurs between the electrode and the wire, and the resulting

ultra-high output (5 kV voltage, 2 A·m⁻² current density) can directly drive electronic devices (Figure 5h,i).

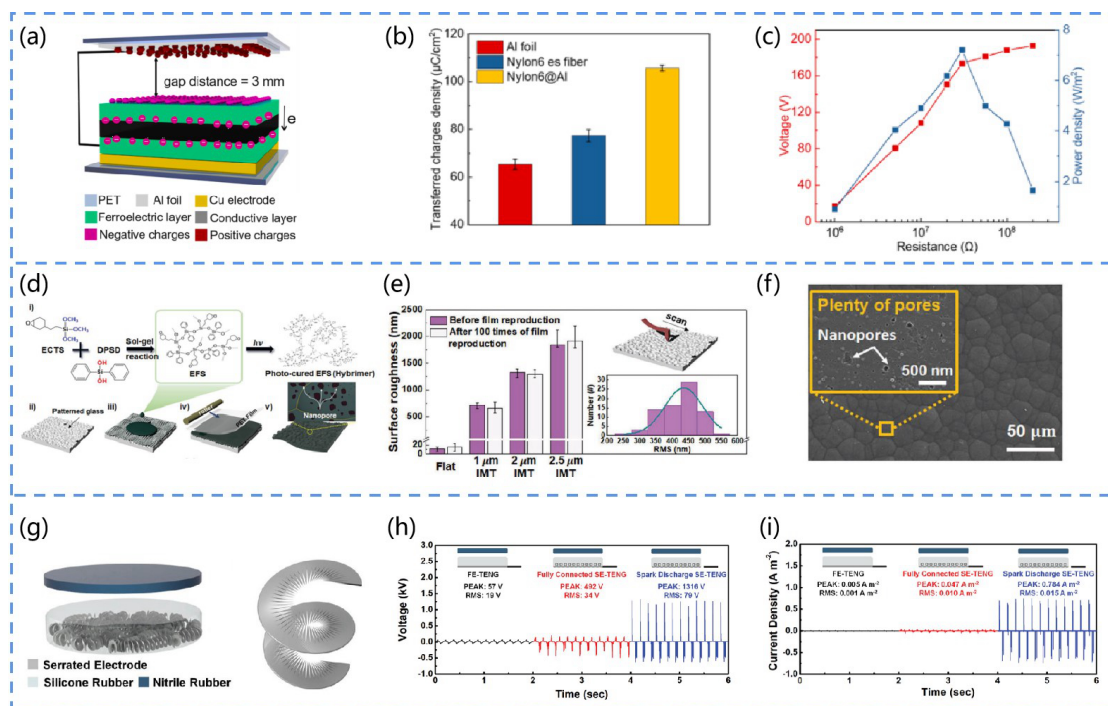


Figure 5. (a) Schematic diagram of the structure of the TENG. (b) Transfer charge density of the TENG. (c) The output power of the optimized TENG. Reprinted from [49] with permission from Elsevier. (d) The manufacturing process of SGH membranes. (e) Surface roughness of SGH films before and after 100 replications. (f) SEM image of the SGH film. Reprinted from [50] with permission from Wiley Online Library. (g) Schematic diagram of the structure of the electrode. (h) The voltage of the TENG and (i) the current density of the TENG. Reprinted from [51] with permission from Wiley Online Library.

Resistance to Harsh Conditions

In practical applications, self-powered chemical sensor systems based on nanogenerators always face complex operating environments such as acid, alkali, temperature, corrosive, high humidity, high salinity, and strong magnetic fields. Here, we review some design strategies of TENGs that work in these complex environments.

A significant application of TENG-based CSSs is in healthcare and therapeutics. However, saliva, sweat, urine, and blood contain many human metabolic substances containing acids, bases, and salts that can cause severe damage to electrode materials once they leak into the TENG. Jiang et al. adopted a self-polymerization reaction to synthesize a hydrogel from β -cyclodextrin (β -CD) molecules (Figure 6a) [52] and used this material to fabricate a Cyc-TENG that can be applied for long-term energy harvesting in the ocean. After simulations, Cyc-TENG could keep the output performance unchanged even in acidic, alkaline, and highly concentrated salt environments (Figure 6b,c).

Besides the medical field, there are high requirements for the stability of some wearable electronic devices during fieldwork. As shown in Figure 6d, Zhao et al. designed an anti-freeze TENG [53]. The friction electrode was synthesized from the components of lithium chloride, graphene oxide micro/nanosheets, and ethylene glycol, and then this electrode was wrapped in a cage as the friction layer of the device. This TENG exhibits 200% tension stretch performance and high output (Figure 6e). In addition, the device shows a stable output even at -40 °C, which has potential applications in low-temperature sensors and wearable electronics (Figure 6f).

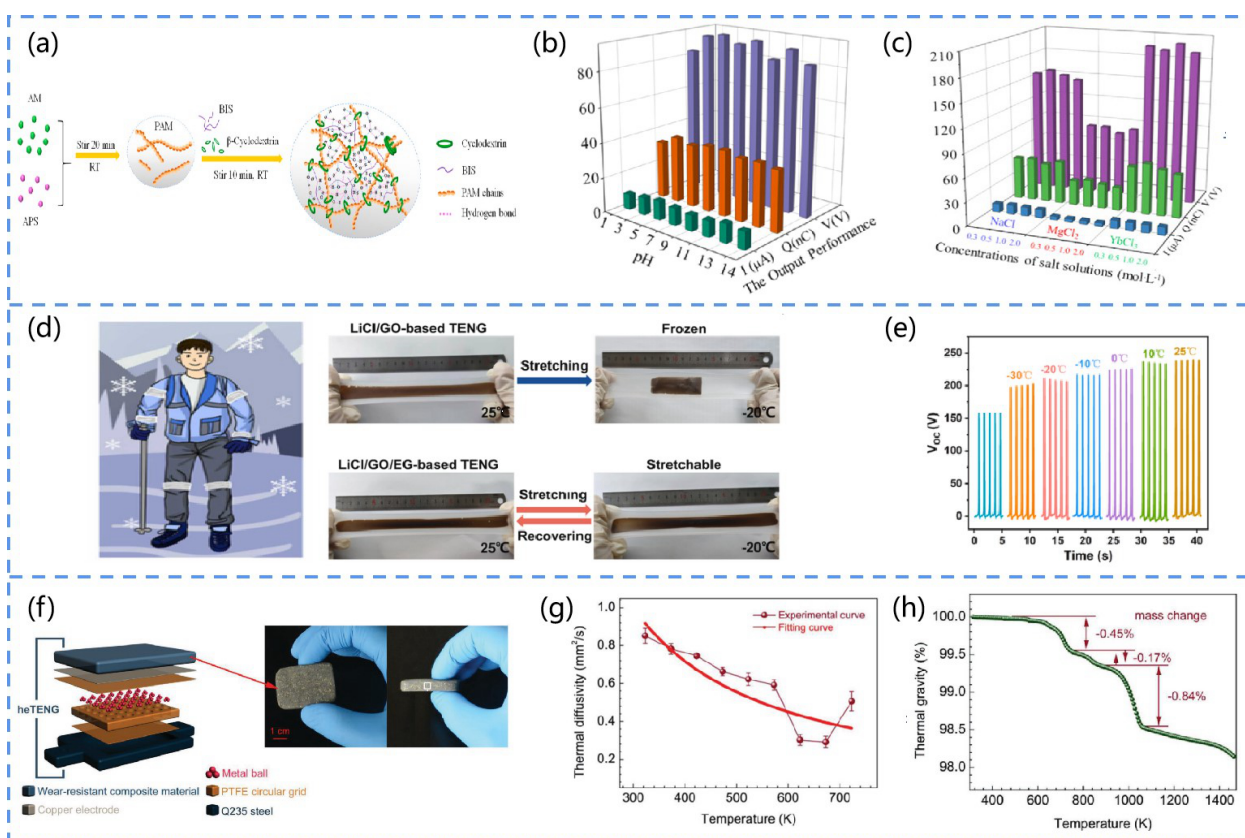


Figure 6. (a) Schematic diagram of the synthesis process of hydrogels. (b) Comparison of the output performance of the Cyc-TENG after treatment with aqueous solutions of different pH values. (c) Comparison of the Cyc-TENG output performance after treatment with different concentrations of salt solutions. Reprinted from [52] with permission from Elsevier. (d) Schematic diagram of the application of the AS-TENG in low-temperature environments and the stretchability of the TENG based on LiCl/GO electrodes and LiCl/GO/EG electrodes after cryogenic treatment. (e) Open-circuit voltage of the TENG at different temperatures. Reprinted from [53] with permission from Elsevier. (f) Diagram of the structure of the he-TENG. (g) Thermophysical properties of micro/nanocomposites. (h) Thermogravimetric measurements of micro/nanocomposites. Reprinted from [54] with permission from Wiley Online Library.

The same goes for high temperatures. Wen et al. designed a TENG (he-TENG) that is adequate for harsh environments [54]. As presented in Figure 6g, the operating mode of this TENG consists of a free-standing and single electrode. It can collect energy from vibrations as well as being vibration sensing. They chose micro/nanocomposite blends as friction electrode materials to obtain wear-resistant and high-temperature-resistant TENGs for applications in components such as brake pads (Figure 6h,i). This work demonstrates a way to improve the wear resistance of TENGs and also render them suitable for high-temperature environments, offering an attractive prospect for multifunctional TENGs.

3.1.3. TENG-Powered Chemical Sensors

TENG can be constructed from a wide range of materials with virtues such as biocompatibility, flexibility, permeability, and so on [55,56]. These features offer a foundation for the further development of CSSs that are powered by TENGs.

Biosensors

Biosensors are important in healthcare and diagnostic treatments. Nevertheless, the battery life of these instruments is limited [57]. Battery replacement is not only an expensive

and risky process for patients but also may be painful and inconvenient for them. Batteries are not ideal power sources for medical devices because they contain toxic chemicals [58,59]. Therefore, self-powered sensors are a promising strategy for the sustainable operation of biosensors.

