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Review

Chemical Sensor Based on Piezoelectric/Triboelectric Nanogenerators: A Review of the Modular Design Strategy

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Abstract: Piezoelectric and triboelectric nanogenerators (P-TENGs) have emerged as promising technologies for converting mechanical energy into electrical energy, with potential applications in self-powered wearable and environmental monitoring devices. Modular design in P-TENGs, characterized by the flexible assembly and customization of device components, enables the development of sustainable and versatile chemical sensors. In this review, we focus on the role of modularity in P-TENG-based chemical sensing, discussing how it enhances design flexibility, sensing versatility, scalability, and integration with other technologies. We explore the various strategies for functionalizing P-TENGs with specific recognition elements, facilitating selective and sensitive detection of target chemicals such as gases, biochemicals, or biomolecules. Furthermore, we examine the integration of modular P-TENGs with energy storage devices, signal conditioning circuits, and wireless communication modules, highlighting the potential for creating advanced, self-powered sensing systems. Finally, we address the challenges and future directions in the development of modular P-TENG-based chemical sensors (PCS and TCS), emphasizing the importance of improving selectivity, stability, and reproducibility for practical applications.

Keywords: piezoelectric and triboelectric nanogenerators; sustainable; chemical sensing; modular design

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1. Introduction

Piezoelectric and triboelectric nanogenerators (P-TENGs) have garnered substantial interest in recent years due to their ability to effectively convert mechanical energy into electrical energy [1,2]. Such promising technologies are particularly suitable for applications in self-powered electronics, such as wearable devices, and environmental monitoring systems [3]. With the growing need for sustainable and adaptable chemical sensors, P-TENG-based chemical sensors have emerged as optimal solutions. These sensors are capable of detecting a wide range of target chemicals, including gases, liquids, and biomolecules, thus catering to diverse requirements in various fields.

A good sensor exhibits key factors that contribute to its performance, including sensitivity, specificity, resolution, repeatability, and response time [4–6]. P-TENG technology, with its compatibility with numerous piezoelectric and triboelectric materials, enables the development of tailored sensors that embody these characteristics [7]. The adaptability of P-TENG technology makes it incredibly versatile, with applications in environmental monitoring, healthcare, and security, such as air quality detection, physiological parameter tracking, and hazardous chemical sensing. By optimizing sensitivity, specificity, resolution, repeatability, and response time, P-TENG sensors can ensure accurate, reliable, and efficient data collection for various applications. Moreover, to enhance practicality, P-TENG-based chemical sensors can be designed as wearable patches or integrated into wearable devices, allowing for continuous monitoring and signal analysis, ultimately combining the essential traits of a sensor with the benefits of P-TENG technology.

Modularity in P-TENGs offers design flexibility, permitting researchers and engineers to explore various combinations of piezoelectric and triboelectric materials, electrode materials, and device structures to customize P-TENGs for specific applications or performance requirements (Figure 1) [8–13]. This is in contrast to conventional sensing technologies, which often rely on more rigid and less adaptable designs. Modularity also facilitates sensing versatility by incorporating multiple sensing components into a single P-TENG device, improving its ability to simultaneously or selectively detect different chemical species, whereas traditional sensors may be limited to detecting a single analyte or require multiple sensors for multi-analyte detection [14,15]. Furthermore, modularity simplifies the integration of P-TENGs with other electronic components such as energy storage devices, signal conditioning circuits, and wireless communication modules. This allows the development of advanced self-powered systems capable of autonomous sensing, data processing, and communication tasks, providing an advantage over other sensing technologies that might require external power sources and complex circuitry. The modular approach streamlines P-TENG fabrication and assembly processes, promoting rapid prototyping and reduced production costs, while also facilitating repair and maintenance by making it easier to identify and replace faulty or damaged components. This ease of assembly and maintenance is another area where P-TENGs can outperform more traditional sensing technologies, which may require specialized equipment or expertise for fabrication and repair [16,17].

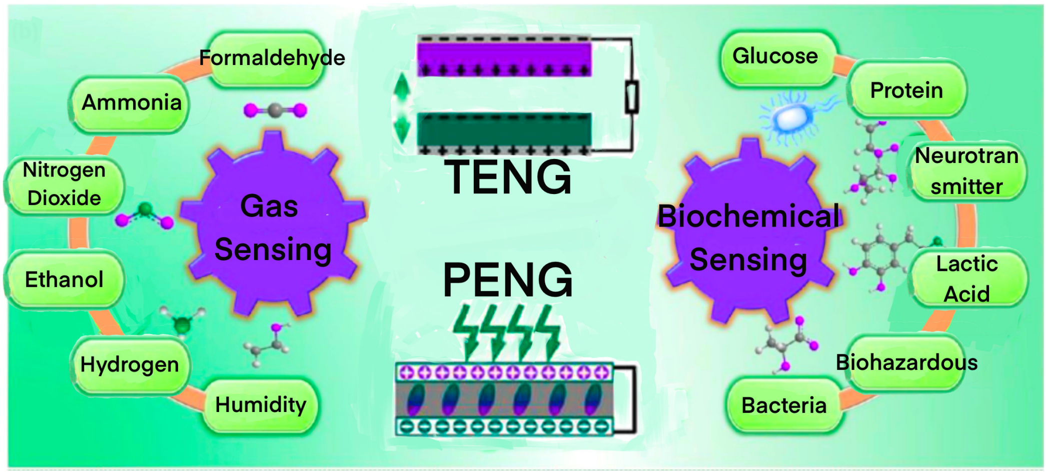

Figure 1. P-TENGs for sustainable chemical sensors.

In this review, we delve into the advancements and applications of modular P-TENG-based chemical sensors across various fields, such as environmental monitoring, healthcare, and security. We showcase the versatility and adaptability of this technology in detecting a wide range of target chemicals, including gases, liquids, and biomolecules. Key examples include air quality detection, biohazardous compound sensing, and the diagnosis of Gram-positive bacteria. By highlighting the modularity and customization options offered by P-TENG technology, we underscore its potential in addressing specific challenges across diverse sectors, emphasizing its significance in promoting innovative solutions for environmental monitoring, healthcare, and security.

2. P-TENGs Energy Collection

2.1. PENGs

2.1.1. Working Principle of PENGs

Piezoelectric nanogenerators (PENGs) utilize the piezoelectric effect to transform mechanical energy into electrical energy [18–22]. This effect generates an electrical charge when mechanical stress or strain is applied to certain materials, such as bending, stretching, or pressing (Figure 2b). PENGs are useful for harvesting energy such as vibrations, body movements, and environmental forces from ambient mechanical sources, making them ideal for self-powered devices and sensors [23,24].

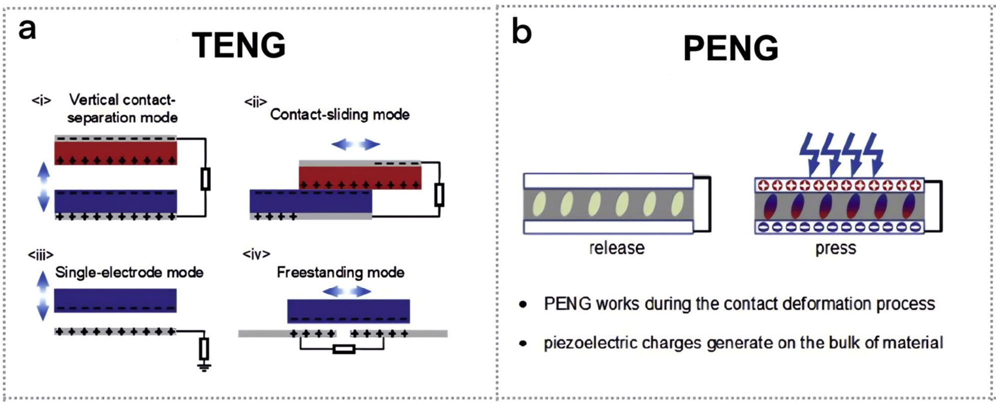

Figure 2. (**a**) TENG working principle. (**b**) PENG working principle. Elsevier 2020 [23].

PENGs convert mechanical energy into electrical energy through the use of piezoelectric materials, which generate a voltage in response to mechanical stress or strain. The various operating modes of PENGs depend on the alignment between mechanical stress and electrical polarization direction. These primary working modes include the following:

Longitudinal mode: Mechanical stress (or strain) is applied perpendicularly to the electrical polarization direction. This model is common in thin-film PENGs, where a piezoelectric layer is deposited on a substrate and generates a voltage across its thickness when bent due to the strain.

Transverse mode: Mechanical stress/strain is applied parallel to the electrical polarization direction. Bulk or thick-film PENGs often exhibit this mode, as the piezoelectric material in the form of a block or thick layer generates a voltage across its thickness when compressed or stretched along the same axis.

Shear mode: Mechanical stress/strain is applied tangentially to the material's surface, neither parallel nor perpendicular to the electrical polarization direction. This shearing stress generates a voltage across the material in a direction perpendicular to both the mechanical stress and the electrical polarization directions. Though less common, this mode is found in certain specialized PENG designs.

Diagonal mode: As a combination of longitudinal and transverse modes, the diagonal mode involves mechanical stress applied at an angle relative to the direction of polarization. PENGs operating in this mode are sensitive to stress, causing the material to undergo a combination of axial and bending deformations.

2.1.2. Strategies for Improving Energy Collection Efficiency of PENGs

Researchers are continually seeking ways to improve the energy collection efficiency of PENGs (Table 1), with notable examples including efforts by Nandang et al. [25]. and Wang et al. [26], in the development of novel materials and structures for enhanced performance. These innovative approaches have the potential to transform the field of energy harvesting and enable the creation of more effective self-powered devices.

In 2023, Nandang et al. [25] made significant strides in this area by focusing on utilizing aluminum-doped zinc oxide nanorods (AZO NRs) coated with nickel oxide (NiO) to create a p–n junction for nanogenerator applications (Figure 3a). This research built on the team's earlier work on the synthesis of AZO NRs using the hydrothermal method and evaluation of their properties with X-ray diffraction (XRD), scanning electron microscopy (SEM), UV–visible spectroscopy, and current–voltage measurements. Their findings indicated that both aluminum doping and the incorporation of NiO composites increased the output power of the nanogenerator compared to pure zinc oxide by widening the bandgap. Furthermore, the study highlighted the advantages of using nanorod structures and NiO composites to improve zinc oxide properties for various applications, including photodetector films and solar cells.

