Research Article

Toward Battery-Free Sensing: A Comparative Overview of TENG-Based Gas Sensor Mechanisms

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ABSTRACT

Gas sensing is critical for environmental monitoring, industrial safety, and healthcare diagnostics, particularly for detecting hazardous or significant gases like volatile organic compounds (VOCs), ammonia, and formaldehyde [1, 2, 3, 4, 8, 10]. Traditional gas sensors often require external power sources, which can limit their portability and deployment in remote or harsh environments. Self-powered gas sensors, which harvest energy from their surroundings, offer a promising solution to this limitation. Triboelectric nanogenerators (TENGs), devices that convert mechanical energy into electrical energy through the coupling of triboelectrification and electrostatic induction, have emerged as effective power sources and active sensing components for self-powered gas detection systems [20, 24, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40]. This review provides a comparative analysis of the sensing mechanisms employed in TENG-based self-powered gas sensors. It examines how the interaction between target gases and the TENG's materials, or integrated sensing layers, leads to detectable changes in the TENG's electrical output. Key mechanisms discussed include changes in triboelectric properties, modulation of integrated resistive or capacitive sensing layers by the TENG's output, and gas ionization effects. Challenges and future perspectives for the development of highly sensitive, selective, and stable self-powered gas sensors based on TENGs are also addressed.

KEYWORDS

Self-powered sensors, Gas sensing, Triboelectric nanogenerators (TENG), Sensing mechanisms, Comparative review, Nanomaterials, Environmental monitoring, Wearable sensors.

INTRODUCTION

The increasing awareness of air quality issues and the need for real-time monitoring of various gases in diverse settings have driven the demand for advanced gas sensing technologies [2, 3]. Hazardous gases from industrial processes, combustion, or even biological sources pose significant health and environmental risks [5, 8]. Furthermore, the analysis of gases in exhaled breath holds potential for non-invasive disease diagnosis [3, 10].

Conventional gas sensors, such as those based on metal oxides, optical principles, or surface acoustic waves, typically require continuous power supply for operation, which can be a limiting factor for portable, wearable, or wirelessly distributed sensing networks [7, 12, 11, 16]. The development of self-powered sensors that can harvest energy from ambient sources presents a compelling alternative.

Triboelectric nanogenerators (TENGs) have gained significant attention as a versatile technology for converting various forms of mechanical energy, such as vibration, rotation, and contact-separation, into electrical energy [20, 24, 26, 27, 28, 29, 30, 32, 33, 34]. Beyond their energy harvesting capabilities, TENGs can also function as active sensors, where changes in the surrounding environment, including the presence of gases, can directly influence their electrical output [20, 37, 38, 39, 40]. This dual functionality makes TENGs particularly well-suited for self-powered gas sensing applications.

Recent research has demonstrated the feasibility of using TENGs for detecting a variety of gases, including ammonia, formaldehyde, ethanol, and humidity, at room temperature and without external power [6, 31, 35, 36, 9, 21]. This review aims to systematically analyze and compare the different sensing mechanisms employed in these TENG-based self-powered gas sensors, providing insights into their operational principles and potential for further development.

METHODS

This review was conducted by systematically searching and analyzing peer-reviewed scientific literature focusing on self-powered gas sensors utilizing triboelectric nanogenerators (TENGs). Academic databases were the primary source of information, using search terms such as "triboelectric nanogenerator," "TENG," "self-powered," "gas sensor," "sensing mechanism," "ammonia," "formaldehyde," "ethanol," "humidity," and combinations thereof.

The identified studies were screened based on their relevance to TENG-based gas sensing and the clear description of the sensing mechanism involved. Articles focusing solely on TENGs for energy harvesting or on gas sensors requiring external power were generally excluded unless they provided foundational knowledge relevant to the sensing principles.

A thematic analysis approach was employed to categorize and compare the different sensing mechanisms reported in the literature. The identified mechanisms were grouped based on how the presence of the target gas influences the TENG's operation and electrical output. The primary sensing mechanisms identified and analyzed include:

1.   Direct Triboelectric Property Modulation: Mechanisms where the target gas directly interacts with the triboelectric layers of the TENG, altering their surface charge density, dielectric properties, or contact area, thereby changing the triboelectric output [6, 31, 35, 36, 44, 45, 46, 47, 48, 49, 50, 51].