For instance, Chen et al. reported a TENG-based blood oxygen monitoring system [60]. The friction layer material consists of a Au electrode and polydimethylsiloxane (PDMS) (Figure 7a). On the one hand, the folded structure of PDMS and the curved surface of the Au electrode provide great flexibility for TENGs, and on the other hand, the rough surface of PDMS and the Au electrode improves the output power density (0.2 mW/cm^2) of the TENG (Figure 7b). Powered by the TENG, the blood oxygen detector monitors a photoelectric volume tracing signal (PPG) that is available for calculating oxygenated hemoglobin saturation and pulse rate (Figure 7c). This work provides a new idea for the further advancement of medical wearable, flexible electronic devices and self-powered systems.

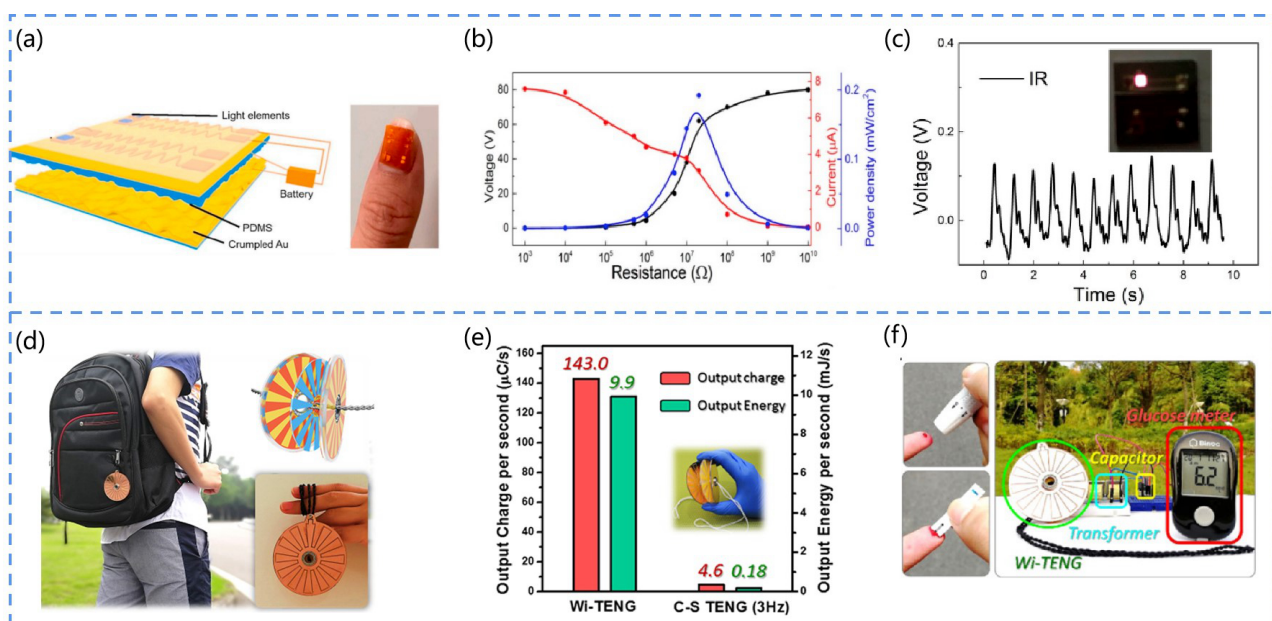


Figure 7. (a) Schematic diagram of the structure of the TENG and the monitoring of blood oxygen. (b) TENG output performance voltage and output power density. (c) PPG signal of the oximeter. Reprinted from [60] with permission from MDPI. (d) Schematic diagram of the structure of the rotating TENG. (e) Schematic diagram comparing the output of the CS-TENG and the WI-TENG. (f) Schematic diagram of a self-powered glucose monitoring system. Reprinted from [61] with permission from Elsevier.

Tang et al. fabricated a high-performance TENG inspired by a spinning toy (Figure 7d) [61] that generated high-frequency spinning at low-frequency traction, up to 11,250 rpm, at which the TENG could generate 310 μC of charge transfer and 40.18 mW of output power per time (Figure 7e). After incorporating power management, the TENG was successfully demonstrated as a portable pendant power source for a blood glucose meter (Figure 7f). This work exhibits the potential of the TENG as an instant power source for personal medical health devices.

Antigens are very important biological molecules that reflect the health status of the body. Fan et al. designed a TENG-based preconcentration device that can be used to preconcentrate antigens [62]. They first sputtered Al films onto PMMA to obtain Al@PMMA films and then covered the top of the films with polydimethylsiloxane (PDMS) and chitosan/glycerol films to obtain the TENG. The integration of the TENG-based preconcentrator and the smartphone-enabled bead immunoassay resulted in a portable and highly sensitive biosensing system.

Glucose is widely present in the human body and contains a lot of biological information. Chang et al. fabricated a TENG-based electrochemical sensing system [63]. The

synthesized highly electrocatalytic Se/Au/Pd NPs greatly improved the sensitivity of the sensor, and the response of the self-powered sensing system for glucose detection was greatly enhanced and showed significant sensitivity. The mechanical energy collected by the TENG from the environment can provide stable and continuous energy, reflecting its key role in the self-powered sensing system.

Gas Sensors

Recently, TENGs have been extensively utilized as a complementary power source for gas sensors, which helps the continuous operation toward the online detection of the environmental atmosphere.

Zhang et al. reported a gelatin–polyimide-based frictional electric nanogenerator (GP-TENG) (Figure 8a) [64]. They prepared a nanostructured gelatin film using sandpaper as a template and employed it as an electrode material, which significantly improved the output performance of the GP-TENG and exhibited good degradability (Figure 8b). In addition, they prepared a PANI nanorod/NiCoO₄-based NH₃ sensor. The sensor, rectifier, and GP-TENG were integrated to constitute a self-powered ammonia sensing system (GPAS), which exhibited good responsiveness, repeatability, and stability in monitoring NH₃ (Figure 8c). This work provides a new idea for wearable self-powered gas sensor designs.

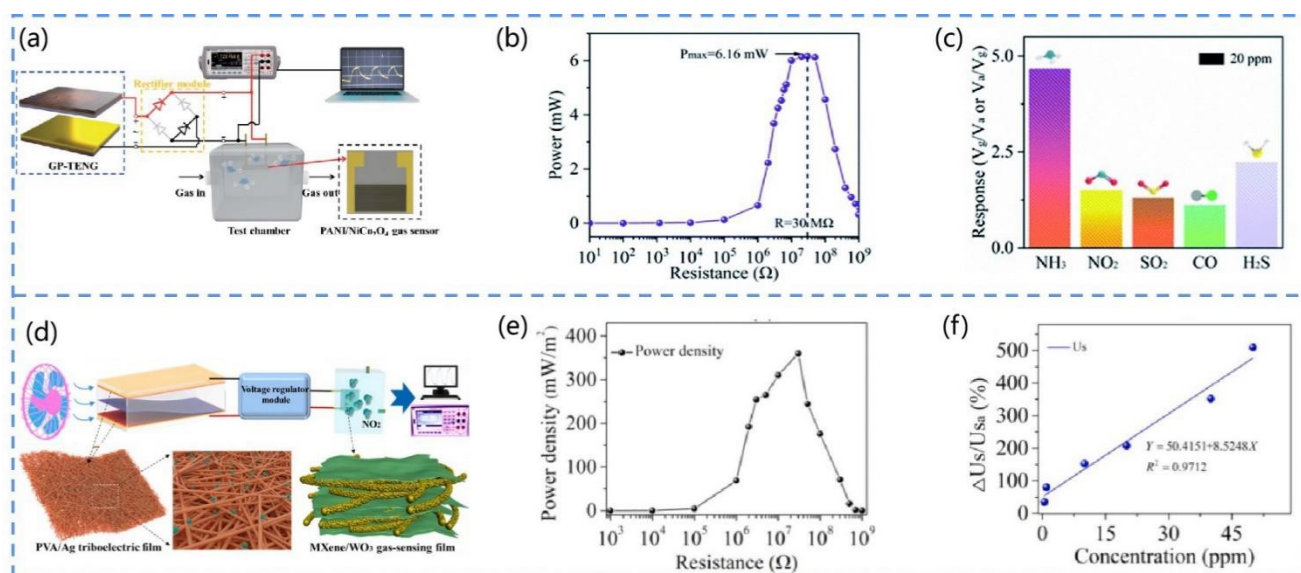


Figure 8. (a) Schematic diagram of the self-powered ammonia sensing system (GPAS). (b) Schematic diagram of the output power of the GP-TENG. (c) Results of the GPAS responsiveness test to ammonia gas. Reprinted from [64] with permission from the Royal Society of Chemistry. (d) Schematic diagram of the self-powered nitrogen dioxide gas sensor. (e) Output power density of the TENG. (f) Voltage response of the sensing system to nitrogen dioxide. Reprinted from [65] with permission from Elsevier.

To monitor gases in the environment, Wang et al. created a polyvinyl alcohol/silver (PVA/Ag)-based nanofiber as an electrode material for TENGs (Figure 8d) [65]. The nanofibers are prepared by the electrospinning technique, which greatly improves the output performance of the TENG, and the peak open-circuit voltage and current density can reach 530 V and 359 mW/m², respectively, during the operation (Figure 8e). A stable output of the voltage (36 V) can be achieved by connecting a voltage regulator. In addition, they fabricated an MXene/WO₃-based gas sensor with an excellent response to NO₂ (Figure 8f). This self-powered sensor system provides a sustainable, maintenance-free platform for environmental monitoring.

The increase in CO₂ gas not only contributes to global warming but also has a significant impact on human health. Therefore, the development of devices to detect CO₂ is important for the environment and human health. Zhao et al. proposed a TENG-based CO₂ gas sensor utilizing a gas discharge [66]. They used the relationship between discharge frequency and current and CO₂ concentration to propose two modes, step detection and continuous detection, for detecting CO₂ gas below the threshold concentration without an external power supply. This system has potential applications in building new self-powered gas sensors.

Ion Sensors

Ion sensors are widely used at present to either detect the environmental chemical composition or monitor physiochemical conditions. For autonomous operation, TENGs should provide the necessary electric power and complement electrochemical power sources.