In a complementary effort, Wang et al. [26] in 2021 pioneered the use of graphitic carbon nitride (g-C_3N_4) in energy harvesting, taking advantage of its robust piezoelectricity due to non-centrosymmetric holes (Figure 3b). Building on Nandang et al. [25]'s research, they developed a g-C_3N_4-based PENG system that significantly improves energy collection efficiency. This system consists of g-C_3N_4 powders synthesized from different precursors, g-C_3N_4 films produced by spin-coating the powders onto flexible substrates, and PENGs assembled by sandwiching the films between electrodes. By adjusting precursors and optimizing the intrinsic lattice strain and crystallinity of g-C_3N_4, the researchers achieved a considerable enhancement in output performance. They found that a urea/melamine precursor mixture combined with a PI substrate resulted in the highest output voltage and current density among the tested samples. These results demonstrate the potential of g-C_3N_4 as a promising material for PENGs and multifunctional self-powered devices, offering an alternative to traditional 2D-layered materials such as MoS_2, WS_2, and h-BN.

In conclusion, the groundbreaking work by Nandang et al. [25] and Wang et al. [26] has not only advanced the field of energy harvesting by optimizing the efficiency of PENGs but also opened the door for further investigation of novel materials such as AZO NRs and g-C_3N_4 in energy harvesting applications. These developments hold promise for the creation of innovative self-powered devices that can address pressing global energy challenges.

2.2. TENGs

2.2.1. Working Principle of TENGs

A triboelectric nanogenerator (TENG) is an innovative energy-harvesting technology that effectively converts mechanical energy into electrical energy via the triboelectric effect and electrostatic induction (Figure 2a). The triboelectric effect occurs when two materials with distinct electron affinities come into contact, leading to electron transfer and charge redistribution. The subsequent separation of these materials generates a potential difference that can be harvested as electrical energy when connected to an external circuit.

TENGs convert mechanical energy into electrical energy through the triboelectric effect, which arises from the contact and separation of two dissimilar materials [27–33]. TENGs primarily operate in different working modes based on the relative motion between the triboelectric materials and their electrode configurations. The main working modes of TENGs include the following:

Vertical contact-separation mode: The two triboelectric materials are in direct contact, with their respective electrodes located on opposite sides. An external force causes the materials to separate vertically, generating a potential difference between the electrodes and driving electron flow through the external circuit. When the materials return to their original positions, the potential difference is neutralized, and the electrons flow back.

Lateral sliding mode: The two triboelectric materials are in direct contact, with their respective electrodes located on the same side. As the materials slide against each other laterally, a potential difference is generated between the electrodes due to the varying contact area between the triboelectric materials, causing electron flow through the external circuit. This process is reversed when the materials slide back to their original positions.

Single-electrode mode: This mode uses only one electrode in contact with one of the triboelectric materials. When the other triboelectric material is brought close to or in contact with the material with the electrode and then separated, a potential difference is generated between the electrode and the ground, resulting in electron flow through the external circuit connected between the electrode and the ground.

Freestanding triboelectric-layer mode: The two triboelectric materials are separated by an air gap, with their respective electrodes on the same side of the materials. When an external mechanical force causes one material to move toward the other, the air gap is reduced, and a potential difference is generated between the electrodes, driving electron flow through the external circuit. When the force is removed, and the materials return to their original positions, the potential difference is neutralized, and the electrons flow back.

In summary, piezoelectric and triboelectric nanogenerators (P-TENGs) offer versatile and innovative methods for harvesting energy from mechanical sources. With various working modes available, P-TENGs provide promising solutions for self-powered devices and sensors across diverse applications. As research and development in this field advance, these nanogenerators will play an increasingly crucial role in promoting sustainable and efficient energy sources.

2.2.2. Strategies for Improving Energy Collection Efficiency of TENGs

This section discusses two innovative TENG designs aimed at improving energy collection efficiency in various environments (Table 1), with each design addressing unique challenges and opportunities. Both developments contribute to the efficient utilization of energy in different settings, such as harsh environments and broadband vibration energy harvesting.

First, in 2023, Li et al. [34] presented a modular TENG (M-TENG) designed to efficiently capture high entropy energy (HEE) in harsh environments, composed of a modular TENG (M-TENG) and a power management circuit (PMC) (Figure 3c). The M-TENG employed an escapement mechanism, ensuring the TENG would produce a stable and continuous electrical output by releasing energy evenly. The research investigated the impact of various structural parameters on the M-TENG's output performance and confirmed its stability and environmental adaptability. The modular design of the energy collection module allows it to be adapted to different application scenarios, such as wind and water energy harvesting. The system's transmission structure consists of a gear train to increase torque and an escapement for stable energy output. The generation unit features a rotation-disk triboelectric nanogenerator (R-TENG), which is protected by encapsulation for operation in harsh conditions. This innovative work offers a paradigm for the efficient utilization of HEE in challenging environments, inspiring the development of emergency self-rescue equipment and providing new insights for modular TENG designs.

Second, building on the need for efficient energy harvesting in various environments and complementing Li et al. [34]'s work, Yu et al. [35] introduced a novel additional mass-enhanced film structure triboelectric nanogenerator (AMF-TENG) in 2023. This design was specifically aimed at efficiently harvesting broadband vibration energy. The device comprises an additional mass, a fluorinated ethylene propylene (FEP) film with a carbon electrode, and a conductive fabric mounted on a hollow frame (Figure 3d). The additional mass significantly boosts the AMF-TENG's electrical output by amplifying the vibration amplitude and contact forces between the FEP film and conductive fabric. The hollow frame structure further enhances the electrical output by 150% compared to an enclosed frame. Both theoretical and experimental investigations were conducted to optimize design parameters, resulting in exceptional electrical performance across a broadband frequency range of 15 to 70 Hz. Under specific vibration conditions, the AMF-TENG generates a maximum power density of 622.59 W/m^3, surpassing previous studies by 155.2%. The AMF-TENG successfully powers temperature and humidity sensors continuously under actual machine vibration, showcasing its potential for efficient vibration energy scavenging in a wide range of applications.

In conclusion, the innovative TENG designs by Li et al. [34] and Yu et al. [35] demonstrated significant advancements in energy collection efficiency in various environments. These developments have the potential to revolutionize the field of energy harvesting and pave the way for novel applications, such as emergency self-rescue equipment and vibration energy scavenging.

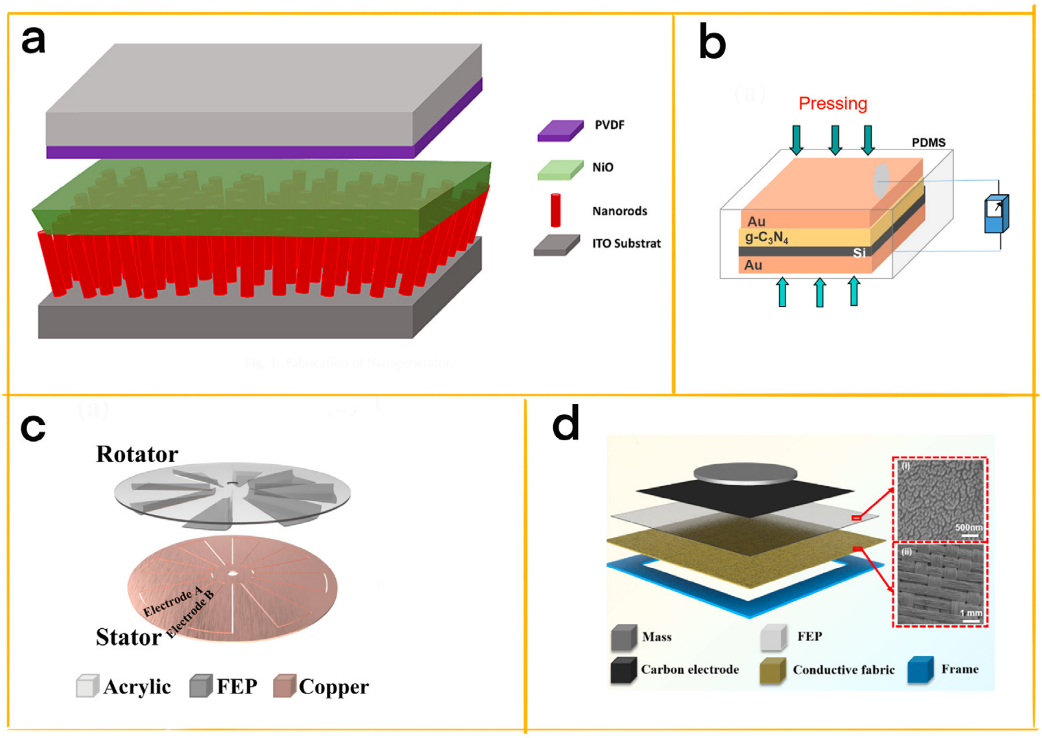

Figure 3. (**a**) Fabrication of nanogenerator, Elsevier 2023 [25]. (**b**) Schematic of g-C_3N_4 PENG, Elsevier 2021 [26]. (**c**) Diagram of R-TENG, Elsevier 2023 [34]. (**d**) AMF-TENG structure, Elsevier 2023 [35].

Table 1. Summary of TENGs and PENGs energy collection.

Date	Sizes	Materials	Energy Sources	Outputs	Applications	Type
2023 [25]	None	AZO NRs	Movement	19.5 µW	Enhance power generation capacity	PENG
2021 [26]	3×3 cm^2	g-C_3N_4	Movement	141 nA/cm^2	Electricity generation	PENG
2023 [34]	None	FEP	Vibration	500 V	Harsh environments energy collection	TENG
2023 [35]	5×5 cm^2	FEP	Vibration	622.59 W/m^3	Broadband vibration energy collection	TENG

3. Modular Design in P-TENGs for Gas Sensing

Gas sensing is crucial in various applications, and P-TENG sensing technology offers significant advantages over ordinary sensing methods. Through the modular design, P-TENGs can be tailored for diverse applications, including toxic gas detection and flammable gas detection, showcasing enhanced versatility. Compared to conventional sensing technologies, P-TENGs provide improved design flexibility, scalability, expansibility, and reconfiguration potential. This adaptability allows P-TENGs to be easily integrated into a wide range of fields, making them a superior choice for gas sensing in an array of situations.

In 2020, Ahmad et al. [36] designed a ZnO-based piezoelectric mechanical transducer to investigate the impact of chemisorbed CO_2 molecules on the ZnO nanowire surface, resulting in enhanced piezoelectric voltage (Figure 4a). The device consists of three primary components: an ITO-coated PET bottom electrode, ZnO nanowires as the intermediate part, and a gold-sputtered electrode as the upper electrode. The authors exposed the transducer to CO_2 for varying time intervals, observing a gradual increase in output piezoelectric potential, which they attributed to the reduction–oxidation mechanism of CO_2 gas on the ZnO nanowire surface. A maximum output voltage of 1.795 V and a maximum power density of 215.8 mW/cm^2 was achieved after 2 h of exposure. Interestingly, the output voltage plateaued after this exposure period with no further significant increases. This study highlighted the potential for utilizing ZnO-based piezoelectric transducers in gas sensing applications, particularly for detecting CO_2 concentrations in various environments.

