Chemical Sensor Based on Piezoelectric/Triboelectric Nanogenerators

Subjects: Biochemistry & Molecular Biology

Contributor: Zequan Zhao , Qiliang Zhu , Yin Lu , Yajun Mi , Xia Cao , Ning Wang

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.

piezoelectric and triboelectric nanogenerators sustainable chemical sensing modular design

1. 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. [1] 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. 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.

1.1. 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 [2][3]. 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).

1.1.1. Formaldehyde

Formaldehyde sensing plays a critical role in monitoring environmental factors that affect human health [4][5][6][7][8][9][10][11], 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. [12] and Wang et al. [13] 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. [12], 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. 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. [13] 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. This approach built upon the earlier work of Zhang et al. [12] 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. [12] and Wang et al. [13] 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.

1.1.2. Ammonia

Self-powered ammonia sensing has emerged as a crucial technology in fields such as environmental monitoring and food quality assessment [14][15][16][17][18][19][20][21][22][23][24][25]. This growing interest has led to groundbreaking research in the development of innovative gas sensing systems, with notable examples from Veeralingam et al. [26], Sardana et al. [27], Cai et al. [28], and Zhang et al. [29]. 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. [26] set the stage with their cutting-edge gas sensing system, which incorporated two modules: a TENG and a gas sensor. 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. [27] introduced another innovative gas sensing system composed of three modules: a TENG-powered sensor, an equivalent circuit, and an LED visualizer. 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. [28] developed an innovative gas sensing system designed for sustainable food quality assessment in cold supply chains. 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. [29] 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.

1.1.3. Nitrogen Dioxide

P-TENGs exhibit significant potential in nitrogen dioxide sensing, as substantiated by recent research, including groundbreaking efforts by Yang et al. [30] and Wang et al. [31]. In 2021, Yang et al. [30] 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. [31] 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. 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.

1.2. Flammable Gas Sensing

P-TENGs can be modularly designed and optimized according to the specific requirements of the flammable gas sensing application [32]. 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 [33][34][35][36][37][38][39][40].

1.2.1. 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 [41]. 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. [42] and Shen et al. [43].

In 2020, He et al. [42] designed a versatile gas-sensing air filtration system that capitalized on the power of modularization in its construction. 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. [42]'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. [43] designed an innovative self-powered breath analyzer composed of two primary modules: a hydroelectric nanogenerator (HENG) and an ethanol sensor. 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 ≈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. [42]

As gas sensing technology continues to advance, researchers are building upon the success of modular designs such as those developed by He et al. [42] and Shen et al. [43]. 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.

1.2.2. Liquefied Petroleum Gas and Hydrogen

In the research conducted in 2019 by Ponnamma et al. [44], 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. 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.

Building upon this, in 2021, Jiang et al. [45] 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 (. 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.

1.3. 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 [46][47][48][49][50][51][52][53][54]. This modularity also allows for straightforward maintenance and upgrading of these systems.

Sun et al. [55] 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. 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. [56] 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. 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.

2. 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. For instance, in an innovative study in 2020 by Fan et al. [57], 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. 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.

2.1. Biomolecular Sensing

2.1.1. 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 [58][59][60][61][62][63][64][65]. 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. [66] 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. 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. [67] introduced a novel biocompatible electronic platform for investigating protein–drug interactions and proof-of-concept theranostics. 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.

2.1.2. 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. [68] 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. 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.

In a study conducted in 2020 by Zhao et al. [69], 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. 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.

2.2. 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. [70] 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. 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.

2.2.1. 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. [71], 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. 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.

2.2.2. 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 [72]. 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. [73]'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. 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. [73]'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.

2.3. 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. [74] 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. 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.

Similarly, in 2022, Zhou et al. [75] 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. Zhou et al. [75]'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.