Song et al. created a TENG-driven sweat sensing system that can monitor markers such as sodium ions in sweat (Figure 9a) [67]. The sensing system consists of a wearable TENG, a wireless sensing circuit module, and a sweat sensor patch that can extract energy from daily human movements such as walking, jumping, and arm movements. The TENG exhibits a high output power (416 mW m⁻²). The sweat sensors are fabricated with ion-selective electrodes and include a pH sensor and a Na ion sensor. The deprotonation of H atoms serves as an indicator of H ion concentration, and the Na ion carrier X and an electron transducer facilitate the measurement of Na sodium ion concentration (Figure 9b,c). This system facilitates the development of self-powered ion sensors for wireless physiological health monitoring and may have wider applications in the future.

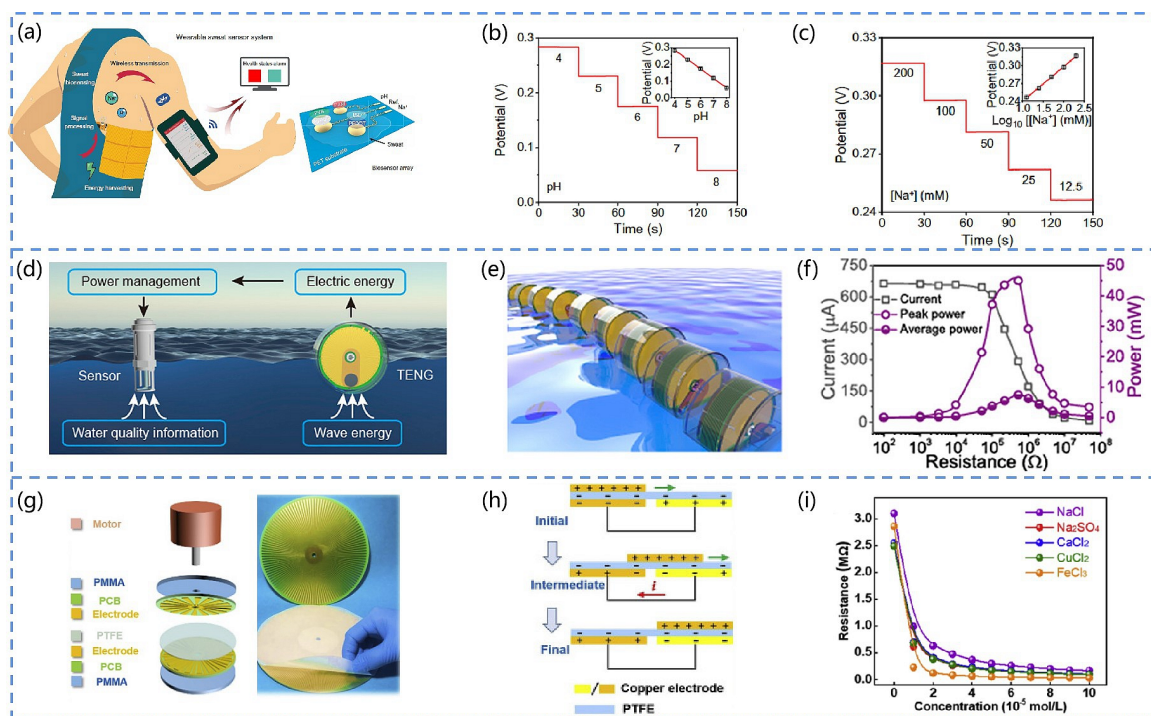


Figure 9. (a) Schematic diagram of the TENG-based sweat sensor for the real-time monitoring of health status during human exercise. (b) Curves of the open-circuit potential of the pH sensing system in a standard buffer solution. (c) Curve of the open-circuit potential of the Na⁺ sensing system in NaCl solution. Reprinted from [67] with permission from Science. (d) Schematic diagram of the TENG-based water quality monitoring system. (e) Schematic diagram of a TENG with a grating structure to collect water wave energy. (f) Output of devices under load resistance. Reprinted from [68] with permission from Elsevier. (g) RD-TENG-based sensing system. (h) The lateral sliding structure of the TENG. (i) Plot of ion concentration and impedance at a frequency of 200 Hz. Reprinted from [69] with permission from Elsevier.

It is well known that the concentration of various ions in water is a critical standard with respect to the evaluation of water quality. Bai et al. presented a high-output performance tandem disk TENG (TD-TENG) for the real-time monitoring of water quality (Figure 9d) [68]. By designing a grating structure that allows the TENG to be stirred even under slow water waves (Figure 9e), the output performance of the TENG is greatly enhanced, thus continuously monitoring the ions in water (Figure 9f). This TENG opens up new approaches to power bottlenecks for a long-term, versatile, real-time sensing system in water.

Similarly, Chen et al. developed a sensing system based on the RD-TENG for the online monitoring of water ion concentrations (Figure 9g) [69]. They adopted polytetrafluoroethylene as the friction electrode and prepared a lateral sliding structure of the TENG (Figure 9h). When the speed of the RD-TENG is 250 rpm, the sensor is equivalent to a pure resistance in water, and the impedance and the resistance change with the ion concentration (Figure 9i).

3.2. TENG-Based Active Chemical Sensor

3.2.1. Basic Principle

During operation, the magnitude of the electrical signals (V_{oc} and I_{sc}) generated by the TENG device is closely related, in some cases, even quantitatively proportional to the triboelectric charge density [70]. As frictional electricity is essentially a chemical potential difference between two electrode surfaces and as the absorption of some chemical substances and their chemical reactions at the surface affect the charge transportation and density, thus affecting the output of the TENG, it is possible to detect the absorbed target substance quantitatively and develop TENG-based active chemical sensors (Figure 10). This multifunctional design reduces power consumption, simplifies the system, and, above all, enables sustainable, straightforward, and reliable sensor operation.

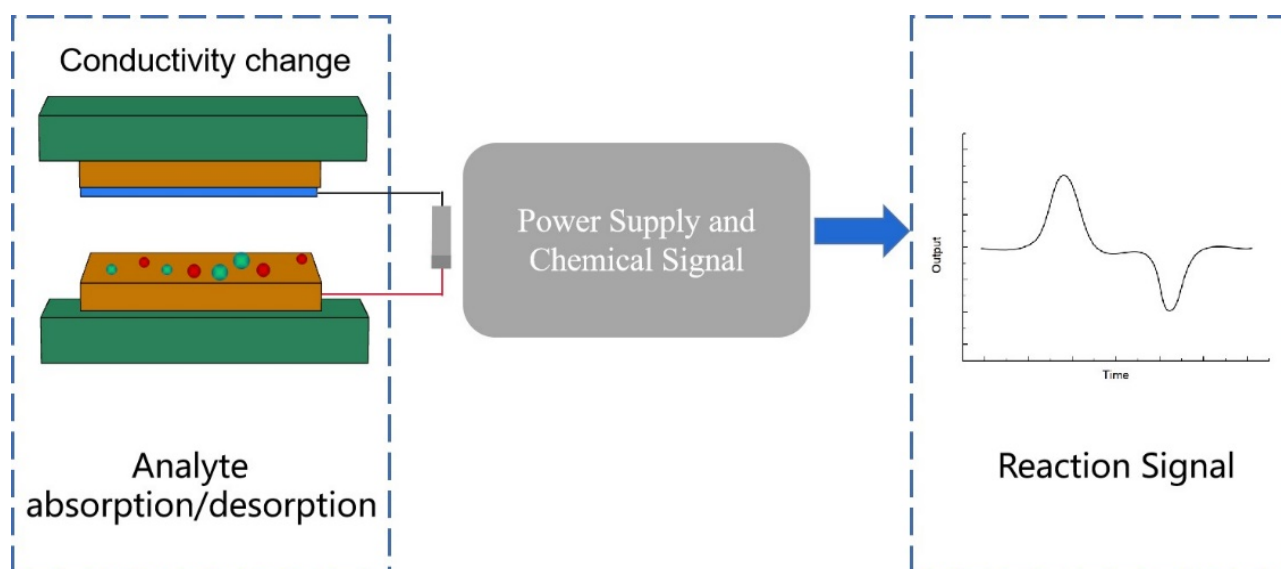


Figure 10. Schematic illustration of TENG-based active CSSs.

To discuss this in more detail, the adsorbed analyte can also change the dominant process of electron transfer, which leads to changes in the potential distribution of the friction electrodes, stemming from the fact that they may influence the forming or the structure of the electrical double layer [71,72]. These influences may change the TENG's output characteristics and enable it to serve as a sensing signal. Unlike traditional sensors, TENGs are able to serve as both an electricity source and a sensor at the same time. Some materials are both frictional electric material for generating electricity and sensitive material for detecting analytes [73]. Thus, the friction layer surface may be regarded as a detector. The properties of TENG-based active sensors depend on the properties of the

friction electrode material, such as conductivity, dielectric constant, temperature sensitivity, light sensitivity, etc. [74–80]. Hence, we can directly employ or synthesize specific target compounds to develop friction electrode materials that can be sensitively detected [81].

3.2.2. Design Criteria of TENG-Based Active Sensors

TENGs can scavenge mechanical energy from the ambient environment and even the human body [82] and, thus, are ideal for powering chemical sensors and building on-body healthcare systems with high sustainability and wearability. Meanwhile, TENGs may also act as chemical sensors due to their intrinsic sensitivity toward the chemical reactions that occur at the triboelectric interface [83]. In this section, the design criteria of TENG-based CSSs will be discussed.

Sensitivity Improvement

In the self-powered sensing system, sensitivity is always considered the most basic index to evaluate the probability of commercialization [84]. Improving sensitivity through structural design, signal processing, and power management to meet or exceed the current commercial requirement of chemical analysis sensors is a hot topic in current research.

Su and his colleagues designed a highly sensitive TENG sensing system that could actively monitor nitrogen dioxide gas through the coupling of the frictional electric effect and the photoelectric effect (Figure 11a) [85]. The prepared TENG can be used for powering the UV light source and the resistive gas sensor in the system by collecting energy from the environment. They adopted a hydrothermal method to deploy zinc oxide nanowires on the electrodes to enable device sensitivity to nitrogen dioxide. In addition, light-activated gas detection is driven by a stimulus external to the device. After testing, the induced voltage drop of the system was proportional to the concentration of NO_2 . Additionally, the sensing system, prepared on the basis of 0.035 mol/L synthesized ZnO nanowires, had higher responsiveness and sensitivity (0.302 ppm^{-1}) compared to other concentrations (Figure 11b,c). This work presents a method for highly sensitive gas sensing, paving the way for the fabrication of high-performance sensing devices for environmental monitoring.