3.1. Toxic Gas Sensing

Toxic gas sensing systems utilizing P-TENGs have gained considerable attention in environmental monitoring, industrial safety, and Internet of Things (IoT) applications [37,38]. These systems typically consist of interconnected modules, including the P-TENG itself, a chemo resistive or other type of gas sensor, and a signal processing circuit. The gas sensors change their electrical properties (e.g., resistance) upon exposure to toxic gases, such as nitrogen dioxide (NO_2), ammonia (NH_4), and formaldehyde (HCHO) (Table 2).

3.1.1. Formaldehyde

Formaldehyde sensing plays a critical role in monitoring environmental factors that affect human health [39–46], and recent studies have focused on developing innovative self-powered gas sensor systems for this purpose. In this context, the work of Zhang et al. [47] and Wang et al. [48] demonstrated how the integration of advanced materials and nanotechnology can pave the way for cutting-edge gas sensing solutions. These solutions have the potential to revolutionize wearable devices for the sustainable monitoring of environmental health factors and applications in the environmental monitoring and healthcare sectors.

In 2021, in a pioneering study by Zhang et al. [47], a self-powered gas sensor system was developed featuring two primary modules: an MXene/Co_3O_4 composite-based formaldehyde sensor, and a ZnO/MXene nanowire array PENG (Figure 4b). The MXene/Co_3O_4 composite sensor exhibited exceptional sensitivity and selectivity toward formaldehyde detection. Simultaneously, the ZnO/MXene nanowire array PENG efficiently harvested human motion energy, making it an ideal candidate for wearable device integration. The researchers conducted extensive tests to assess the sensor's performance in terms of humidity influence, flexibility, and potential gas sensing mechanism. Building on this foundation, the modular system exemplifies the potential of combining advanced materials and nanotechnology to develop cutting-edge gas sensing solutions.

In a subsequent innovative study in 2022, Wang et al. [48] further advanced the field of gas sensing devices by effectively integrating two key components: a respiration-activated TENG, and a support vector machine (SVM) model (Figure 4c). This approach built upon the earlier work of Zhang et al. [47] by employing a Ti_3C_2Tx MXene/amino-functionalized multi-walled carbon nanotube (MXene/NH_2-MWCNT) composite, which functioned as both an energy source and a formaldehyde gas sensor. In parallel, the SVM model was employed to distinguish between various respiratory patterns by analyzing the TENG's output voltage. This modularized approach enabled the self-powered sensing system to showcase exceptional performance characteristics, including sensitivity, selectivity, detection limit, response time, and overall accuracy. Consequently, this groundbreaking device holds significant potential for applications in environmental monitoring and healthcare sectors, offering a valuable tool for diagnosing diseases associated with exhaled gases and analyzing distinct respiratory behaviors.

In conclusion, the innovative studies by Zhang et al. [47] and Wang et al. [48] highlighted the potential of integrating advanced materials, nanotechnology, and data analysis techniques to develop self-powered gas sensing solutions. These developments offer promising applications in wearable devices for the sustainable monitoring of environmental health factors and diagnostic tools in the environmental monitoring and healthcare sectors, ultimately contributing to the well-being of individuals and communities worldwide.

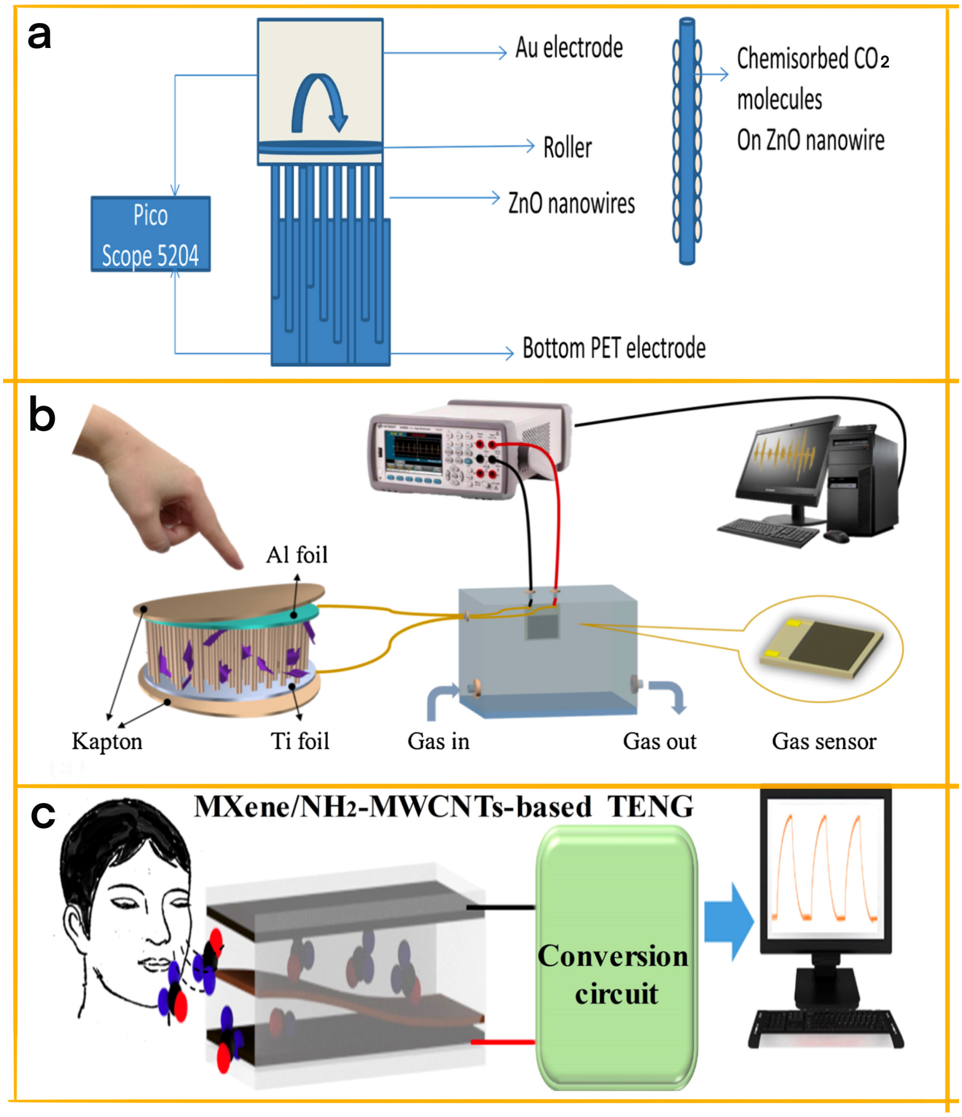

Figure 4. (**a**) ZnO energy harvester: schematic of ZnO nanowire with CO_2 molecules, Elsevier 2020 [36]. (**b**) Self-powered HCHO sensor driven by PENG: schematic illustration, Elsevier 2021 [47]. (**c**) MXene/NH_2-MWCNTs-based TENG application diagram, Elsevier 2022 [48].

3.1.2. Ammonia

Self-powered ammonia sensing has emerged as a crucial technology in fields such as environmental monitoring and food quality assessment [49–60]. This growing interest has led to groundbreaking research in the development of innovative gas sensing systems, with notable examples from Veeralingam et al. [61], Sardana et al. [62], Cai et al. [63], and Zhang et al. [64]. These studies demonstrated the multifunctional nature of novel materials and modular designs, paving the way for future advancements in self-powered health diagnostic applications and the role of modularization in gas sensing systems.

In 2023, Veeralingam et al. [61] set the stage with their cutting-edge gas sensing system, which incorporated two modules: a TENG and a gas sensor (Figure 5a). The innovative design of the TENG, based on Ti@MoS_2/PP:nylon fabric, served as both a highly sensitive respiration sensor and a self-powered ammonia gas sensor. Building on this foundation, in 2022, Sardana et al. [62] introduced another innovative gas sensing system composed of three modules: a TENG-powered sensor, an equivalent circuit, and an LED visualizer (Figure 5b). This system showcased the potential of harnessing human motion energy to drive intelligent gas-sensing networks for environmental monitoring.

Taking a step further, in 2021, Cai et al. [63] developed an innovative gas sensing system designed for sustainable food quality assessment in cold supply chains (Figure 5c). The system consisted of two main modules: a TENG component, and a wireless circuit module for data transmission to a user interface. By using porous wood coated with carbon nanotubes, the system achieved integrated power supply and gas sensing functionality, demonstrating immense potential for food safety and quality assessment.

In a similar vein, Zhang et al. [64] designed an innovative gas sensing system in 2021 that encompassed three modules: a gelatin-polyimide-based triboelectric nanogenerator (GP-TENG), a circuit module for rectification and voltage regulation, and a PANI/$NiCo_2O_4$ gas sensor. This eco-friendly self-powered ammonia gas sensor leveraged the GP-TENG as a backup power source, ensuring continuous operation even when the primary power source was unavailable. The system exhibited exceptional performance in detecting ammonia at room temperature, contributing significantly to the development of "smart factories" and new energy technologies.

In summary, the research efforts by Veeralingam et al. [61], Sardana et al. [62], Cai et al. [63], and Zhang et al. [64] underscore the potential of self-powered ammonia sensing in various applications. These studies highlight the innovative use of novel materials and modular designs to develop cutting-edge gas sensing solutions, which can contribute to advancements in environmental monitoring, food safety, and smart factories. As self-powered ammonia sensing technology continues to evolve, it holds tremendous promise for improving our understanding and management of environmental factors and the safety and quality of the food supply.