2.   TENG-Driven Resistive Sensing: Mechanisms where the TENG's harvested energy powers a separate resistive gas sensing layer, and the gas concentration is determined by measuring the change in resistance of this layer [9, 41].

3.   TENG-Driven Capacitive Sensing: Mechanisms where the TENG's output is used to power a capacitive sensing element, and the presence of gas alters the dielectric properties of the material between the capacitor plates, leading to a change in capacitance [20].

4.   Gas Ionization/Discharge Effects: Mechanisms where the high voltage generated by the TENG in the presence of certain gases leads to gas ionization or discharge, which can be detected as a change in electrical signal [23].

For each mechanism, the underlying principles, typical materials used, target gases, and reported performance characteristics (e.g., sensitivity, response time, selectivity) were extracted and analyzed. The advantages and limitations of each mechanism for self-powered gas sensing were also considered.
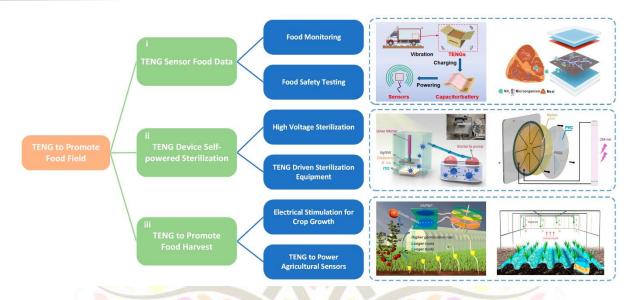
Figure 1. Schematic diagram of three ways in which TENG equipment can be used in the food field. i. TENG-based, self-powered sensor for food quality sensing. ii. TENG-based, self-powered sterilization equipment for food sterilization. iii. TENG-based, self-powered system to promote crop growth.

The gathered information was synthesized to provide a comparative overview of the different sensing approaches. The Results section presents the findings categorized by sensing mechanism. The Discussion section provides a comparative analysis, highlights the strengths and weaknesses of each mechanism, discusses challenges, and outlines future research directions based on the identified themes.

RESULTS

The review of the literature revealed several distinct mechanisms by which TENGs are utilized for self-powered gas sensing.

Direct Triboelectric Property Modulation

In this mechanism, the target gas directly interacts with the triboelectrically active materials of the TENG, altering their surface properties and thus influencing the triboelectric effect. This interaction can involve adsorption of gas molecules onto the surface, leading to changes in surface charge density or work function [6, 31, 35, 36, 44, 45, 46, 47, 48, 49, 50, 51]. For example, materials like poly(dimethylsiloxane) (PDMS) and various polymers are commonly used as triboelectric layers, and their interaction with gases like ammonia or formaldehyde can alter their electron affinity or charge trapping capabilities [6, 31, 35, 36].

The sensing signal in this mechanism is typically a change in the open-circuit voltage (Voc), short-circuit current (Isc), or transferred charge (Qsc)

of the TENG upon exposure to the target gas. The magnitude of this change is proportional to the gas concentration. This approach offers the advantage of a direct sensing mechanism integrated within the energy harvesting unit, potentially simplifying device design. Studies have demonstrated room-temperature sensing of ammonia and formaldehyde using this principle [6, 31, 36]. The use of specific materials like PDMS combined with conductive polymers (e.g., polypyrrole - Ppy) has been explored to enhance sensitivity and selectivity [35]. Surface engineering of the triboelectric layers is a key strategy to improve the performance of sensors based on this mechanism [31, 37, 38].

TENG-Driven Resistive Sensing

This approach utilizes the electrical energy harvested by the TENG to power a separate gas sensing element whose resistance changes upon exposure to the target gas. Metal oxide semiconductors (MOS) are common materials for resistive gas sensors, exhibiting changes in conductivity due to the adsorption and reaction of gas molecules on their surface [7, 15, 18]. Quantum dots have also been explored as resistive sensing materials [14].

In a TENG-driven resistive sensor, the TENG provides the necessary voltage or current to operate the MOS or other resistive sensing layer. The change in resistance of the sensing layer is then measured, often through a simple circuit powered by the TENG. This mechanism allows for the use of well-established and highly sensitive resistive sensing materials. For example, a TENG has been used to power a CuO thin film sensor for formaldehyde detection [9]. This hybrid approach separates the energy harvesting function from the primary sensing mechanism, which can allow for independent optimization of each component. However, it requires integrating two distinct functional units.