To improve the sensitivity of the sensor, Yu et al. developed a high-sensitivity contact-separated TENG sensing system (CS-TENG) for human physiological information monitoring [86]. The friction layer consists of flexible polydimethylsiloxane (PDMS) film and copper electrodes and exhibits the merit of direct and intimate contact with human skin (Figure 11d). By fabricating a homogeneous and controllable mf-array structure on the polydimethylsiloxane (PDMS) film, the sensitivity (5.67 V/105 Pa), linearity ($R_2 = 0.99$ of voltage), and stability (over 80,000 cycles) of this system are improved. Due to its excellent sensitivity, this CS-TENG can perceive the slightest change in pulse rate, like a doctor (Figure 11e). Overall, the proposed sensing system has great potential for biomedical applications.

Similarly, Hu et al. reported a sensitive, superhydrophobic, liquid–solid contact TENG-based sensing system for application in biomedicine (Figure 11f) [87]. This superhydrophobic TENG is repulsive to a variety of solutions, including blood. As liquid flows over the superhydrophobic layer, it can collect and release electrical energy (Figure 11g). The TENG output depends on the size and fall height of the liquid droplet. In addition, the self-powered sensor is self-cleaning, well-bent, and simple to manufacture and can be combined with an intravenous infusion tube to prepare an infusion monitoring sensing system for the precise monitoring of infusions. This superhydrophobic TENG sensing system holds great promise for clinical monitoring in the future.

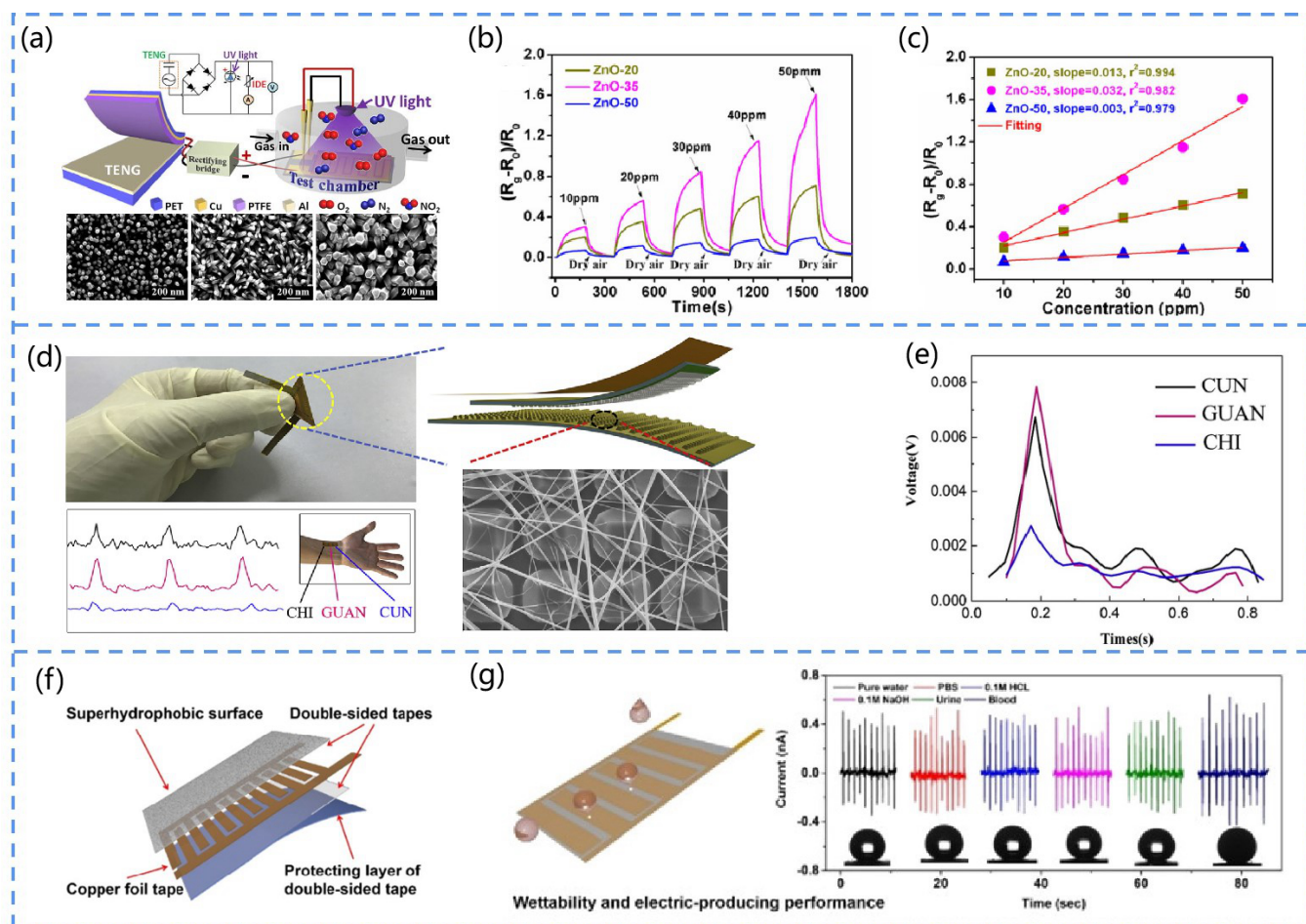


Figure 11. (a) Schematic diagram of the TENG-based sensing system for active NO₂ detection. (b) Schematic diagram of the response of ZnO nanowire films from 0 to 100 ppm NO₂. (c) Plot of ZnO nanowire film versus NO₂ concentration. Reprinted from [85] with permission from AIP Publishing. (d) Schematic diagram of the principle and structure of the sensing system. (e) Comparative analysis of real-time voltage signals at different locations on the hand: the CUN, GUAN, and CHI. Reprinted from [86] with permission from Elsevier. (f) Schematic diagram of the superhydrophobic TENG structure. (g) Current output generated by different liquids sliding on the superhydrophobic TENG. Reprinted from [87] with permission from ACS Publications.

Integration Optimization

In practical applications, TENGs need to be integrated with a chemical sensor and other information devices to realize the automatic analysis of collected data and provide scientific guidance.

Ren et al. reported a versatile TENG-based humidity sensor (Figure 12a) [88]. They coupled a perfluoro sulfonic acid ionomer (PFSA) with a TENG device. PFSA is an intelligent deformable material that enables TENGs to automatically bend to a certain angle at different humidity levels. This adaptive deformability enables the multiple functionalities of the TENG, such as collecting energy from raindrops at high humidity, wind energy at medium humidity, and reflecting light at low humidity. The switching of these functions can be automated in response to changes in the steam drive (Figure 12b). This work can promote the development of TENG sensing systems in the direction of intelligence and multifunctionality.

Xu et al. fabricated a dual-TENG sensing system for humidity monitoring by applying a polyvinylidene fluoride propylene (FEP) film and copper foil (Figure 12c) [89]. The sensitive film was synthesized from chitosan and activated carbon materials. In addition,

they integrated a WIFI module and the sensing system to monitor the humidity signal from a smart terminal in real-time. This TENG sensing system exhibits a wide detection range and excellent stability and recognizes signals from human breathing and finger movements clearly in practical applications (Figure 12d,e). This work opens up new horizons for the integration and application of TENG wireless sensing systems.

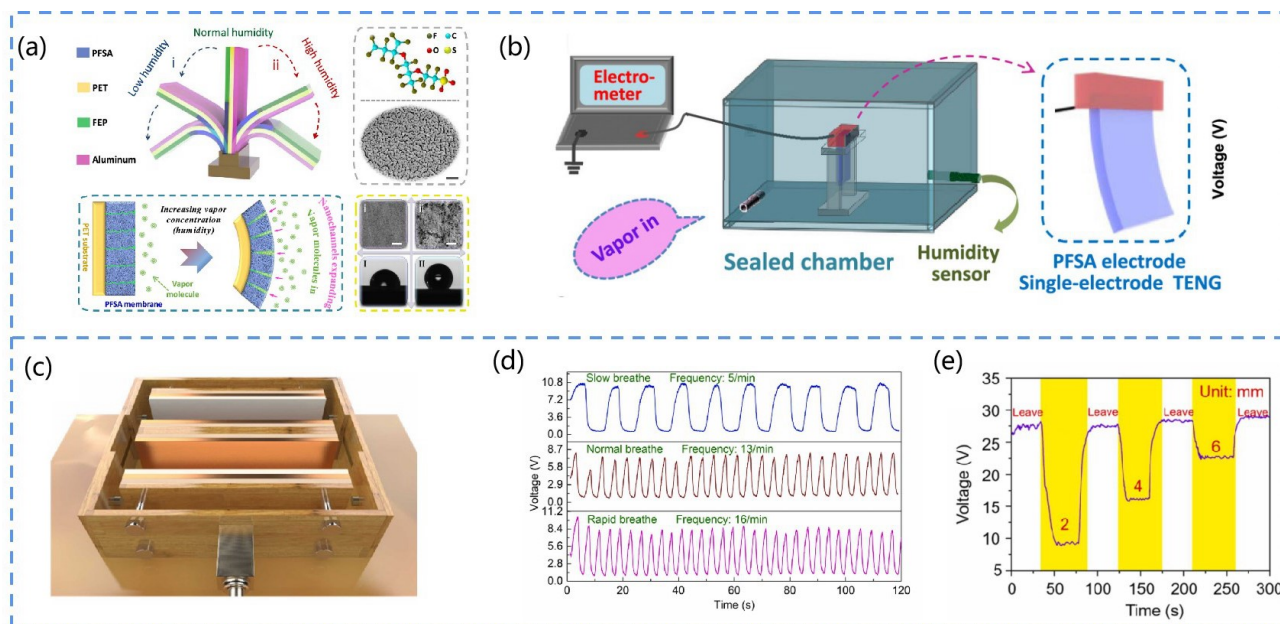


Figure 12. (a) Schematic diagram of the TENG-based humidity sensing system. (b) Schematic diagram of the operation of the TENG sensing system under steam drive. Reprinted from [88] with permission from ACS Publications. (c) Schematic diagram of the dual-TENG. (d) Real-time monitoring of breathing conditions by the sensor. (e) Signal of the sensor on finger movement. Reprinted from [89] with permission from Elsevier.