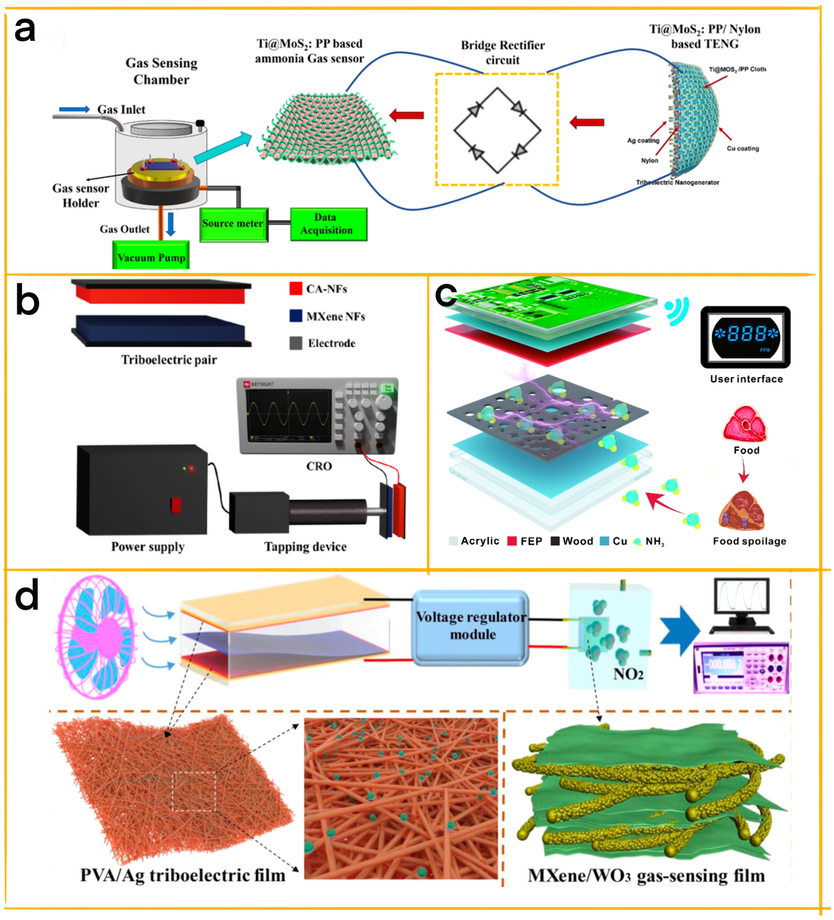

Figure 5. (**a**) Gas sensing chamber and integrated self-powered ammonia gas sensing setup: schematic, Elsevier 2023 [61]. (**b**) Home-made tapping device, Elsevier 2022 [62]. (**c**) TWGSS structure design, Elsevier 2021 [63]. (**d**) Self-powered NO_2 sensor driven by TENG: schematic illustration, Elsevier 2021 [65].

Table 2. Summary of P-TENGs gas sensing.

Date	Sizes	Key Materials	Energy Sources	Outputs	Applications	Type
2020 [36]	100 nm (nanowire)	ZnO nanowires	Vibration	215.8 mW/cm^2	Carbon dioxide detection	PENG
2021 [47]	500 nm (ZnO)	MXene/Co_3O_4	Movement	750 mV	Formaldehyde sensing	PENG
2022 [48]	5 × 2 × 1 cm^3 (TENG)	MXene/NH_2-MWCNTs	Breathe	136 V	Formaldehyde sensing	TENG
2023 [61]	None	Polypropylene/nylon	Breathe	2.7 µA/cm^2	Ammonia gas sensor	TENG
2022 [62]	3 × 3 cm^2 (TENG)	MXene/TiO_2/cellulose	Movement	1361 mW/m^2	Ammonia gas sensor	TENG
2021 [63]	4 × 4 cm^2 (TENG)	Porous wood	Movement	47 V	Ammonia gas sensor	TENG
2021 [65]	1 × 2 × 3 cm^3 (TENG)	PVA/Ag	Wind	530 V a	NO_2 gas sensor	TENG

3.1.3. Nitrogen Dioxide

P-TENGs exhibit significant potential in nitrogen dioxide sensing, as substantiated by recent research (Table 3), including groundbreaking efforts by Yang et al. [65] and Wang et al. [66]. In 2021, Yang et al. [65] developed a modular, self-powered gas-sensing system for detecting nitrogen dioxide (NO_2) at room temperature. This innovative system consisted of three main components: a TENG using weighing paper and PTFE film as friction materials, an In_2O_3/SnS_2 composite-based chemo resistive gas sensor, and a signal processing circuit. The TENG effectively converts mechanical energy into electrical energy, powering the gas sensor that changes its resistance upon NO_2 exposure. The signal processing circuit processes the sensor's output voltage and triggers an alarm if NO_2 concentrations exceed a preset threshold. With its high response, sensitivity, selectivity, and stability towards NO_2 at room temperature, the In_2O_3/SnS_2 composite makes this self-powered gas sensor a promising solution for environmental monitoring and industrial IoT applications.

Expanding on this concept, Wang et al. [66] presented a sophisticated gas sensing system in 2020 composed of four interconnected modules: a wind-powered TENG featuring poly(vinyl alcohol)/silver (PVA/Ag) nanofibers and fluorinated ethylene propylene (FEP) film, a voltage regulator module for TENG output voltage conversion, a Ti_3C_2Tx MXene/WO_3-based NO_2 sensor powered by the TENG, and a comprehensive detection system integrating four TENGs and a gas sensor to determine wind direction and wind-borne NO_2 levels (Figure 5d). This multifunctional, self-powered NO_2 detection system offers exceptional sensitivity, selectivity, and stability for NO_2 gas at room temperature while maintaining consistent voltage output across various wind speeds and humidity levels. Furthermore, the system can identify the origin of harmful gases by determining wind direction, making it a sustainable and maintenance-free platform with immense potential for environmental monitoring applications.

In conclusion, P-TENGs are revolutionizing toxic gas sensing by providing self-powered, energy-efficient solutions for sustainable monitoring and alarming. Their versatility and sustainability make them highly attractive options for applications in environmental monitoring, industrial safety, and IoT, paving the way for innovative and eco-friendly sensing technologies.

3.2. Flammable Gas Sensing

P-TENGs can be modularly designed and optimized according to the specific requirements of the flammable gas sensing application (Table 3) [7]. This flexibility allows for the fine-tuning of energy conversion and gas sensing characteristics to enhance sensitivity, selectivity, and stability in detecting flammable gases such as ethanol, hydrogen, and liquefied petroleum gas [67–74].

3.2.1. Ethanol

Modular P-TENGs can be readily integrated with other components of the gas sensing system, such as chemo-resistive or other types of gas sensors, signal processing circuits, and warning systems [75]. Modularity simplifies the development and deployment of flammable gas sensing systems, as well as their maintenance and upgrading, with notable examples including efforts by He et al. [76] and Shen et al. [77].

In 2020, He et al. [76] designed a versatile gas-sensing air filtration system that capitalized on the power of modularization in its construction (Figure 6a). The system comprises a self-supporting smart air filter (SSSAF) built around a PZT/PVDF electrospun nanofiber composite membrane. This innovative filter consists of four modules: two metal mesh electrodes enclosing the PZT/PVDF membrane, the membrane itself with its electroactivity and swelling properties, a VOC sensor for detecting ethanol vapors, and an antibacterial system fueled by harvested wind energy. The modular design enables the SSSAF to achieve exceptional performance across various aspects, including high filtration efficiency, VOC sensing, pressure drop monitoring, energy harvesting, and antibacterial functionality. The PZT/PVDF membrane's unique characteristics allow it to respond to different stimuli, such as pressure drop, organic vapors, and wind energy. Moreover, the system's energy-harvesting capabilities eliminate the need for an external power source while still generating electric fields to inhibit bacterial growth. He et al. [76]'s design showcases the potential of multi-functional smart air filters for enhancing indoor air quality management.

Expanding on this concept, in 2021, Shen et al. [77] designed an innovative self-powered breath analyzer composed of two primary modules: a hydroelectric nanogenerator (HENG) and an ethanol sensor (Figure 6b). This modularized system successfully addressed the limitations of traditional self-powered devices by eliminating mechanical vibrations, which are typically present in piezoelectric or TENGs. The HENG derives electrical power from the water vapor in exhaled human breath, providing a stable energy source for the ethanol sensor. This highly sensitive sensor can detect ethanol concentrations in breath, ranging from 50 to 1000 ppm, with a remarkable gas response of $\approx$80% at 100 ppm ethanol. The development of this noninvasive, low-cost, and miniature breath analyzer presents a promising advancement in gas sensing technology, enabling early detection of various health conditions such as inebriation, asthma, diabetes, and lung cancer. Furthermore, this new approach to self-powered gas sensing paves the way for the design and implementation of innovative electronic devices in a diverse array of applications, building on the foundation established by modular P-TENGs and the work of He et al. [76]

As gas sensing technology continues to advance, researchers are building upon the success of modular designs such as those developed by He et al. [76] and Shen et al. [77]. The integration of various components, such as energy harvesting systems, sensors, and antibacterial systems, creates opportunities for versatile and highly functional devices. These innovations have the potential to revolutionize a range of applications, from indoor air quality management to personal health monitoring.

3.2.2. Liquefied Petroleum Gas and Hydrogen

In the research conducted in 2019 by Ponnamma et al. [78], they presented a gas sensing system utilizing PVDF nanocomposite films embedded with TiO_2/CNT hybrid nanotubes on sensing electrodes. The innovative modular design was showcased through the hydrothermal synthesis of hybrid nanotubes and the spin-coating preparation of nanocomposite films (Figure 6c). By examining the effect of filler concentration and the synergy between the materials on the gas sensing response, stability, electrical conductivity, and piezoelectric properties, they were able to optimize the device's performance. The PVDF/TiO_2-CNT composite with a 2.5 wt.% concentration displayed the highest sensing response to liquefied petroleum gas (LPG), with a response time of 0.45 s (at 400 ppm LPG), which is nearly nine times greater than composites containing solely 2.5 wt.% TiO_2 or 2.5 wt.% CNT. In addition to its remarkable gas sensing abilities, this composite exhibited impressive piezoelectric properties, attributable to enhanced filler dispersion and interfacial interactions. The study demonstrated the potential for developing self-powered gas sensors using PVDF nanocomposites, paving the way for future advancements in this field.