References

1. Ahmad, M.; Ahmad, M.K.; Nafarizal, N.; Soon, C.F.; Suriani, A.B.; Mohamed, A.; Mamat, M.H. Chemisorbed CO2 Molecules on ZnO Nanowires (100 Nm) Surface Leading towards Enhanced Piezoelectric Voltage. Vacuum 2020, 182, 109565.
2. Wang, F.; Wang, M.; Liu, H.; Zhang, Y.; Lin, Q.; Chen, T.; Sun, L. Multifunctional Self-Powered E-Skin with Tactile Sensing and Visual Warning for Detecting Robot Safety. Adv. Mater. Interfaces 2020, 7, 2000536.
3. Yang, J.; An, J.; Sun, Y.; Zhang, J.; Zu, L.; Li, H.; Jiang, T.; Chen, B.; Wang, Z.L. Transparent Self-Powered Triboelectric Sensor Based on PVA/PA Hydrogel for Promoting Human-Machine Interaction in Nursing and Patient Safety. Nano Energy 2022, 97, 107199.
4. Cheng, Y.; Cai, Z.; Xu, Z.; Sang, X.; Song, C. Smart Sensing Device for Formaldehyde That Based on Uniform Lanthanide CPs Microsphere. J. Mol. Struct. 2023, 1281, 135004.
5. Feng, B.; Feng, Y.; Li, Y.; Su, Y.; Deng, Y.; Wei, J. Synthesis of Mesoporous Ag2O/SnO2 Nanospheres for Selective Sensing of Formaldehyde at a Low Working Temperature. ACS Sens. 2022, 7, 3963–3972.
6. Güntner, A.T.; Schenk, F.M. Environmental Formaldehyde Sensing at Room Temperature by Smartphone-Assisted and Wearable Plasmonic Nanohybrids. Nanoscale 2023, 15, 3967–3977.
7. Ranjitha Mathiarasu, R.; Panneerselvam, K.; Selvaraj, B.; Dharmaraj, S.; Ashokkumar, V.; Show, P.L.; George, M. Chemiresistive La-Doped BaTiO3 Microspheres for Ambient-Temperature Formaldehyde Gas Sensing. Sustain. Energy Technol. Assess. 2022, 53, 102604.
8. Sima, Z.; Song, P.; Wang, Q. Ag Nanoparticles Decorated ZnSnO3 Hollow Cubes for Enhanced Formaldehyde Sensing Performance at Low Temperature. Appl. Surf. Sci. 2023, 614, 156215.
9. Yang, X.-Y.; Shi, Y.-T.; Xie, K.-F.; Wang, J.-Y.; Wang, Y.-F.; Zheng, Y.; Fang, S.-M.; Zhang, Y.-H. Engineering of In-Plane SnO2-Sn3O4 Hierarchical Nanoflower Heterojunctions for Enhanced Formaldehyde Sensing. Appl. Surf. Sci. 2023, 614, 156110.
10. Xiang, H.; Zeng, Y.; Huang, X.; Wang, N.; Cao, X.; Wang, Z.L. From Triboelectric Nanogenerator to Multifunctional Triboelectric Sensors: A Chemical Perspective toward the Interface Optimization and Device Integration. Small 2022, 18, 2107222.
11. Xiang, H.; Yang, J.; Cao, X.; Wang, N. Flexible and Highly Sensitive Triboelectric Nanogenerator with Magnetic Nanocomposites for Cultural Heritage Conservation and Human Motion Monitoring.

Nano Energy 2022, 101, 107570.