Meanwhile, Wang et al. developed a TENG wireless sensing system that consists of a spherical TENG, an ammonia nitrogen sensor, and a Bluetooth module to achieve the real-time monitoring of meat freshness [90]. The system exhibits excellent sensing performance for 0.5–20 ppm NH_3 and is sustainable, portable, and wireless for real-time monitoring, which is promising for the future of the gas detection field.

3.2.3. Applications of TENG-Based Active Chemical Sensors

TENG-based active chemical sensors have received broad attention and undergone rapid development in response to stimuli from chemical molecules or other factors, for instance, ethanol, phenol, and pH, where the output performance of the TENG and the stimulation shows a linear relationship. This section discusses recent examples of TENG-based active chemical sensors and the research trends in these areas to provide direction for future research.

TENG-Based Active Biosensors

Human body physiological signals are important physiological indicators for public healthcare and health monitoring [91]. Monitoring these small but complex physiological signals in real-time with simple, convenient, economical, and accurate methods remains a challenge for healthcare devices [92,93]. As a result, new methods for analyzing these biological analytes are required.

Zhao et al. created a stretchable fiber-based TENG (F-TENG) (Figure 13a) [94]. This TENG is fabricated by covering MWCNTs and PANI on super-stretchable Ecoflex fibers. Moreover, the device can be modified with different enzymes and act as an active biosensor to sense biomarkers in sweat, including substances such as lactate, glucose,

creatinine, etc. (Figure 13b,c). Such active biosensors have great potential for the future real-time monitoring of physiological data during human movement.

It is critical to develop effective and specific detection methods for bacteria in order to mitigate their threats. Wang et al. created a TENG-based biosensing system for monitoring Gram-positive bacteria in water (Figure 13d) [95]. They first used vancomycin to identify Gram-positive bacteria in water; then, they used guanidine-based functionalized multi-walled carbon nanotubes (CNT-Arg) as the signal amplification material and, finally, realized the real-time, simple, and specialized monitoring of bacteria by the voltage change of the biosensor. The experimental results showed that this biosensing system has the advantages of good linearity, high selectivity, and low detection limit (Figure 13e,f). The self-powered biosensing system, which replaces molecular probes, has the potential to specifically recognize bacteria and aid in the prevention of environmental pollution, iatrogenic diseases, and microbiological corrosion.

Creatinine concentration in human blood or urine is strongly associated with kidney problems, muscle disorders, and thyroid dysfunction [96]. Thus, the development of sensing devices for detecting creatinine is crucial, especially in the case of the rapidly growing healthcare field. For example, Luo et al. fabricated a TENG-based creatinine sensing system (Figure 13g) [97]. This TENG is composed of polyaniline (PANI) and polydimethylsiloxane (PDMS) and produces a frictional electrical output upon deformation. They modified PANI with creatinase, creatine lyase, and sarcosine oxidase, respectively, and the frictional electrical output could respond to the creatinine concentration due to its product H_2O_2 , which can induce PANI protonation and change the electrical conductivity of PANI (Figure 13h). The sensitivity of the device reached 51.42% when the creatinine concentration was 10^{-3} mol/L (Figure 13i). Meanwhile, it showed favorable selectivity for creatinine at room temperature. Its working principle can be attributed to the coupling of the TENG and creatinine enzymatic reactions. These results suggest important applications in areas such as self-powered and personalized healthcare.

Dopamine is crucial for the functioning of the hormonal, renal, and central neurological systems. Nervous system diseases, including Parkinson's, Huntington's, and schizophrenia, may be brought on by abnormal dopamine levels. For energy harvesting in an oil/water multiphase, Jiang et al. fabricated a liquid–solid contact TENG (Figure 13j) [98]. After they adopted the self-polymerization method to coat the PTFE and glass surfaces with a layer of PDA, the two electrical signals of the TENG showed opposite trends: on the one hand, the V-TENG and I-TENG kept decreasing, while, on the other hand, the oil/water interface signals of $V_{\text{interface}}$ and $I_{\text{interface}}$ continued to increase (Figure 13k) and showed a good linear relationship with the dopamine concentration (Figure 13l). This research will help create more dependable and sophisticated self-powered biosensor systems.

Thrombin is a serine protease that is almost absent in the blood of healthy individuals [99,100]. It is an important research direction to develop self-powered biosensors for the detection of thrombin based on the intermolecular recognition between thrombins and ligands. Jung et al. proposed a TENG-based biosensor for the detection of thrombin [101]. They first assembled Au nanoparticles (Au NPs) on an Al membrane to enhance the output of the TENG (Figure 13m). Then, a thrombin detection nanosensor with high selectivity was obtained by modifying the anti-thrombin aptamer on Au NPs with a sulfhydryl group modification (Figure 13n). The sensitivity of the sensor reached 0.41 nM, showing the great potential of the device as a simple, fast, and low-cost detection system.

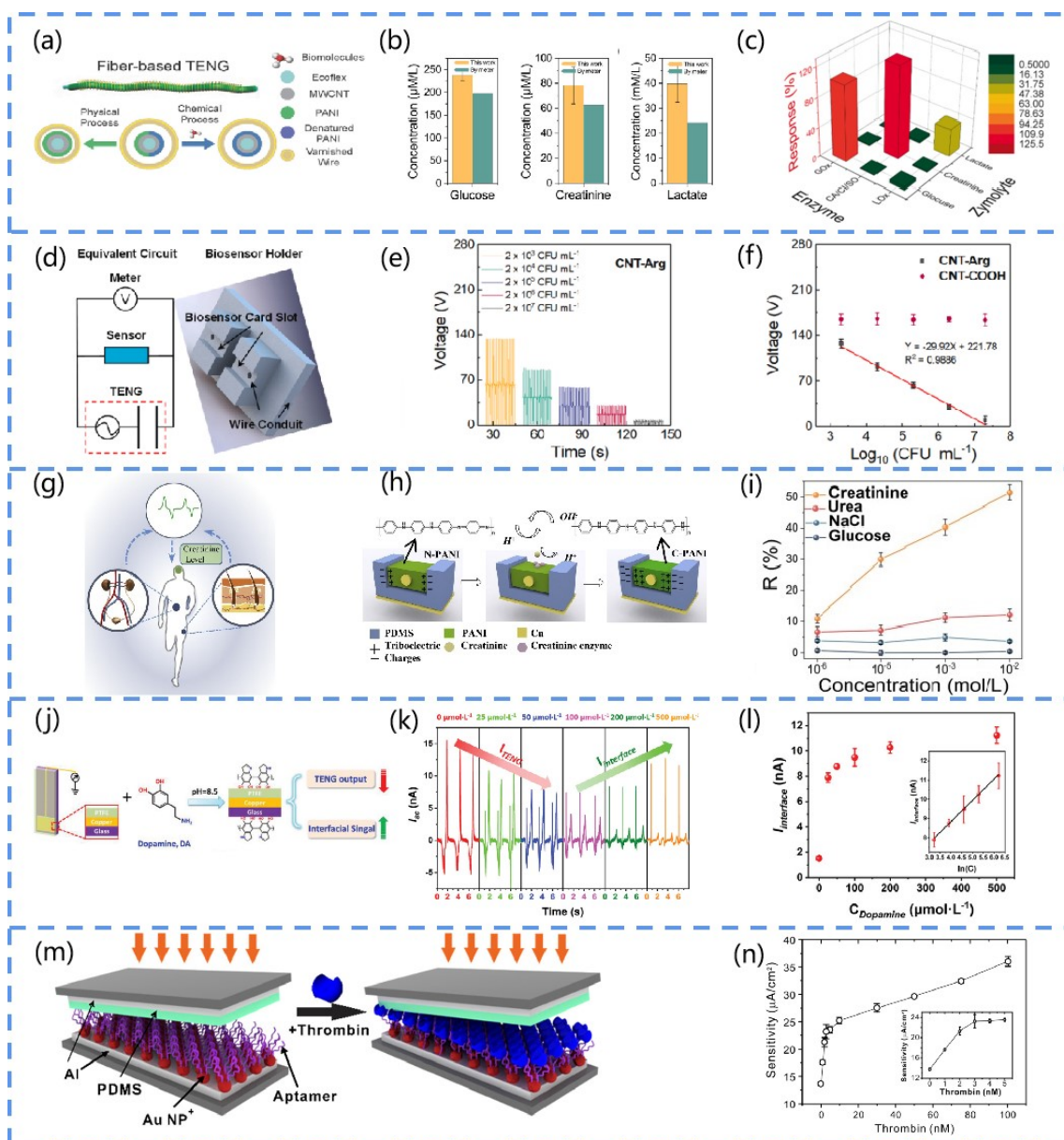


Figure 13. (a) Schematic diagram of the fiber structure of the F-TENG. (b) Schematic diagram of the comparative biosensitivity of the F-TENG and commercial sensors for glucose, creatinine, and lactate. (c) Selectivity of the TENG for the detection of glucose, lactate, and creatinine. Reprinted from [94] with permission from Elsevier. (d) Schematic diagram of the TENG-based biosensing system and its equivalent circuit. (e) Voltage of CNT-Arg under a range of concentrations of *S. aureus* (2×10^3 CFU mL⁻¹ to 2×10^7 CFU mL⁻¹). (f) Linear fit of the response of *S. aureus* from 2×10^3 to 2×10^7 CFU mL⁻¹ concentrations. Reprinted from [95] with permission from Elsevier. (g) TENG-based sensing system detects creatinine in body fluids. (h) The protonation and deprotonation process of PANI and its sensing mechanism. (i) The response of the sensor to creatinine. Reprinted from [97] with permission from Elsevier. (j) Schematic diagram of dopamine coated on the surface of a liquid–solid TENG electrode. (k) Schematic diagram of the short-circuit current of the TENG modified by dopamine in an oil/water environment. (l) Plot of I_{interface} and I_{TENG} versus dopamine concentration in an oil/water environment. Reprinted from [98] with permission from Wiley Online Library. (m) Schematic diagram of thrombin detection by the TENG biosensor. (n) Detection sensitivity of the TENG-based biosensor. Reprinted from [101] with permission from Elsevier.

TENG-Based Active Gas Sensors

It is essential to develop rapid and precise real-time safety monitoring systems, such as chemical gas sensors, to find gases such as alcohol, acetylene, ammonia, aniline, etc., considering the increasing worry about the security of places where people work and reside. Due to their ability to implement portable gas sensors without a separate power source, self-powered gas sensors with TENGs are drawing a lot of attention [102]. The most recent progress in TENG-based self-powered active gas sensors is presented and explored in this section.