TENG-Driven Capacitive Sensing

Similar to resistive sensing, this mechanism employs the TENG to power a capacitive gas sensing element. Capacitive gas sensors operate based on changes in the dielectric properties of a material upon gas adsorption, which alters the capacitance of the sensor [20]. Materials like polymers or metal-organic frameworks (MOFs) can be used as the dielectric layer in capacitive sensors, and their interaction with polar gas molecules or changes in humidity can lead to measurable capacitance changes [17, 20].

The TENG provides the electrical energy to charge the capacitive sensor and measure the capacitance change. This can be achieved by integrating the TENG with circuitry that converts the TENG's output into a suitable signal for capacitance measurement. This mechanism is particularly relevant for detecting gases that significantly influence the dielectric constant of the sensing material, such as humidity [20, 21]. A TENG-based system has been developed for self-powered humidity sensing using a composite film [21].

Gas Ionization/Discharge Effects

This less common but intriguing mechanism leverages the high voltage that can be generated by a TENG, particularly in certain configurations or under specific mechanical excitation. In the presence of certain gases, this high voltage can induce gas ionization or electrical discharge phenomena [23]. The characteristics of this ionization or discharge (e.g., breakdown voltage, current pulses) are dependent on the composition and concentration of the surrounding gas.

The sensing signal is derived from detecting changes in these electrical discharge characteristics. This mechanism has been explored for sensing inert gases, where the TENG's output can ionize the gas, and the resulting current is measured [23]. This approach is distinct in that the gas itself participates in an electrical process driven by the TENG's high voltage output. It may be particularly suitable for detecting gases that are easily ionizable.

DISCUSSION

The comparative analysis of sensing mechanisms in TENG-based self-powered gas sensors highlights the versatility of TENG technology in this application. Each mechanism offers unique advantages and is suited for different types of gas sensing tasks.

Direct triboelectric property modulation provides a compact and potentially simpler device architecture by integrating sensing directly into the energy harvesting component. This mechanism is particularly sensitive to gases that strongly interact with the surface chemistry and electronic properties of the triboelectric materials. However, achieving high selectivity for a specific gas using this mechanism alone can be challenging, as multiple gases might interact with the triboelectric surfaces. Material selection and surface functionalization are critical for tuning the sensitivity and selectivity [31, 37, 38].

TENG-driven resistive and capacitive sensing mechanisms offer the advantage of utilizing well-established and highly sensitive sensing materials and principles. This allows for leveraging existing knowledge and optimizing the sensing layer independently of the TENG's energy harvesting function. The TENG effectively replaces the need for an external power supply, enabling self-powered operation. The challenge lies in efficiently converting the TENG's output into a stable power source for the sensing circuit and integrating the two components effectively. This hybrid approach can potentially offer better selectivity by choosing sensing materials specific to the target gas [9, 20].

The gas ionization/discharge mechanism is a less explored but potentially powerful approach, particularly for gases that are difficult to detect by other means. The high voltage capability of TENGs is uniquely leveraged here. However, controlling and reliably measuring the discharge phenomena can be complex, and the sensitivity and selectivity of this mechanism for a wide range of gases require further investigation [23].

Overall, the choice of sensing mechanism depends on the specific application requirements,

including the target gas, desired sensitivity and selectivity, operating environment, and cost constraints. Future research should focus on improving the sensitivity and selectivity of all these mechanisms. This can involve developing novel triboelectric materials with tailored gas interactions, integrating highly selective sensing layers with TENGs, and optimizing the design of TENGs to enhance their output characteristics for sensing purposes [37, 38, 39, 40].

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Furthermore, the development of TENG-based sensor arrays, combining multiple sensing elements or mechanisms, could lead to electronic nose-like devices capable of detecting and identifying complex gas mixtures [41]. The integration of TENG-based gas sensors into wearable platforms and IoT networks is another promising direction, enabling continuous and distributed environmental monitoring and personal healthcare applications [24, 25, 34, 102].

Addressing challenges related to long-term stability, response time, and recovery time for different gases is also crucial for practical implementation.

CONCLUSION

In conclusion, TENGs offer a compelling pathway towards the development of self-powered gas sensors with diverse sensing mechanisms. Continued research into material science, device design, and integration strategies will be key to unlocking the full potential of TENG-based gas sensing for a wide range of applications, contributing to a healthier and safer environment.

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