12. Zhang, D.; Mi, Q.; Wang, D.; Li, T. MXene/Co3O4 Composite Based Formaldehyde Sensor Driven by ZnO/MXene Nanowire Arrays Piezoelectric Nanogenerator. Sens. Actuators B Chem. 2021, 339, 129923.
13. Wang, D.; Zhang, D.; Chen, X.; Zhang, H.; Tang, M.; Wang, J. Multifunctional Respiration-Driven Triboelectric Nanogenerator for Self-Powered Detection of Formaldehyde in Exhaled Gas and Respiratory Behavior. Nano Energy 2022, 102, 107711.
14. Boomashri, M.; Perumal, P.; Gunavathy, K.V.; Alkallas, F.H.; Trabelsi, A.B.G.; Shkir, M.; AlFaify, S. Detection of Ammonia Gas at Room Temperature through Sb Doped SnO2 Thin Films: Improvement in Sensing Performance of SnO2. Ceram. Int. 2023, 49, 10096–10106.
15. Kumar, S.; John, T.T. Quick Surface Adsorption and Sensing of Ammonia at Room Temperature by In2S3 Thin Films. Appl. Surf. Sci. 2023, 620, 156816.
16. Lakshmi, P.R.; Mohan, B.; Kang, P.; Nanjan, P.; Shanmugaraju, S. Recent Advances in Fluorescence Chemosensors for Ammonia Sensing in the Solution and Vapor Phases. Chem. Commun. 2023, 59, 1728–1743.
17. Lawaniya, S.D.; Meena, N.; Kumar, S.; Yu, Y.-T.; Awasthi, K. Effect of MWCNTs Incorporation into Polypyrrole (PPy) on Ammonia Sensing at Room Temperature. IEEE Sens. J. 2023, 23, 1837–1844.
18. Li, W.; Sun, L.; Liu, C.; Rotaru, A.; Robeyns, K.; Singleton, M.L.; Garcia, Y. Supramolecular FeII4L4 Cage for Fast Ammonia Sensing. J. Mater. Chem. C 2022, 10, 9216–9221.
19. Li, Q.; Sun, M.; Jiang, C.; Song, S.; Li, T.; Xu, M.; Chen, W.; Peng, H. Phosphorus Doping of Graphene for Conductometric Room Temperature Ammonia Sensing. Sens. Actuators B Chem. 2023, 379, 133234.
20. Liu, Y.; Zheng, Y.; Wu, Z.; Zhang, L.; Sun, W.; Li, T.; Wang, D.; Zhou, F. Conductive Elastic Sponge-Based Triboelectric Nanogenerator (TENG) for Effective Random Mechanical Energy Harvesting and Ammonia Sensing. Nano Energy 2021, 79, 105422.
21. Qian, F.; Zhang, B.; Yin, X.; Xu, X.; Li, W.; Chen, S.; Wang, C. Ammonia Sensing Performance of Manganese Vanadate at High Temperature. IEEE Sens. J. 2022, 22, 7599–7607.
22. Singh, S.K.; Shukla, R.K.; Kumar, R.; Tripathi, U.K.; Mishra, S.K. Investigation on PANI/CuO Nanocomposites for Ammonia Gas Sensing Applications. Mater. Lett. 2022, 309, 131325.
23. Wang, X.; Zhou, W.; Wang, Y.; Gong, L.; Liu, X.; Zhou, X. MoO2/Mo Heterostructures for Hydrogen Evolution Reaction and Ammonia Sensing in Self-Powered Mode. Nano Energy 2023, 109, 108253.

24. Xing, X.; Du, L.; Feng, D.; Wang, C.; Tian, Y.; Li, Z.; Liu, H.; Yang, D. Twistable and Tailorable V2O5/PANI/GO Nanocomposites Textile for Wearable Ammonia Sensing. Sens. Actuators B Chem. 2022, 351, 130944.

25. Zakaria, S.A.; Ahmadi, S.H.; Amini, M.H. Alginate/Dye Composite Film-Based Colorimetric Sensor for Ammonia Sensing: Chicken Spoilage. Food Control 2023, 147, 109575.

26. Veeralingam, S.; Badhulika, S. 2 Incorporated Polypropylene/Nylon Fabric-Based Porous, Breathable Triboelectric Nanogenerator as Respiration Sensor and Ammonia Gas Sensor Applications. Sens. Actuators B Chem. 2023, 380, 133346.

27. Sardana, S.; Kaur, H.; Arora, B.; Aswal, D.K.; Mahajan, A. Self-Powered Monitoring of Ammonia Using an MXene/TiO2/Cellulose Nanofiber Heterojunction-Based Sensor Driven by an Electrospun Triboelectric Nanogenerator. ACS Sens. 2022, 7, 312–321.

28. Cai, C.; Mo, J.; Lu, Y.; Zhang, N.; Wu, Z.; Wang, S.; Nie, S. Integration of a Porous Wood-Based Triboelectric Nanogenerator and Gas Sensor for Real-Time Wireless Food-Quality Assessment. Nano Energy 2021, 83, 105833.

29. Zhang, D.; Yang, Y.; Xu, Z.; Wang, D.; Du, C. An Eco-Friendly Gelatin Based Triboelectric Nanogenerator for a Self-Powered PANI Nanorod/NiCo2O4 Nanosphere Ammonia Gas Sensor. J. Mater. Chem. A 2022, 10, 10935–10949.

30. Multifunctional Poly(Vinyl Alcohol)/Ag Nanofibers-Based Triboelectric Nanogenerator for Self-Powered MXene/Tungsten Oxide Nanohybrid NO2 Gas Sensor. Nano Energy 2021, 89, 106410.

31. Yang, Y.; Zhang, D.; Wang, D.; Xu, Z.; Zhang, J. A High-Stability Weighing Paper/Polytetrafluoroethylene-Based Triboelectric Nanogenerator for Self-Powered In2O3 Nanocubes/SnS2 Nanoflower NO2 Gas Sensors. J. Mater. Chem. A 2021, 9, 14495–14506.

32. Majder-Łopatka, M.; Węsierski, T.; Dmochowska, A.; Salamonowicz, Z.; Polańczyk, A. The Influence of Hydrogen on the Indications of the Electrochemical Carbon Monoxide Sensors. Sustainability 2020, 12, 14.