Wen et al. designed a gas sensor for alcohol detection on a BD-TENG [103]. The alcohol sensor, as it is now designed, can use airflow to generate energy, operating as an active alcohol breath analyzer (Figure 14a). The delivered voltage remains proportional to the amount of alcohol exhaled over a range of 10 to 200 ppm (Figure 14b). The as-developed BD-TENG is distinguished by a short response time of 11 s, a response of 34 at the ideal sensor operating temperature, and a quick recovery time of 20 s, which demonstrate the exceptional performance of selectivity anti-interference for alcohol detection (Figure 14c). In addition, the reported breath analyzer is made of widely available polymer materials that are lightweight and affordable, which significantly expands the use of the TENG as a self-powered active sensor.

From previous studies, we know that conductive and semiconducting polymers have been used in numerous applications for many years, including active layers, interconnects, and electrodes. Among these polymeric materials, poly (3,4-ethylene dioxythiophene):poly (styrene sulfonate) has proven to be adaptable. Employing PEDOT:PSS that has been appropriately functionalized may be a potential option for improving wearables, nano-generators, and self-powered active sensors. Iftekhar-Uddin described a TENG made of nylon fiber film, conductive PEDOT:PSS elastomers, and PDMS with wrinkle patterns (Figure 14d) [104]. With a load resistance of 3.8 M, this TENG achieved a maximum output power of 0.09 mW indoors and 0.2 mW outdoors (Figure 14e). They replaced the pure nylon fiber with an Ag@ZnO/nylon fiber film to achieve the self-powering of the active sensor. Moreover, the sensor showed a high sensitivity of 70.9% indoors and 89% outdoors at a C₂H₂ gas concentration of 1000 ppm. The strategy for energy and sensing harvesting has potential benefits in real-world applications and could inspire fresh research.

Real-time perishable food quality monitoring is essential for lowering societal expenses and foodborne illness rates. A wireless gas sensor system (TWGSS) developed on a wood-based TENG was created by Cai (Figure 14g) [105]. The TWGSS retains excellent stability at 75% humidity and 18 °C (Figure 14h) and also enables the real-time, continuous, stable monitoring of food spoilage marker gases such as ammonia. The output of the TENG decreases as the ammonia concentration rises. In principle, this is due to the fact that the researchers have taken advantage of the three-dimensional porous structure of wood, which is sensitive to ammonia, and introduced this property into the sensor design. Furthermore, the TENG showed a high sensitivity of 0.85 at a concentration of 500 ppm ammonia (Figure 14i), which is significantly higher than other typical gases, indicating that the selectivity of the device is also high.

By changing the doping ratio and improving the annealing temperature, Chang et al. synthesized an rGO-In₂O₃ composite and used this material as a friction electrode for a TENG (Figure 14j) [106]. They applied this TENG to the monitoring of hazardous gases such as aniline in the environment. The results show that the TENG has many advantages; for example, it shows great sensitivity in the concentration range of 200–1200 ppm aniline, good reactivity with aniline, and high selectivity (Figure 14k,l). The response/recovery time of the device is significantly shorter compared to other typical room-temperature semiconductor gas sensors.

Considering that white sugar particles are hydrophilic, Liu et al. used them to prepare a TENG (WS-TENG) [107] that can be used both as a power source and directly as a humidity sensor (Figure 14m). The friction layer is composed of a polytetrafluoroethylene (PTFE) film and white sugar. In addition, this WS-TENG shows a clear and stable signal distinction

in short-circuit current (I_{sc}) and open-circuit voltage (V_{oc}) at different humidity levels, which can directly and reliably reflect changes in humidity in the surrounding environment (Figure 14n,o). These works are quite promising and contribute to the development of TENGs for active gas sensors.

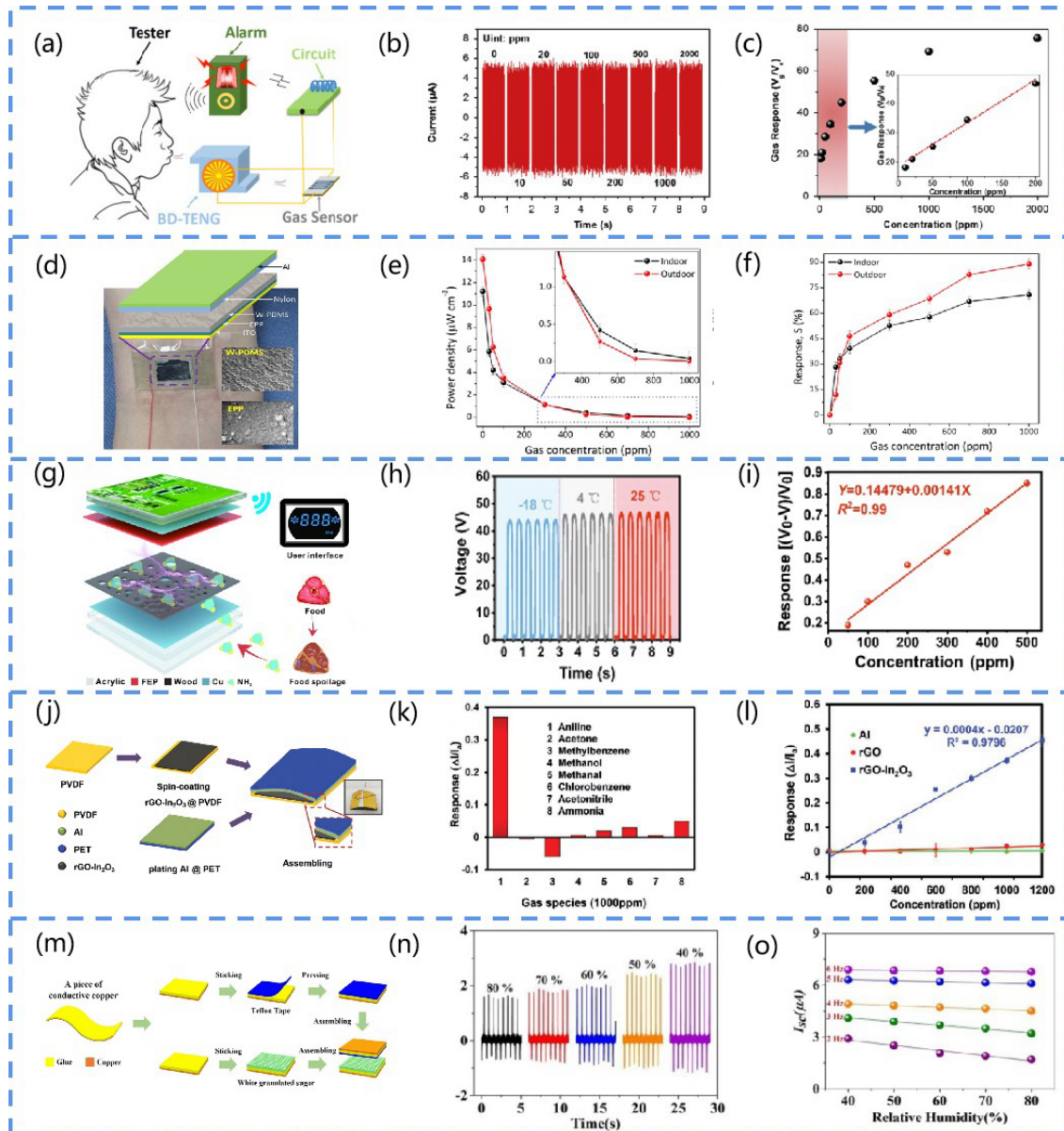


Figure 14. (a) Schematic diagram of the TENG as an active alcohol sensor. (b) Output current of the device under alcohol (concentration from 10 to 2000 ppm). (c) Plot of output voltage versus alcohol. Reprinted from [103] with permission from Elsevier. (d) Schematic diagram of the TENG device. (e) Plot of power density versus C₂H₂ concentration. (f) Response of the device to different concentrations of C₂H₂ concentration. Reprinted from [104] with permission from ACS Publications. (g) Schematic diagram of the TWGSS device. (h) Open-circuit voltage of the TENG at different temperatures. (i) Response of the TENG to different concentrations of ammonia gas. Reprinted from [105] with permission from Elsevier. (j) Schematic diagram of the fabrication process of rGO-In₂O₃-TENG films. (k) Open-circuit voltage of the TENG monitoring gas. (l) The concentration response of the TENG to the gas. Reprinted from [106] with permission from Wiley Online Library. (m) Schematic diagram of the fabrication process of the TENG. (n) Output current of the TENG under different relative humidity environments. (o) Schematic diagram of I_{sc} versus relative humidity at different operating frequencies. Reprinted from [107] with permission from Elsevier.

TENG-Based Active Ion Sensors

Chemical ion sensors are commonly used in sectors to detect inorganic, organic, and biological ions, particularly ions in liquids such as H^+ , Hg^{2+} , Cu^{2+} , Pb^{2+} , and so on. With high selectivity, great sensitivity, and a wide sensing range, self-powered TENG-based active ion sensors are able to detect various types of substances. The ions in the detection target can be identified by the friction layer surface of the TENG or the outside dopant material [108,109]. The following typical examples demonstrate these applications and advances.

Liu et al. created a TENG with a single-electrode mode and applied it to detect pH in acid rain (Figure 15a) [110]. They used PTFE doped with PDMS solution to fabricate a film with more hydrophobicity and higher surface roughness. This film was used to prepare a friction layer for a water-drop-based TENG. After testing, the film doped with 0.07 wt.% PDMS showed the largest output difference in monitoring prepared normal water (pH = 7) and acid rain droplets (pH = 4) (Figure 15b), which indicates that the pH sensor constructed by this hybridization method performs well.