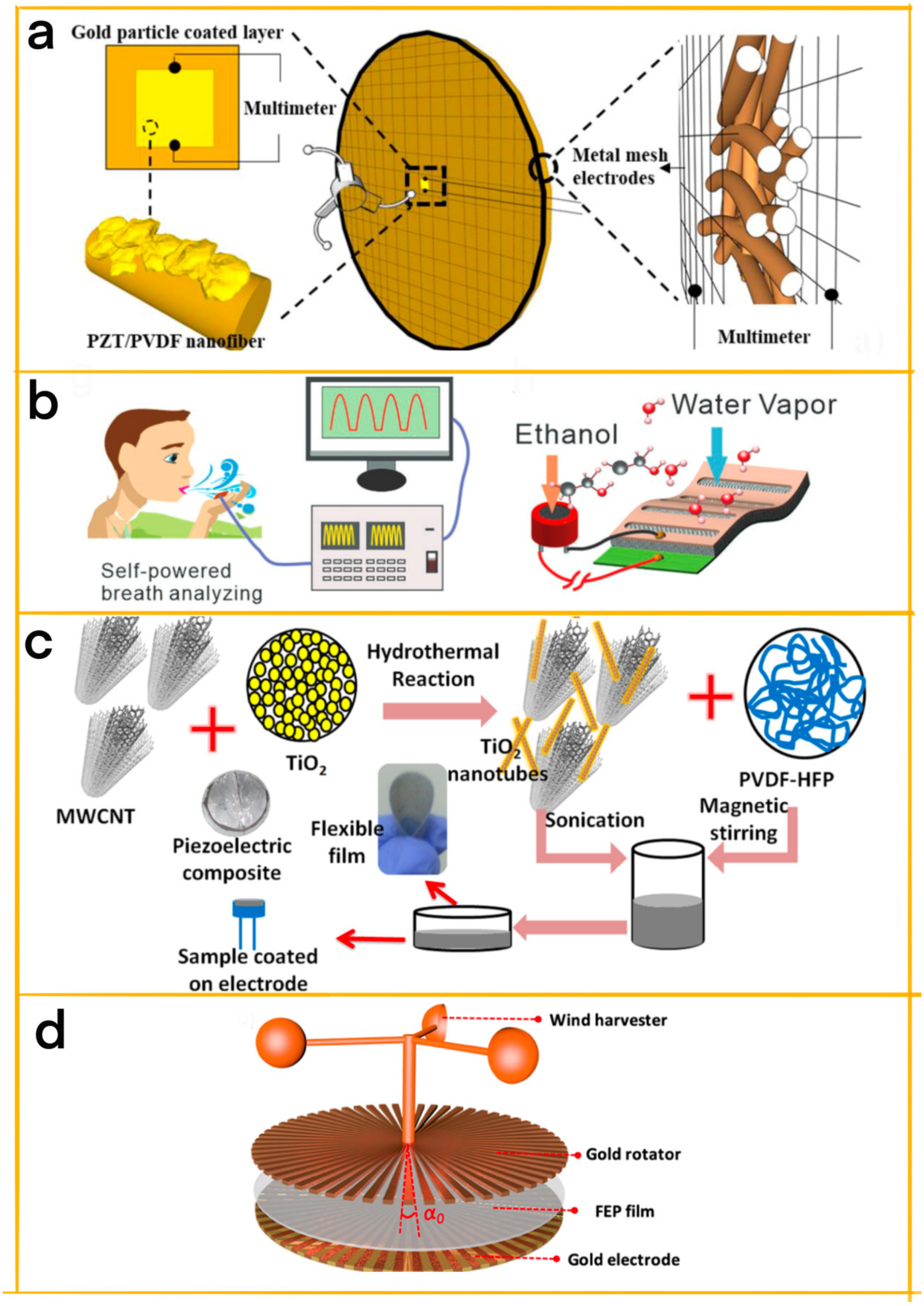

Figure 6. (**a**) SSSAF schematic diagram, Elsevier 2021 [76]. (**b**) Self-powered breath analyzer: measurement process and working principle, John Wiley and Sons 2020 [77]. (**c**) Sample preparation: schematic representation, Springer 2020 [78]. (**d**) WL-TENG structure: schematic, Elsevier 2021 [79].

Building upon this, in 2021, Jiang et al. [79] developed a gas sensing system comprising three key modules: a windmill-like triboelectric nanogenerator (WL-TENG), a Pd/ZnO nanorod-based hydrogen sensor, and an LED-based alarm. This self-powered hydrogen leakage detector utilized an impedance-adjustable WL-TENG to harvest wind energy generated during the operation of hydrogen energy vehicles, powering the entire sensing system (Figure 6d). By altering the center angle, the inherent impedance and matching region of the WL-TENG can be effectively adjusted, allowing for optimal impedance matching with the Pd/ZnO nanorods hydrogen sensor. The output voltage of the WL-TENG, influenced by the varying working states of the gas sensor, directly reflects the on/off status of the LED alarm, providing sustainable leak detection. This innovative approach of adjusting the inherent impedance of the TENG, rather than the traditional method of altering the gas sensing material's resistance, opens up new opportunities for self-powered gas sensing devices and contributes to the advancement of TENG impedance matching theory.

These studies highlight the importance of modularity in the development of gas sensing systems for detecting liquefied petroleum gas (LPG) and hydrogen. By optimizing components such as PVDF nanocomposite films, TENGs, and hydrogen sensors, researchers have been able to create efficient, self-powered gas-sensing devices with remarkable sensitivity and response times. These advancements not only contribute to the enhancement of gas sensing technology but also provide a foundation for future innovations in self-powered gas sensing applications.

3.3. Humidity Sensing

Modularly-designed P-TENGs offer simplified development and deployment of humidity sensing systems by enabling easy integration with components such as capacitive or resistive humidity sensors, signal processing circuits, and warning systems [80–88]. This modularity also allows for straightforward maintenance and upgrading of these systems.

Sun et al. [89] designed a cutting-edge, self-powered flexible monitoring system that effectively combines gas sensing and modularity, showcasing the potential of integrating TENG and PENG technologies. This innovative system features four distinct modules, including a TENG for energy harvesting, a PENG-based ultrasonic transducer array for temperature and humidity sensing, a TENG sensor for CO_2 detection, and a polyethyleneimine (PEI) coating for gas adsorption (Figure 7a). The integration of these modules enables the simultaneous monitoring of vital environmental parameters such as temperature, humidity, and CO_2 concentration, making it an ideal candidate for a range of applications in IoT devices and flexible electronics. Through optimization of the PEI volume fraction in the PEI/graphene oxide composite, the pMUT humidity sensor exhibits exceptional sensitivity, linearity, and selectivity over CO_2 gas. The system's self-powering capabilities and high sensitivity demonstrate a novel approach to humidity detection and offer a new strategy for configuring comprehensive, flexible, self-powered multifunctional sensing systems.

From this concept, Wang et al. [90] developed an innovative self-powered flexible humidity sensing device that incorporates two primary modules: a monolayer $MoSe_2$-based PENG on a polyethylene terephthalate (PET) substrate, and a flexible poly(vinyl alcohol)/Ti_3C_2Tx (PVA/MXene) humidity sensor created using electrospinning technology (Figure 7b). This modular design enables the device to harvest energy from human body movements while simultaneously detecting human skin moisture and ambient humidity levels. The $MoSe_2$ PENG demonstrates exceptional performance in terms of output voltage, power density, and its potential for wearable device applications. Moreover, the PVA/MXene-based humidity sensor exhibits a high response, quick response and recovery times, low hysteresis, and excellent repeatability. The integration of these two modules in a self-powered flexible humidity sensing device highlights the potential of 2D nanomaterials in the development of advanced self-powered electronic devices, paving the way for new applications in wearable technology and flexible electronics.

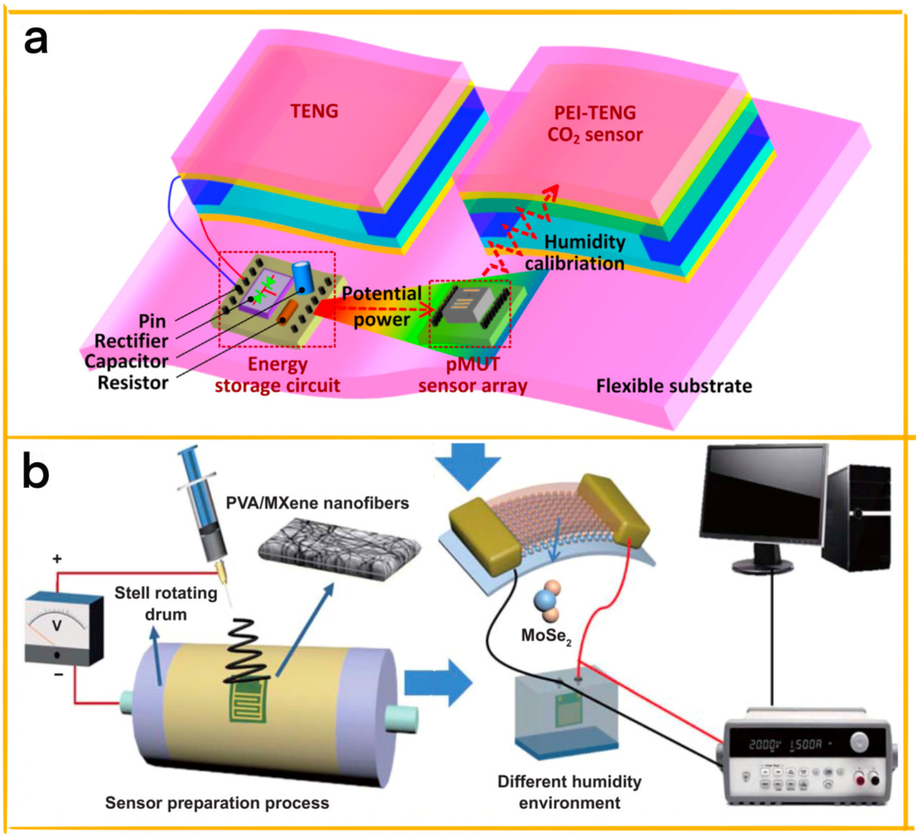

Figure 7. (**a**) Flexible self-powered multifunctional sensing system: schematic illustration, Elsevier 2019 [89]. (**b**) PVA/MXene humidity sensor, Springer 2021 [90].

Table 3. Summary of P-TENG flammable gas sensing.

Date	Sizes	Materials	Energy Sources	Outputs	Applications	Type
2021 [76]	None	PZT/PVDF	Wind	8V	Ethanol sensing	PENG
2020 [77]	None	ITO/PET	Breath	0.7 μW cm^{-2}	Ethanol sensing	TENG
2020 [78]	None	TiO_2/CNT	Vibration	1.3 V	Liquefied petroleum gas	PENG
2021 [79]	11.4 cm (DIA)	Pd/ZnO	Wind	60 V	Hydrogen sensing	TENG
2019 [89]	50 × 50 mm^2	PEI	Vibration	50V	Humidity sensing	TENG
2021 [90]	8 × 8 mm^2	PVA/MXene	Movement	42 mW m^{-2}	Humidity sensing	PENG

4. Modular Design in P-TENGs for Biochemical Sensing

P-TENGs provide versatility for a wide range of biochemical sensing applications. These applications range from small, portable devices to large-scale distributed monitoring networks, enabling tailored solutions for specific contexts such as medical diagnostics, environmental monitoring, and food safety. Modularity allows for the design and optimization of these nanogenerators to meet the unique requirements of each application, ensuring that energy conversion and biochemical sensing characteristics can be finely tuned. This adaptability results in increased sensitivity, selectivity, and stability in detecting biomolecules such as proteins or small molecules, ultimately facilitating the development of tailored self-powered biochemical sensing systems that effectively address diverse sensing needs across various settings (Table 4). For instance, in an innovative study in 2020 by Fan et al. [91], a biochemistry sensing system was developed consisting of three distinct modules: a TENG module, a nanofluidic preconcentrating module, and a smartphone-enabled bead immunoassay module (Figure 8a). The modular design allows the TENG module to generate self-powered voltage, initiating ion concentration polarization (ICP) and electrical kinetic trapping (EKT) of biomolecules within the nanofluidic module. Once preconcentrated, the biomolecules are detected using the bead immunoassay module via a smartphone camera.