33. Fan, M.; Wu, L.; Hu, Y.; Qu, M.; Yang, S.; Tang, P.; Pan, L.; Wang, H.; Bin, Y. A Highly Stretchable Natural Rubber/Buckypaper/Natural Rubber (NR/N-BP/NR) Sandwich Strain Sensor with Ultrahigh Sensitivity. Adv. Compos. Hybrid Mater. 2021, 4, 1039–1047.

34. Meng, F.; Yang, Z.; Yuan, Z.; Zhang, H.; Zhu, H. Hydrothermal Synthesis of CuO/RGO Nanosheets for Enhanced Gas Sensing Properties of Ethanol. Ceram. Int. 2023, 49, 5595–5603.

35. Paprocki, S.; Qassem, M.; Kyriacou, P.A. Review of Ethanol Intoxication Sensing Technologies and Techniques. Sensors 2022, 22, 6819.

36. Qi, Y.; Kou, D.; Sun, Y.; Hu, T.; Yuan, H.; Zhou, C.; Li, C.; Lu, A.-H.; Wu, S.; Zhang, S. Portable Colorimetric Photonic Indicator for Ethanol Concentration Sensing. Chem. Eng. J. 2023, 457,

141184.

37. Sun, F.; Qi, H.; Xie, Y.; Xu, D.; Shao, H.; Yu, W.; Li, F.; Dong, X. Conjugated Electrospinning-Made Heterostructured TiO2//Bi2WO6 Janus Nanofibers for Ethanol Gas Sensing. Mater. Lett. 2023, 336, 133904.
38. Wang, S.K.; Wang, A.C.; Zhang, C.Y.; Liu, Q.Y.; Cheng, J.D.; Wang, Y.C.; Gao, X.P.; Xie, Q.F.; Zhang, Z.X.; Sun, G.Z.; et al. Sandwich-Structured In2S3/In2O3/In2S3 Hollow Nanofibers as Sensing Materials for Ethanol Detection. ACS Appl. Nano Mater. 2023, 6, 2625–2635.
39. Zhang, J.; Kong, M.; Li, K.; Chen, X.; Li, X.; Yue, L.; Yang, X.; Guan, R.; Zhang, W. Fabrication and Ethanol Sensing Properties of Hierarchical S-Doped In2O3 Networks. Sens. Actuators B Chem. 2023, 376, 132965.
40. Zhang, S.; Song, P.; Sun, J.; Ding, Y.; Wang, Q. MoO3/Ti3C2Tx MXene Nanocomposites with Rapid Response for Enhanced Ethanol-Sensing at a Low Temperature. Sens. Actuators B Chem. 2023, 378, 133216.
41. Li, X.-H.; Jin, Z.; Li, D.; Zhang, H.; Xu, M.-D. Facile Synthesis and Ethanol Sensing Performance of the SnO2 Nanoplates. J. Phys. Conf. Ser. 2022, 2371, 012001.
42. He, W.; Guo, Y.; Zhao, Y.-B.; Jiang, F.; Schmitt, J.; Yue, Y.; Liu, J.; Cao, J.; Wang, J. Self-Supporting Smart Air Filters Based on PZT/PVDF Electrospun Nanofiber Composite Membrane. Chem. Eng. J. 2021, 423, 130247.
43. Shen, D.; Xiao, Y.; Zou, G.; Liu, L.; Wu, A.; Xiao, M.; Feng, J.; Hui, Z.; Duley, W.W.; Zhou, Y.N. Exhaling-Driven Hydroelectric Nanogenerators for Stand-Alone Nonmechanical Breath Analyzing. Adv. Mater. Technol. 2020, 5, 1900819.
44. Ponnamma, D.; Sharma, A.K.; Saharan, P.; Al-Maadeed, M.A.A. Gas Sensing and Power Harvesting Polyvinylidene Fluoride Nanocomposites Containing Hybrid Nanotubes. J. Electron. Mater. 2020, 49, 2677–2687.
45. Jiang, J.; Zhang, Y.; Shen, Q.; Zhu, Q.; Ge, X.; Liu, Y.; Wen, Z.; Sun, X. A Self-Powered Hydrogen Leakage Sensor Based on Impedance Adjustable Windmill-like Triboelectric Nanogenerator. Nano Energy 2021, 89, 106453.
46. Afzal, U.; Afzal, J.; Aslam, M. Analyzing the Imprecise Capacitance and Resistance Data of Humidity Sensors. Sens. Actuators B Chem. 2022, 367, 132092.
47. Arman Kuzubasoglu, B. Recent Studies on the Humidity Sensor: A Mini Review. ACS Appl. Electron. Mater. 2022, 4, 4797–4807.
48. Cuana, R.; Nasution, T.I.; Agusnar, H.; Susilowati, A.; Lubis, N.S.; Pradana, I.S. Humidity Detection Based on Chitosan/PEO Film Sensor. J. Phys. Conf. Ser. 2023, 2421, 012038.