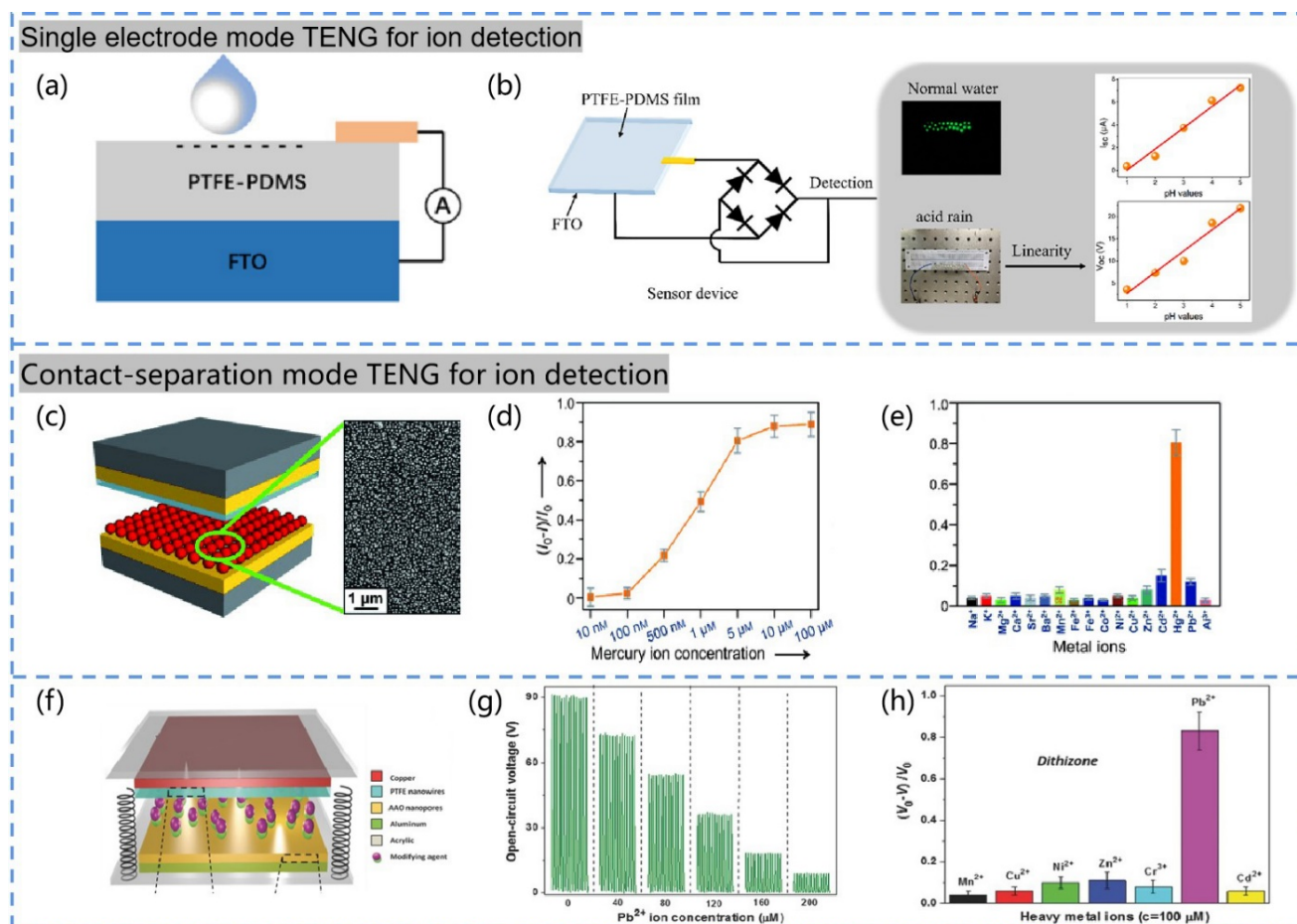


Figure 15. (a) Schematic diagram of a single-electrode mode TENG for sensing ions in liquid droplets. (b) Circuit diagram of a TENG sensor for detecting raindrops with different pH. Reprinted from [110] with permission from ACS Publications. (c) Schematic diagram of the structure of the contact separation TENG and the microscopic morphology of the friction layer. (d) Sensitivity of the TENG for Hg^{2+} detection. (e) Selectivity of the TENG for the detection of Hg^{2+} . Reprinted from [111] with permission from Wiley Online Library. (f) Schematic diagram of the structure of the TENG. (g) Plot of the relationship between the open-circuit voltage and Pb^{2+} concentration. (h) Selectivity of the TENG-based sensor for Pb^{2+} detection. Reprinted from [112] with permission from Wiley Online Library.

Different from the single-electrode mode, the TENG-based sensor in contact separation mode may not be used directly to determine ions in water due to the potential for charge dissipation caused by the water film at the friction–electric interface. Thus, it is preferable to place a drop of liquid on the surface of the friction electrode and wait for the liquid to evaporate before testing. For example, Lin et al. reported an active TENG-based sensor for monitoring Hg^{2+} in water (Figure 15c) [111]. They first increased the effective contact area of the friction layer with gold nanoparticles (NPs), which greatly increased the output of the TENG (105 V and 63 mA) (Figure 15d,e), and then used 3-mercaptopropionic acid (3-MPA)-modified NPs as the recognition element to detect Hg^{2+} . This method achieves a highly sensitive and selective monitoring capability for TENG-based ion sensors.

Meanwhile, Li and his colleagues designed a contact-separated TENG for selectively monitoring metal ions in wastewater (Figure 15f) [112]. This TENG uses acrylic acid as the support substrate and an aluminum foil with AAO nanopores as the contact surface of another layer. They adopted different ligand molecules, including dithizone, diphenyl carbazide, and sodium diethyldithiocarbamate, to modify the aluminum foil with AAO nanopores as the recognition component of the sensor, which can selectively detect Pb^{2+} in wastewater (Figure 15g,h). Further, the device generates an electric field capable of inducing the electrolysis of effluent to produce OH^- , which promotes the precipitation of Pb^{2+} . This work can act as a springboard for future TENG research and stimulate TENG advancement toward ion detection.

Other Active Sensors

Aside from TENG-based activity sensors, as discussed above, there is a solid–liquid interface-based TENG that can detect organic compounds in solution [113,114], such as ethanol and acetone in solution. The sensing mechanism is the same as that of gas detection; the effect of different molecules or concentrations on the friction layer will cause the performance of the TENG to change. The detection method is similar to the case of ion sensors; TENG-based chemical sensors detect target molecules in a solution by dropping the solution onto the surface of a frictional electric material and observing its reaction with the counter electrode after the surface of that material has dried, enabling the analysis of the solution. The following example demonstrates this mechanism.

Wang et al. developed a multifunctional DC output triboelectric nanogenerator (DC-TENG) for energy harvesting and chemical analysis at liquid–media interfaces [115]. The device consists of FEP and copper tape in a toroidal tube structure, where two brushes are bi-directionally anchored as alternating contact electrodes, thus converting AC power to DC power (Figure 16a–c), and can be used to analyze fluid composition and moisture content. There is a positive correlation between output and liquid polarity.

Li et al. reported a nanosensor that can be applied for detecting phenol [116], which is schematically depicted in Figure 16d. They used a contact TENG structure consisting of a titanium foil with TiO_2 nanowires on the surface and a PTFE film coated with a copper electrode. The TiO_2 nanowires were then combined with β -cyclodextrin (β -CD) as the sensing recognition element, allowing the direct and effective detection of phenol molecules in aqueous solutions (Figure 16e). The output voltage of the device is linearly related to the phenol concentration (Figure 16f). Additionally, the device is reusable after washing with ethanol. TENG can be used not only for the detection and degradation of phenol in the environment but also for the detection and treatment of other organic pollutants in wastewater, thus changing the current wastewater treatment model.

Chatterjee et al. fabricated a solid–liquid triboelectric nanosensor (TENS) that can be used for the detection of catechins in green tea solutions [117]. They used TiO_2 nanosheet arrays as a solid triboelectric layer to separate from the contact of the solution cycle (Figure 16g), in which the affinity of catechin and TiO_2 nanosheet arrays can reduce the work function and greatly increase the transferred charge, thus producing a higher output (Figure 16h). Meanwhile, they used ethanol and acetone volatile solvents instead of water to overcome the requirement of a hydrophobic surface in solid–liquid TENSs. Moreover,

they validated the chemical enhancement of the TENG by using catechins as targeting substances (Figure 16i). It is shown that solid–liquid TENGs can provide new ideas for developing sensors in the field of environmental detection.