4.1. Biomolecular Sensing

4.1.1. Glucose and Protein

By ingeniously harnessing energy from ever-present ambient sources, such as the natural kinetic motion of blood flow or subtle temperature gradients within the body, P-TENGs offer a remarkable solution to the challenges of powering electronic devices for biomedical applications [92–99]. By circumventing the need for cumbersome external power supplies or the inconvenience of recurrent battery replacements, P-TENGs pave the way for seamless and sustainable biomolecular sensing. This innovative technology ushers in a new era of continuous, real-time monitoring and diagnostics, enhancing the overall efficacy of healthcare and the quality of life for countless individuals.

In 2017, Kim et al. [100] presented a groundbreaking biosensor that utilized the piezoelectric and semiconducting properties of barium titanate nanoparticles (BT NPs) for active glucose detection. The system comprised three modules: an Al/BT/ITO nanogenerator (NG), a glucose oxidase (GOx) enzyme layer, and a glucose detection circuit. The NG operates both as an energy source and a biosensing signal, generating piezoelectric output upon mechanical deformation (Figure 8b). The GOx layer catalyzes the oxidation of glucose molecules, altering the charge-carrier density of the BT NPs film. The glucose detection circuit then measures the change in piezoelectric output resulting from the presence of glucose molecules. This innovative biosensor demonstrates excellent selectivity and sensitivity, providing a prototype for self-powered nanosystems in theranostic applications.

Based on this advancement, in 2020, Sophia et al. [101] introduced a novel biocompatible electronic platform for investigating protein–drug interactions and proof-of-concept theranostics (Figure 8c). The platform consisted of several modules: casein micelle, a primary milk protein that carries drugs and nanoparticles while responding to pH changes; cysteamine, a model drug interacting with casein and cysteine; BT NPs, multifunctional nanomaterials with semiconducting, piezoelectric, biocompatible, and optical properties; agarose, a biopolymer serving as a substrate and alternative electrode for the protein; and metal–protein–metal electrical junctions, solid-state devices that convert chemical or biological binding events into electrical signals. The study demonstrated the platform's ability to detect the pH-responsive behavior of casein and its interaction with cysteamine and cysteine using the current–voltage (I–V) technique. Additionally, the platform generated piezoelectricity from the casein-BT film through PENGs. This innovative platform shows potential as a preliminary tool for exploring possible interactions and theranostic applications before initiating clinical trials.

4.1.2. Lactic Acid and Neurotransmitter Sensing

Lactic acid and neurotransmitter sensing play essential roles in clinical practice, as they provide valuable insights into various physiological and pathological processes. Accurate and sustainable measurements of these biomolecules can facilitate early diagnosis, guide treatment decisions, and monitor the effectiveness of therapies.

In 2019, Gao et al. [102] designed an innovative wearable device for sustainable monitoring of both biochemical and electrophysiological signals from human sweat. The biochemical sensing system comprised four modules: a flexible lactate sensor utilizing an enzyme-based reaction to produce an electrical signal proportional to sweat lactate concentration; a wireless potentiostat amplifying and digitizing the lactate sensor signal; a flexible electrocardiogram (ECG) sensor detecting heart electrical activity from the skin surface; and a wireless ECG module amplifying, digitizing, and transmitting the ECG sensor signal to a smartphone via Bluetooth (Figure 8d). This lightweight, comfortable, and durable device can be worn on various body locations and offers valuable information for athletes, patients, and health-conscious individuals seeking to monitor their physical performance and well-being. Furthermore, the device exemplifies the potential of integrating multiple sensing modalities into a single wearable platform for simultaneous multisensing applications, such as personal care, artificial skin, and human–machine interactions.

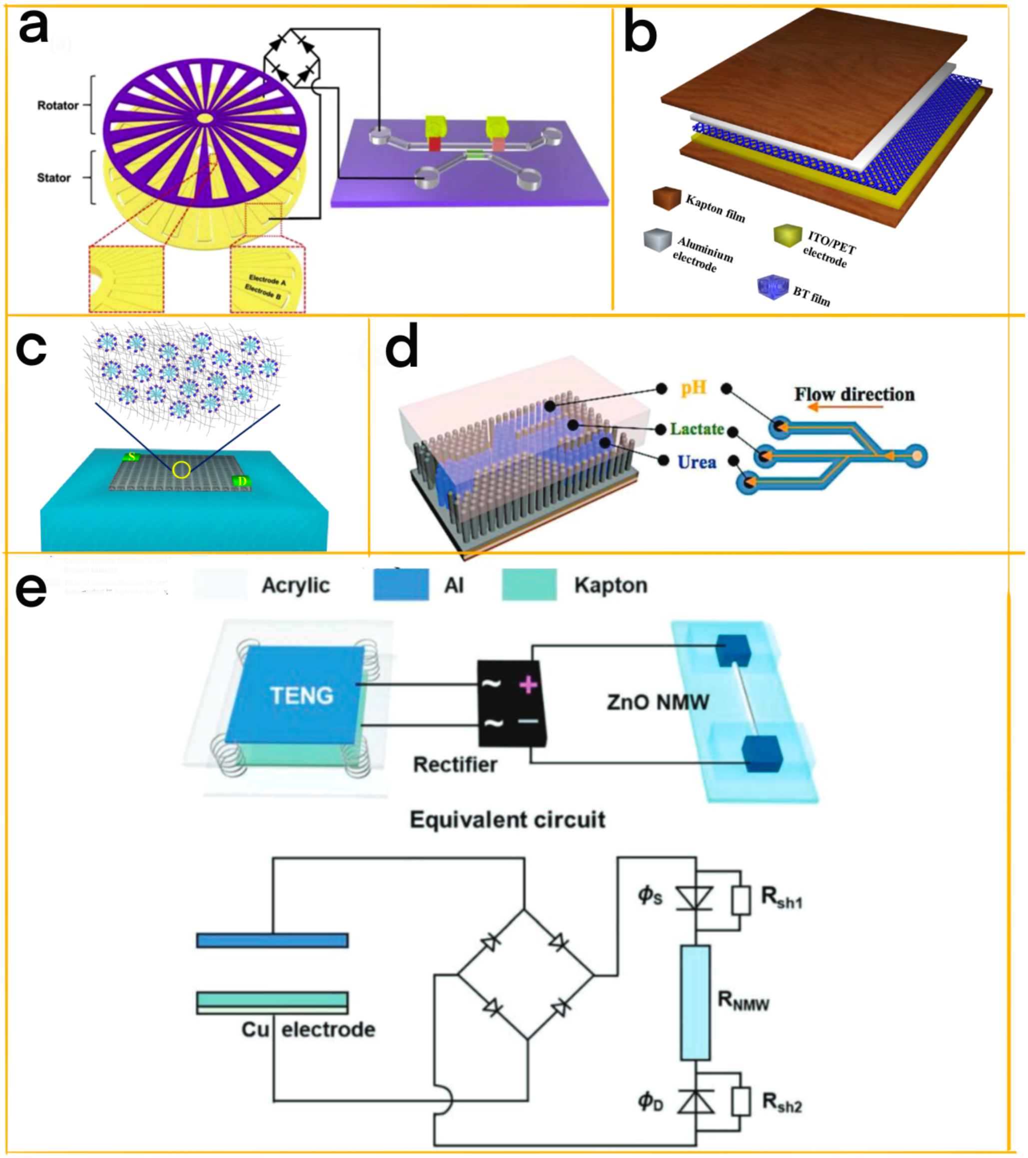

Figure 8. (**a**) TENG-driven nanofluidic preconcentrating device: normal direction contact-separation mode, Elsevier 2020 [91]. (**b**) $BaTiO_3$ (BT) film-based PENG: schematic diagram, Elsevier 2017 [100]. (**c**) Device structure: schematic representation, Elsevier 2020 [101]. (**d**) Integrated microfluidic and nanogenerator artificial skin: schematic diagram, John Wiley and Sons 2019 [102]. (**e**) Experiment setup and equivalent circuit: schematic diagram, John Wiley and Sons 2020 [103].

In a study conducted in 2020 by Zhao et al. [103], a modular biochemistry sensing system was designed comprising three key components: a semiconductor nano/microwire (NMW)-based field-effect transistor (FET), a TENG, and a metal–semiconductor interface (Figure 8e). This unique approach enabled the reversible conversion between Schottky and Ohmic contacts within a single device by utilizing TENG, allowing for highly sensitive detection of biomolecules such as neurotransmitters and neural electric signals at different contact states. The article highlighted the potential of using a single, multifunctional biosensor for diverse sensing applications. By effectively tuning the Schottky barrier height (SBH) with TENG, the researchers developed a Schottky to Ohmic reversible (SOR) biosensor capable of detecting neurotransmitters in the Schottky contact state and neural electric signals in the Ohmic contact state. This innovative method not only broadened the application possibilities of Schottky contact devices but also paved the way for the development of implantable, high-sensitivity, multifunctional biosensors for various clinical and research purposes.

4.2. Biohazardous Compound Sensing

The concept of modularity in P-TENGs enables easy integration of various sensing elements, such as ultrasonic, thioacetamide sensing, and catechol sensing into the same platform for convenient detection of biohazardous compounds. This flexibility simplifies customization for specific applications. For instance, in 2021, Mistewicz et al. [104] developed a groundbreaking chemical sensor system that combined a PENG made from SbSeI nanowires, a voltage amplifier circuit, and an oscilloscope. This innovative system used sonochemical reaction products as sensing materials in self-powered ultrasonic reactor devices, allowing for the determination of ultrasound parameters (Figure 9a). With the help of voltage signals and fast Fourier transform analysis, the device provided two rapid evaluation methods for measuring acoustic power in liquids. Furthermore, the compound content could be estimated by measuring the sound power of the liquid. This sensing technology demonstrated significant potential for sonochemistry applications and emphasized the versatility of modular chemical sensing systems.