49. Ginja, G.A.; de Campos da Costa, J.P.; Gounella, R.H.; Izquierdo, J.E.E.; Carmo, J.P.; Fonseca, F.J.; Cavallari, M.R.; Junior, O.H.A.; de Souza, S.S. A Humidity Sensor Based on Bacterial Nanocellulose Membrane (BNC). IEEE Sens. J. 2023, 23, 3485–3492.

50. Ma, Z.; Fei, T.; Zhang, T. An Overview: Sensors for Low Humidity Detection. Sens. Actuators B Chem. 2023, 376, 133039.

51. Natashah, F.A.; Sabri, A.A.M.; Alzahrani, H.; Mamat, M.H.; Roslan, N.A.; Bawazeer, T.M.; Alsenany, N.; Alsoufi, M.S.; Supangat, A. Dicarbocyanine-Based Organic Humidity Sensors. Synth. Met. 2023, 293, 117299.

52. Nikulicheva, T.B.; Zakhvalinskii, V.S.; Pilyuk, E.A.; Nikulin, I.S.; Vyazmin, V.V.; Mishunin, M.V. New Humidity Sensor Material (CaSO4·2H2O)0.975-(CuSO4·5H2O)0.025. Materialia 2023, 27, 101662.

53. Pan, S.; Gayathri, G.; Reshma, T.S.; Mangamma, G.; Prasad, A.K.; Das, A. A Sensitive Humidity Sensor at Low Pressure with SnO2 QDs. Sens. Actuators Phys. 2022, 346, 113835.

54. Song, Z.; Li, S.; Hou, B.; Cheng, Z.; Xue, Y.; Chen, B. High-Sensitivity Paper-Based Capacitive Humidity Sensors for Respiratory Monitoring. IEEE Sens. J. 2023, 23, 2291–2302.

55. Sun, C.; Shi, Q.; Hasan, D.; Yazici, M.S.; Zhu, M.; Ma, Y.; Dong, B.; Liu, Y.; Lee, C. Self-Powered Multifunctional Monitoring System Using Hybrid Integrated Triboelectric Nanogenerators and Piezoelectric Microsensors. Nano Energy 2019, 58, 612–623.

56. Wang, D.; Zhang, D.; Li, P.; Yang, Z.; Mi, Q.; Yu, L. Electrospinning of Flexible Poly(Vinyl Alcohol)/MXene Nanofiber-Based Humidity Sensor Self-Powered by Monolayer Molybdenum Diselenide Piezoelectric Nanogenerator. Nano-Micro Lett. 2021, 13, 57.

57. Fan, Y.-J.; Huang, M.-Z.; Hsiao, Y.-C.; Huang, Y.-W.; Deng, C.-Z.; Yeh, C.; Husain, R.A.; Lin, Z.-H. Enhancing the Sensitivity of Portable Biosensors Based on Self-Powered Ion Concentration Polarization and Electrical Kinetic Trapping. Nano Energy 2020, 69, 104407.

58. Bai, X.; Yin, H.; Wang, Z.; Wang, W.; Zhang, C.; Yang, Z. Morphology-Dependent Electrochemical Sensing Properties of NiCo2O4 for Glucose. Nano 2022, 17, 2250088.

59. Dong, L.; Ren, S.; Zhang, X.; Yang, Y.; Wu, Q.; Lei, T. In-Situ Synthesis of Pt Nanoparticles/Reduced Graphene Oxide/Cellulose Nanohybrid for Nonenzymatic Glucose Sensing. Carbohydr. Polym. 2023, 303, 120463.

60. Fan, B.; Spindler, B.D.; Zhao, W.; Chan, H.; Wang, Z.; Kim, M.; Chipangura, Y.; Bühlmann, P.; Stein, A. Comparison of Copper(II) Oxide Nanostructures with Different Morphologies for Nonenzymatic Glucose Sensing. ACS Appl. Nano Mater. 2023, 6, 1475–1486.