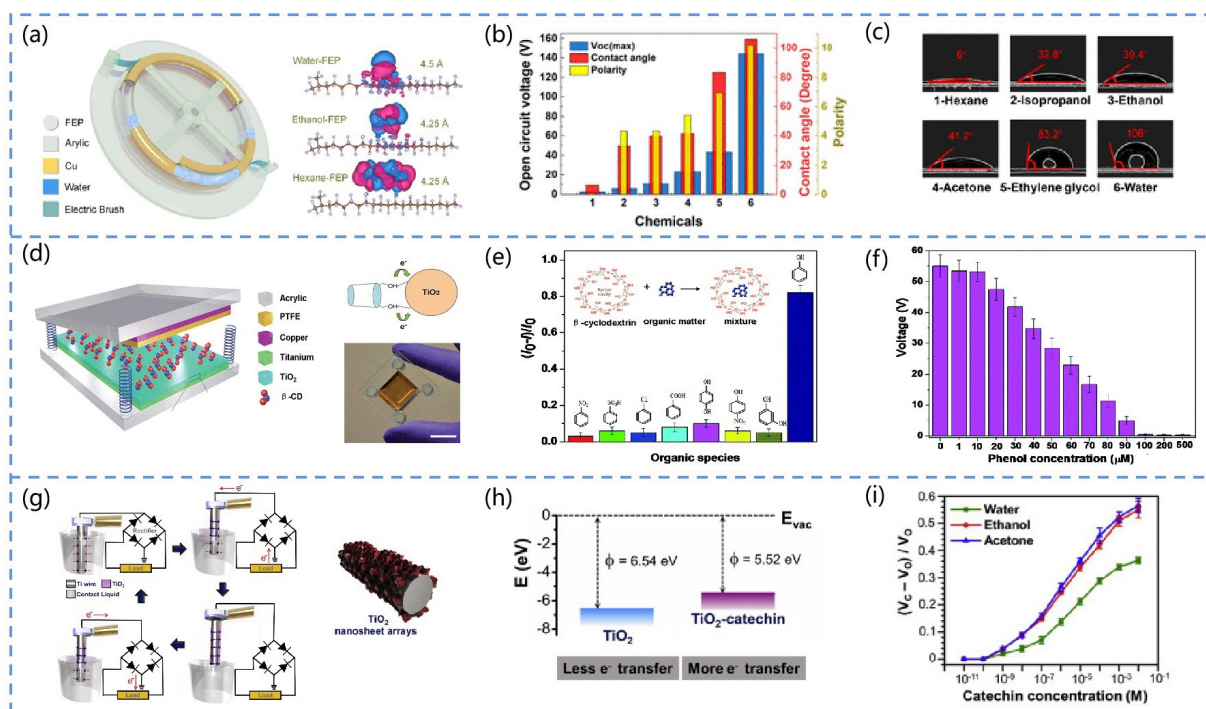


Figure 16. (a) The structure of a DC-TENG. (b) Effect of liquid on the output performance of the TENG (1, hexane; 2, isopropanol; 3, ethanol; 4, acetone; 5, ethylene glycol; 6, deionized water). (c) Liquid contact angle test. Reprinted from [115] with permission from ACS Publications. (d) Schematic diagram of a TENG modified with cyclodextrin. (e) Schematic representation of the selectivity of the device for monitoring phenol. (f) Schematic diagram of voltage signal for monitoring phenol concentration. Reprinted from [116] with permission from the Royal Society of Chemistry. (g) Diagram of solid–liquid TENG operation and TiO₂ nanosheet arrays. (h) Plot of catechin-induced change in work function. (i) Comparison of the output voltage ratio profiles and voltage enhancement coefficients for different catechin concentrations in different contact liquids, such as water, ethanol, and acetone, respectively. Reprinted from [117] with permission from Elsevier.

The characteristics and performance of numerous TENGs as power and active chemical sensors are listed in Table 1. The performance of TENG-based active chemical sensors is outstanding in terms of detection range and sensitivity. Compared to conventional sensors, the sensors can achieve self-power and exhibit high output, sensitivity, and selectivity at low analyte concentrations due to the ability of the frictional electric layer to recognize specific molecules.

Table 1. Comparison of the characteristics of TENGs as power sources and active chemical sensors.

Application	Function	Structure		Outputs Performance ^a		Sensing Performance		Refs.
		Materials	Analyte	I _{max}	U _{max}	Detection Range	Selectivity	
Biosensor	Power source	Au/PDMS-Au	Blood oxygen	7.4 μA	75.3 V	—	—	[60]
		Cu/PTFE-Cu	Blood glucose	317 μA	153 V	—	—	[61]
		PDMS-Chitosan/glycerol	Antigen	—	250 V	1.05~8.4 μg mL ^{−1}	—	[62]
		Al/PTFE-Gelatin/Al	Glucose	45 μA	500 V	200 μM~2 mM	Good	[63]
	Active chemical sensor	Ecoflex/MWCNT-PANI	Lactic acid	—	—	0~200 mm L ^{−1}	Good	[94]
			Glucose	—	—	0~56 mm L ^{−1}	Good	
			Creatinine	—	—	0~88 mm L ^{−1}	Good	
		Al/FEP/ITO-Van-Al	Gram-positive bacteria	—	165 V	2 × 10 ³ ~2 × 10 ⁷ cfu/mL	Good	[95]
		Cu/PDMS-PANI	Creatinine	1.47 nA	—	10 ^{−6} ~10 ^{−3} mol L ^{−1}	Good	[97]
		PTFE/Cu/Glass	Dopamine	1.9 nA	4.5 V	25~500 μmol L ^{−1}	Good	[98]
		Al/PDMS-Au NPs/Al	Thrombin	18 μA	17 V	0~100 nm L ^{−1}	Good	[101]
Gas sensor	Power source	Cu/PTFE-Cu	Humidity	4 μA	22.5 V	0~97% RH	Good	[46]
		Cu/PI-Gelatin/Cu	Ammonia	49 μA	400 V	0~20 ppm	Good	[64]
		Cu/PVA/Ag-FEP	NO ₂	5.6 μA	530 V	0~50 ppm	—	[65]
		PMMA/Cu-PTFE	CO ₂	20.1 μA	1160 V	1~200 × 10 ³ ppm	—	[66]
	Active chemical sensor	Cu/FEP/Elastic	Alcohol	5.9 μA	2.3 V	10~200 ppm	Good	[103]
		Al/Nylon- PDMS/EPP/ITO	C ₂ H ₂	3.94 μA	191.6 V	30~1000 ppm	—	[104]
		Cu/Wood-FEP/Cu	Ammonia	2.4 μA	47 V	10~500 ppm	Good	[105]
		PVDF/rGO-In ₂ O ₃ -Al/PET	Aniline	1.2 μA	4 V	200~1200 ppm	Good	[106]
		Cu/Sugar-Cu/PTFE	Humidity	6.35 μA	95.68 V	40~80% RH	—	[107]
		Ion sensor	Power source	PTFE-ENIG/polyimide/Cu	H ⁺	42.25 μA	190 V	4~8 pH
Cu/PTFE/Glass	Na ⁺			120 μA	365 V	12.5~200 mM	—	[68]
Cu/PCB/PMMA-PTFE/Cu	Water			112 μA	210 V	—	—	[69]
Active chemical sensor	FTO/PTFE–PDMS/Cu		H ⁺	26.37 μA	69.04 V	5~1 pH	—	[110]
	Glass/ Au film-Au NPs		Hg ²⁺	63 μA	105 V	100 nM~ to 5 μM	Good	[111]
	Cu/PTFE-Modifying agent/ AAO		Pb ²⁺	0.18 mA	310 V	0–200 × 10 ^{−6} μM	Good	[112]
			Cr ³⁺					
Other	Active chemical sensor	FEP/Cu/Electric brushes	Multiple compounds	11.5 μA	228 V	—	—	[115]
		Cu/PTFE-β-CD/TiO ₂ /Ti	Phenol	6.5 μA	57 V	10~100 μM	Good	[116]
		Ti/TiO ₂ nanosheet	Catechin	—	1.2 V	100 nM~100 μM	Good	[117]

^a “—” in the table implies that the data were not recorded in research.

4. Conclusions and Prospect

This review systematically summarizes the progress of TENG-based CSSs and their potential for future practical applications. TENG-based CSSs not only demonstrate the sensitive detection of physiological activity, gases, and ions but may also achieve independent, continuous, and reliable operation by scavenging mechanical energy from nature or biology. Although this TENG-based sensor system has achieved significant progress through the design strategy of TENG-based active sensors, it is still not systematic and comprehensive enough. The challenges that TENG-based power sources face are relatively simple; the enhancement of output performance is always the prime target, which can be effectively promoted by improved power management, material selection, and structure design. For TENG-based active sensors, the main starting point is the adsorption or chemical reaction of specific targets at the triboelectric interface, whose reliability is susceptible to environmental conditions and the TENG's own signal interference. Nevertheless, in both cases, the coupling of different material properties can bring new insights into the design of TENG-based CSSs with higher performance, thus innovating their applications in a wide range of multidisciplinary areas, such as disease diagnosis, environmental monitoring, and the defense industry. For the guidance of future research, the challenges and most urgent issues of TENG-based CSSs that should be addressed are listed as follows:

4.1. Power Supplies

4.1.1. High Energy Conversion Efficiency

The most urgent issue related to present TENG devices is their relatively low conversion efficiency. Chemical modification is always the most fundamental approach for output enhancement. For example, adding several active functional groups at the friction layer interface can lead to a stronger electrical response in the friction electrification process. Furthermore, modulating the surface energy of the friction layer surface, increasing the porosity and roughness, controlling the film morphology, improving the polarity of the electrodes, etc., are also effective solutions for improving the energy conversion efficiency of TENGs.

4.1.2. Longer Service Life

In practical applications, the service life of TENG-based CSSs is affected by different factors such as the device structure, the mechanical strength of aging component materials, the surface wear of the friction layer, weak connections between electrodes, and moisture contamination in the environment [118]. For example, during the operation of TENG-based CSSs, electrons tend to accumulate on the surface of the friction layer and absorb dust from the air, which diminishes the performance of the TENG [119]. In addition, the device may also be penetrated by water, which neutralizes the electrical charge as well as deteriorates performance [120]. Therefore, proper encapsulation techniques should be considered to solve these problems without affecting the operation of the system, and the stability of TENG-based CSSs may be adjusted by using triboelectric materials with self-cleaning properties [121]. The service life may also be optimized by enhanced stability designs, the diversification of materials, and stronger bonding agents. Overall, TENG-based sensors with a controlled service life are an important research direction for the future.

4.2. Active Chemical Sensor

In a typical TENG-based active chemical sensor, additional attention should be paid to issues such as anti-interference capability, stability, and multifunctionality, besides the issues that are faced by all TENG-based chemical sensors, as mentioned above.

4.2.1. Anti-Interference

TENGs can directly serve as active chemical sensors. However, interference signals may be generated, either due to the complex environments or as a result of the TENG itself, of which the latter may interfere with the analyte signals more seriously. Therefore, we can

position ourselves in the direction of synthesizing a more interference-resistant sensing material. In addition, various minor interferences inevitably occur during the sensing process, which will seriously affect the accuracy of sensing. Therefore, we can reduce the interference by optimizing the circuit design to filter out interfering waves in the future.

4.2.2. Stability and Reliability

Since chemical sensors are commonly applied for the quantitative analysis of analytes, stability is one of their most important characteristics. Besides the environmental parameters that affect their stability and reliability, currently, the reusability of the sensor seems to be a serious challenge, and the adsorption of chemical molecules and chemical reactions at the triboelectric interface seem irreversible. As a result, the repeatability of the TENG-based active chemical sensor may be affected. Future research could focus on the development of more wear-resistant, repeatable materials, reversible chemical reactions at the interface, and a low-loss triboelectrification design strategy.

4.2.3. Multifunctionality

TENGs with multifunctionality will reduce the size and energy consumption of the device. Currently, TENG-based active chemical sensors are generally designed on the base of sensitive materials with satisfactory triboelectrification effects or triboelectric active materials that respond to the adsorption or reaction of chemical molecules at the interface. In addition, the interaction of triboelectrification and surface reaction/adsorption also deserves further research, which may initiate the study of the chemical processes in the friction layer. Meanwhile, the introduction of smart materials into the triboelectric interface as the electrode material in TENGs may result in multifunctional systems with intelligent responses due to the interesting function of such materials.

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