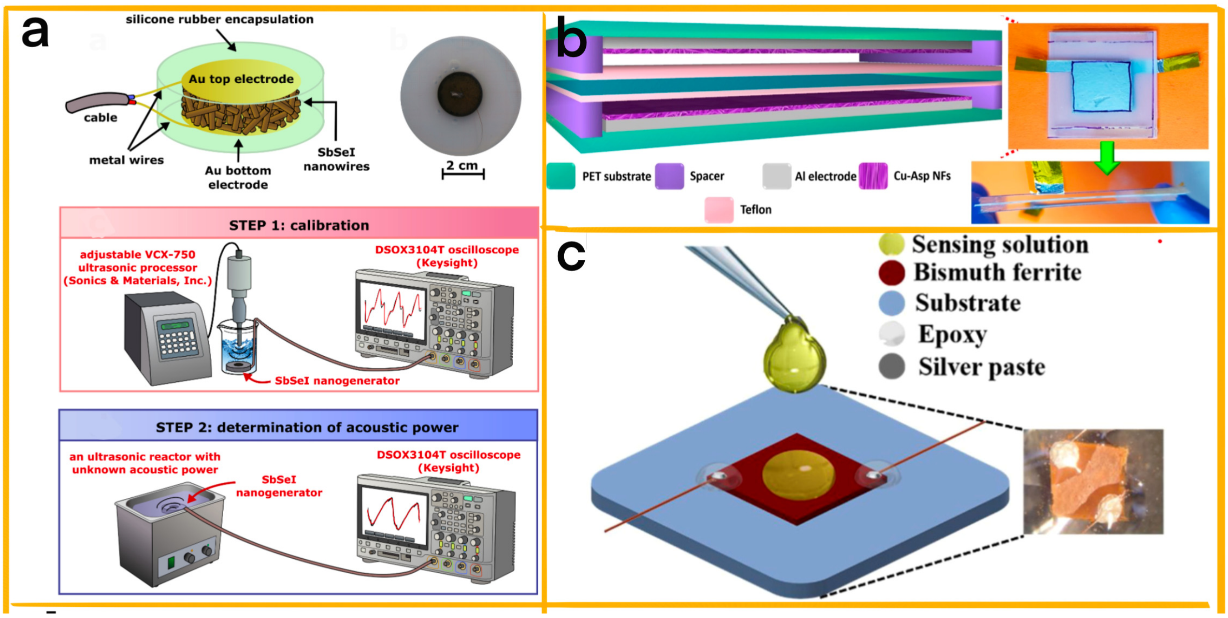

Figure 9. (**a**) SbSeI nanogenerator: schematic diagram, photograph, calibration, and ultrasonic power determination setup, Elsevier 2021 [104]. (**b**) Freestanding layer mode NF-TENG: 3D schematic illustration and device photos, ACS 2021 [105]. (**c**) $BiFeO_3$ catechol sensor: schematic and digital image of as-fabricated device, Elsevier 2020 [106].

4.2.1. Thioacetamide

Thioacetamide is an organosulfur compound commonly used as a substitute for hydrogen sulfide in laboratory settings due to its lower toxicity and ease of handling. However, it can still be harmful, especially when it contaminates water or food sources. As a result, thioacetamide sensing plays a critical role in environmental monitoring and in ensuring public health and safety. To address these challenges, researchers have explored the concept of modularity in thioacetamide sensing, designing systems with interchangeable components that offer flexibility, adaptability, ease of use, scalability, and cost-effectiveness. These modular systems can be adapted to various sample types, environmental conditions, and use cases while remaining user-friendly and cost-effective.

One such innovative approach was demonstrated in 2021 by Khandelwal et al. [105], who expertly designed a cutting-edge, modularized thioacetamide sensing system incorporating two modules: a contact-separation mode triboelectric nanogenerator (cNF-TENG), and a copper aspartate nanofiber (Cu-Asp NF) coated electrode (Figure 9b). The cNF-TENG provides dual functionality as both a power source and signal generator, while the Cu-Asp NF coated electrode effectively acts as a selective sensor for thioacetamide detection. In their research, the team synthesized Cu-Asp NFs using copper and aspartic acid, showcasing the application of these nanofibers in TENGs to convert mechanical energy into electrical energy. Furthermore, they demonstrated the potential for powering various low-power electronics with a freestanding layer mode TENG (NF-TENG), highlighting the practical applications of this innovative technology in the realm of thioacetamide sensing and beyond.

4.2.2. Catechol

Catechol, an organic compound with toxic properties, can be found in various sources, including industrial processes, natural plant metabolites, and pollutant breakdown products. Monitoring catechol levels is crucial due to its potential health and environmental risks, such as aquatic life toxicity and human skin, eye, and respiratory irritation [107]. Prolonged exposure may lead to severe health effects such as metabolic disturbances and damage to the liver, kidneys, and central nervous system. Catechol sensing is vital for environmental protection, industrial processes, public health, and biomedical applications, ensuring contamination monitoring, quality control, and minimized environmental impacts. Modular catechol sensing systems, scalable from portable field testing devices to high-throughput laboratory setups, offer value in maintaining environmental and public health safety across various applications.

In 2020, Kim et al. [106]'s study exemplified these principles by designing a novel self-powered catechol sensor to detect organic contaminants in water samples, addressing the critical need for effective environmental monitoring (Figure 9c). Their liquid sensor system comprised four modules: a sensing element, a transducer, a power supply, and a data processing unit. The innovative sensor is based on $BiFeO_3$ nanoparticles and utilizes a transitional flow-based piezoelectric nanogenerator (TFPNG) to convert both physical and chemical stimuli into electrical signals, eliminating the need for an external power supply or sensing unit.

The TFPNG-SPCS sensor demonstrates excellent selectivity, sensitivity, eco-friendliness, and detection limits for catechol concentrations. The transitional flow of catechol solution within the TFPNG differentiates between physical and chemical stimuli, resulting in readable electrical signals. This unique working mechanism not only showcases the potential of self-powered devices in the detection of biomolecules but also expands their applicability to a wide range of analytes based on different responses. Kim et al. [106]'s innovative approach highlights the advancements in self-powered sensing technology, reinforcing the benefits of modularity in catechol sensing for improving environmental monitoring and safeguarding of public health.

4.3. Gram-Positive Bacteria Sensing

In clinical settings, the sustainable diagnosis of Gram-positive bacteria is essential for determining appropriate treatment for patients suffering from bacterial infections. Early and accurate identification helps medical professionals make informed decisions regarding antibiotic selection, reducing complications and improving patient outcomes. Sustainable diagnosis also assists in preventing and controlling nosocomial infections, ensuring a safer healthcare environment.

In 2022, Wang et al. [108] developed a modular, self-powered biochemistry sensing system specifically designed for detecting Gram-positive bacteria in solutions, highlighting the modularity concept. This innovative system comprises three main components: a vancomycin-modified indium tin oxide glass (ITO-Van) for selective bacteria capture, guanidine-functionalized multi-walled carbon nanotubes (CNT-Arg) for signal amplification, and a TENG as a stable voltage signal source (Figure 10a). The system relies on vancomycin's specific interactions with Gram-positive bacterial cell walls for accurate detection, while CNT-Arg's high conductivity enhances the electrical signal. *Staphylococcus aureus* serves as a model, demonstrating low limits of detection and high selectivity. Additionally, a warning program is integrated to convert the voltage signal into a visual signal for easy observation. This self-powered biosensing system powered by TENG offers a promising design concept for applications in fields such as environmental pollution, iatrogenic diseases, and microbiological corrosion.

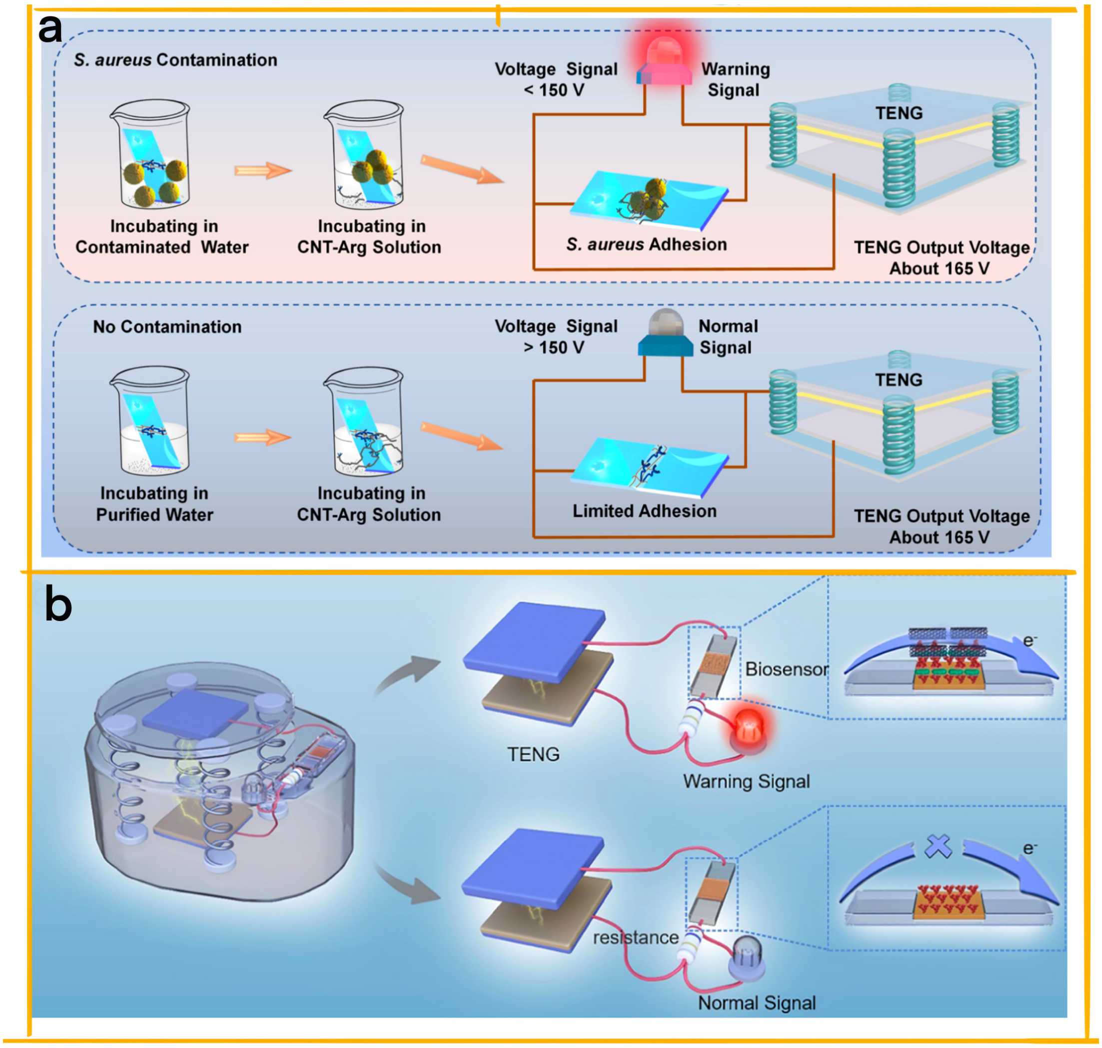

Figure 10. (**a**) *S. aureus* detection: self−powered biosensing system, detection process in liquid environment, vertical contact-separation TENG as voltage signal source, Elsevier 2022 [108]. (**b**) Bacterial detection process: schematic illustration, alarm triggering with bacteria presence, no alarm for few or no bacteria, Elsevier 2022 [109].