61. Gomes, N.O.; Paschoalin, R.T.; Bilatto, S.; Sorigotti, A.R.; Farinas, C.S.; Mattoso, L.H.C.; Machado, S.A.S.; Oliveira, O.N.; Raymundo-Pereira, P.A. Flexible, Bifunctional Sensing Platform

Made with Biodegradable Mats for Detecting Glucose in Urine. ACS Sustain. Chem. Eng. 2023, 11, 2209–2218.

62. Guo, Z.; Fang, B.; Du, X.; Zhao, L.; Li, X.; Cao, Z.; Huang, X.; Sheng, Y.; Zhong, J.; Zhao, G.; et al. Investigation of Glucose Sensing Based on Graphene Conductance. Phys. Status Solidi A 2023, 220, 2200624.
63. Hina, A.; Saadeh, W. A 186 μW Photoplethysmography-Based Noninvasive Glucose Sensing SoC. IEEE Sens. J. 2022, 22, 14185–14195.
64. Silva-Galindo, G.; Zapata-Torres, M. Synthesis and Characterization of TiO2 Thick Films for Glucose Sensing. Biosensors 2022, 12, 973.
65. Yu, L.; Ji, X.; Zhao, X.; Zhang, Y.; Zhu, H. Enhanced Photoelectrochemical and Sensing Performance of TiO2/NiOOH/Ag to Glucose. Appl. Phys. A 2023, 129, 92.
66. Selvarajan, S.; Alluri, N.R.; Chandrasekhar, A.; Kim, S.-J. Unconventional Active Biosensor Made of Piezoelectric BaTiO3 Nanoparticles for Biomolecule Detection. Sens. Actuators B Chem. 2017, 253, 1180–1187.
67. Selvarajan, S.; Alluri, N.R.; Chandrasekhar, A.; Kim, S.-J. Biocompatible Electronic Platform for Monitoring Protein-Drug Interactions with Potential in Future Theranostics. Sens. Actuators B Chem. 2020, 305, 127497.
68. Gao, B.; Wang, X.; Li, T.; Feng, Z.; Wang, C.; Gu, Z. Gecko-Inspired Paper Artificial Skin for Intimate Skin Contact and Multisensing. Adv. Mater. Technol. 2019, 4, 1800392.
69. Zhao, L.; Li, H.; Meng, J.; Wang, A.C.; Tan, P.; Zou, Y.; Yuan, Z.; Lu, J.; Pan, C.; Fan, Y.; et al. Reversible Conversion between Schottky and Ohmic Contacts for Highly Sensitive, Multifunctional Biosensors. Adv. Funct. Mater. 2020, 30, 1907999.
70. Mistewicz, K.; Jesionek, M.; Kim, H.J.; Hajra, S.; Kozioł, M.; Chrobok, Ł.; Wang, X. Nanogenerator for Determination of Acoustic Power in Ultrasonic Reactors. Ultrason. Sonochem. 2021, 78, 105718.
71. Khandelwal, G.; Ediriweera, M.K.; Kumari, N.; Maria Joseph Raj, N.P.; Cho, S.K.; Kim, S.-J. Metal-Amino Acid Nanofibers Based Triboelectric Nanogenerator for Self-Powered Thioacetamide Sensor. ACS Appl. Mater. Interfaces 2021, 13, 18887–18896.
72. Kim, J.-N.; Lee, J.; Lee, H.; Oh, I.-K. Stretchable and Self-Healable Catechol-Chitosan-Diatom Hydrogel for Triboelectric Generator and Self-Powered Tremor Sensor Targeting at Parkinson Disease. Nano Energy 2021, 82, 105705.
73. Abisegapriyan, K.S.; Raj, N.P.; Alluri, N.R.; Chandrasekhar, A.; Kim, S.J. All in One Transitional Flow-Based Integrated Self-Powered Catechol Sensor Using BiFeO3 Nanoparticles. Sens. Actuators B Chem. 2020, 320, 128417.

74. Wang, C.; Wang, P.; Chen, J.; Zhu, L.; Zhang, D.; Wan, Y.; Ai, S. Self-Powered Biosensing System Driven by Triboelectric Nanogenerator for Specific Detection of Gram-Positive Bacteria. Nano Energy 2022, 93, 106828.
75. Zhou, Z.; Wang, P.; Li, J.; Wang, C.; Chen, J.; Zhu, L.; Zhu, H.; Zhang, D. A Self-Powered Microbiosensor System for Specific Bacteria Detection Based on Triboelectric Nanogenerator. Nano Energy 2022, 98, 107317.