Similarly, in 2022, Zhou et al. [109] developed a biochemistry sensing system consisting of three distinct modules: ConA-modified etched ITO (ITO-ConA), ConA-modified multi-wall carbon nanotube (CNT-ConA), and a TENG. This self-powered microsensor system effectively detects Gram-negative bacteria (Gnb) in seawater by utilizing ConA as a biorecognition material to capture Gnb on ITO-ConA and CNT-ConA electrodes. As the concentration of Gnb changes, the resistance and voltage of the micro biosensor also vary. The system incorporates an alarm circuit, which conveys detection results through a light-emitting diode (Figure 10b). Zhou et al. [109]'s sensing system demonstrated excellent performance in detecting *Desulforibrio* sp. Huiquan 2017, a common sulfate-reducing bacteria responsible for microbiological-induced corrosion in marine environments. This innovative system showcases the benefits of modularization, offering portability, specificity, and stability for bacterial detection while highlighting the potential for further advancements in TENG-based sensor systems.

Both of these studies emphasize the advantages of modularity in the design and application of sensing systems. By integrating various components such as TENGs, functionalized nanomaterials, and biorecognition materials, these modular systems can address specific challenges in environmental monitoring, healthcare, and other industries, showcasing the versatility and potential of modular sensor systems.

Table 4. Summary of P-TENGs for biochemical sensing.

Date	Sizes	Materials	Energy Sources	Outputs	Applications	Type
2020 [91]	None	PDMS	Movement	80 V	Biochemical sensing	TENG
2017 [100]	2×2 cm^2	ITO/PET	Vibration	30 V	Glucose sensing	PENG
2020 [101]	1.5×1.5 cm^2	ITO/AL	Vibration	40 V	Protein sensing	PENG
2019 [102]	1×0.2 cm^2	PVDF	Movement	0.8 µA	Lactic acid-sensing	PENG
2020 [103]	8×8 cm^2	ZnO/Ag	Vibration	500 V	Neurotransmitter sensing	TENG
2021 [104]	2 cm (DIA)	SbSeI	Vibration	70 mV	Compound sensing	PENG
2021 [105]	1×1 cm^2	Cu-Asp NFs	Vibration	300 V	Thioacetamide sensing	TENG
2020 [106]	2×2 cm^2	$BiFeO_3$	Vibration	223 V	Catechol sensing	TENG
2022 [108]	3.5×3.5 cm^2	CNT-Arg	Vibration	165 V	Gram-positive bacteria	TENG
2022 [109]	3×3 cm^2	CNT-ConA	Vibration	160 V	Gram-positive bacteria	TENG

5. Conclusions and Prospects

In conclusion, modular design enables P-TENG-based chemical sensing to integrate various functional components, thus endowing them with enhanced design flexibility, sensing versatility, scalability, expansibility, and reconfiguration. The potential applications of P-TENGs are vast, including air quality monitoring in cities, the detection of hazardous gases in chemical plants, and wearable devices for continuous monitoring of patients' vital signs or diagnosing specific conditions through biomarker detection. Here, the various strategies for functionalizing P-TENGs with specific recognition elements were discussed, and the current progress in design strategies that facilitate selective and sensitive detection of target chemicals, such as gases, biochemistry, or biomolecules, was illustrated. Additionally, the integration of modular P-TENGs with energy storage devices, signal conditioning circuits, and wireless communication modules was discussed and highlighted, which is increasingly important in the era of wireless connection for developing self-powered sensing systems with interactivity.

However, to meet the gap between lab demonstration and market-oriented large-scale production, the following challenges must be addressed in P-TENG-based chemical sensors (PCS and TCS), emphasizing the importance of improving selectivity, stability, and reproducibility for practical applications.

5.1. Gas Sensing

Modular design in TENG gas sensing offers numerous advantages, including design flexibility, sensing versatility, scalability, expansibility, reconfiguration, and integration with other systems. This approach allows for easy incorporation of various functional components, enabling tailored sensing systems for specific applications and facilitating the modification of existing designs. Modular TENG gas sensors can be equipped with different recognition elements, making them capable of detecting a wide range of gases or biomolecules, and can be easily scaled up or down to suit different requirements. Moreover, the expandability and reconfiguration capabilities allow for the addition or replacement of components, ensuring adaptability to changing needs or technological advancements. Lastly, modular TENG gas sensors can be integrated with energy storage devices, signal conditioning circuits, and wireless communication modules, enabling the development of self-powered sensing systems with advanced interactivity, resulting in highly versatile and adaptable devices suitable for a wide range of applications and environments.

5.1.1. Material Selection

We can explore innovative materials possessing advanced piezoelectric/triboelectric properties and exceptional gas sensing capabilities. These materials may include metal oxides (e.g., ZnO, SNO_2, or WO_3), conductive polymers (e.g., polyaniline, polypyrrole, or PEDOT:PSS), or nanocomposites that incorporate carbon nanotubes, graphene, or metal-organic frameworks (MOFs). By utilizing these materials, we can enhance the sensitivity, selectivity, response time, and overall efficiency of gas sensors while also promoting better stability and environmental sustainability.

5.1.2. Sensing Optimization

We can develop highly sensitive and selective sensing layers for target gas analytes by employing nanostructured materials (e.g., nanowires, nanoparticles, or nanosheets), molecularly imprinted polymers, or other cutting-edge materials such as zeolites or metal-organic frameworks (MOFs). These innovative materials are capable of selectively binding to target gas molecules, thereby enhancing signal transduction while offering superior thermal stability and expedited response times. Moreover, it is crucial to consider optimizing the thickness, porosity, and morphology of the sensing layer to further improve its performance and adaptability in various sensing applications.

5.1.3. Sustainability and Adaptability

Hybrid energy harvesting systems may also be developed that integrate P-TENGs with complementary energy harvesting technologies, such as solar, thermoelectric, or electromagnetic. By combining these technologies, we can significantly bolster the sustainability and reliability of chemical sensing systems. This innovative approach guarantees continuous operation in diverse environments, where energy sources may fluctuate, and ensures a more robust and adaptable energy solution for sensing applications.

5.1.4. Energy Storage

P-TENGs can be incorporated with energy storage devices, such as supercapacitors, thin-film batteries, or even emerging technologies such as solid-state batteries or pseudocapacitors. These energy storage solutions can effectively store the generated energy, guaranteeing continuous, stable operation of the gas sensor. This integration paves the way for the development of fully self-powered, autonomous sensing systems that can operate efficiently in remote or inaccessible environments, expanding the scope of sensing applications and enhancing their versatility.

5.2. Biochemical Sensing

Modular approaches in biochemical sensing offer numerous advantages that enhance the overall effectiveness and adaptability of these systems. By utilizing modular components, researchers and developers can more easily customize and optimize sensor performance for specific target analytes or sensing environments. This flexibility enables rapid prototyping, testing, and fine-tuning of various sensor configurations, ultimately accelerating the development and deployment of new sensing technologies. Additionally, modularity promotes interoperability, allowing for the seamless integration of diverse sensing elements, signal processing units, and data analysis tools. This in turn fosters collaboration and knowledge sharing among researchers, contributing to the growth and advancement of the field. Furthermore, modular systems often benefit from reduced production costs, as standardized components can be mass-produced and easily replaced, improving the scalability and maintainability of these sensing technologies. Overall, the modularity in biochemical sensing greatly enhances versatility, efficiency, and accessibility, paving the way for innovative solutions to address a wide array of biomedical, environmental, and industrial applications.

5.2.1. Energy Harvesting

In the future, researchers can dedicate their efforts to optimizing material properties, contact surfaces, and device geometries to improve energy harvesting efficiency in P-TENGs. Enhancing the operational frequency range by using materials with different frequency responses or tuning the device structure can enable the harvesting of energy from various sources and frequencies. Additionally, by integrating piezoelectric and triboelectric mechanisms into a single device, researchers can harvest energy from multiple sources or modes of mechanical stimuli, thereby significantly enhancing overall efficiency and expanding the scope of practical applications.

5.2.2. Sensitivity and Selectivity

To improve sensitivity and selectivity in biochemical sensing, we can explore novel surface functionalization strategies using specific recognition elements, such as antibodies, aptamers, or molecularly imprinted polymers, to improve the affinity towards target analytes. Furthermore, employing signal amplification techniques such as nanomaterial-based or enzymatic amplification can lead to better sensitivity, crucial for detecting trace amounts of target molecules. In the future, developing multiplexed sensing systems capable of simultaneously detecting multiple analytes will enable more comprehensive analysis and improved selectivity, leading to advancements in areas such as healthcare, environmental monitoring, and food safety.

5.2.3. Wireless

In the future, the capabilities of biochemical sensing may be enhanced by developing advanced self-powered wireless sensing systems. By integrating P-TENGs with low-power wireless communication technologies, such as Bluetooth Low Energy (BLE), LoRaWAN, or Zigbee, they can create cutting-edge self-powered, wireless chemical sensing systems. These innovative systems have the potential to revolutionize monitoring and data transmission in remote, inaccessible, or hazardous environments, providing real-time insights for improved decision-making and timely interventions. The development of such systems not only highlights the importance of interdisciplinary research but also opens up new possibilities for sustainable, efficient, and accessible biochemical sensing in various applications.

5.2.4. Cost-Effectiveness

To ensure cost-effectiveness, future research may focus on implementing scalable fabrication techniques, such as roll-to-roll processing, inkjet printing, or 3D printing, which enable large-scale production of nanogenerators at reduced costs. Investigating alternative low-cost materials, such as polymers or metal oxides, can retain the desired properties while reducing production costs, making the technology more accessible for a broader range of applications. In the future, developing strategies for recycling and recovering materials used in nanogenerators will contribute to reducing waste, enhancing sustainability, and promoting circular economy practices. These efforts will significantly improve the performance of P-TENGs for sustainable biochemical sensing in real-world applications and drive widespread adoption of the technology.

5.2.5. Biocompatibility

To improve the biocompatibility of P-TENGs for sustainable biochemical sensing, further steps may be taken in selecting biocompatible materials, modifying surfaces to enhance cell adhesion and tissue integration, and rigorously testing the devices in vitro and in vivo. Additionally, developing minimally invasive integration methods, investigating appropriate sterilization techniques, and studying biodegradation and bioreabsorption properties of materials are essential for ensuring safe and effective use in biological systems.

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