

## Review

# Flexible Sensors Based on Carbon-Based Materials and Their Applications

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## Abstract

In recent years, the rapid commercialization and widespread adoption of portable and wearable electronic devices have imposed increasingly stringent performance requirements on flexible sensors, including enhanced sensitivity, stability, response speed, comfort, and integration. This trend has driven extensive research and technological advancement in sensor material systems, among which carbon-based materials have emerged as core candidates for high-performance flexible sensors due to their exceptional electrical conductivity, mechanical flexibility, chemical stability, and highly tunable structural features. Meanwhile, new sensing mechanisms and innovative device architectures continue to emerge, demonstrating significant value in real-time health monitoring, early disease detection, and motion-state analysis, thereby expanding the functional boundaries of flexible sensors in the health-care sector. This review focuses on the application progress and future opportunities of carbon-based materials in flexible sensors, systematically summarizing the critical roles and performance-optimization strategies of carbon nanotubes, graphene, carbon fibers, carbon black, and their derivative composites in various sensing systems, including strain and pressure sensing, physiological electrical signal detection, temperature monitoring, and chemical or environmental sensing. In response to the growing demands of modern health-monitoring technologies, this review also examines the practical applications and challenges of flexible sensors—particularly those based on emerging mechanisms and novel structural designs—in areas such as heart-rate tracking, blood-pressure estimation, respiratory monitoring, sweat-component analysis, and epidermal electrophysiological signal acquisition. By synthesizing the current research landscape, technological pathways, and emerging opportunities of carbon-based materials in flexible sensors, and by evaluating the design principles and practical performance of diverse health-monitoring devices, this review aims to provide meaningful reference insights for researchers and support the continued innovation and practical deployment of next-generation flexible sensing technologies.



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**Keywords:** carbon-based materials; flexible sensors; health monitoring

## 1. Introduction

Today, wearable devices are evolving toward lower power consumption, higher integration, and enhanced intelligence. Among them, the most widely used are those designed for human health monitoring [1,2]. In which flexible sensors are responsible for

receiving external signals and transmitting them to the processor, thereby constituting the most essential hardware foundation of the entire device architecture [3–6].

This article focuses on the application of carbon-based materials in flexible sensors, which is crucial for achieving miniaturization, intelligence, and integration within such devices. In addition, the operating mechanisms of various types of sensors warrant close attention, as they fundamentally determine the sensors' power consumption and overall performance. The deployment of flexible sensors in health-related contexts is also of significant interest. In recent years, numerous wearable devices incorporating flexible sensors have demonstrated notable advancements in health monitoring. Moreover, the transmission of signals between sensors and other devices constitutes an indispensable aspect of sensor operation. In indoor environments, such signal propagation is intimately influenced by the electromagnetic properties of building materials.

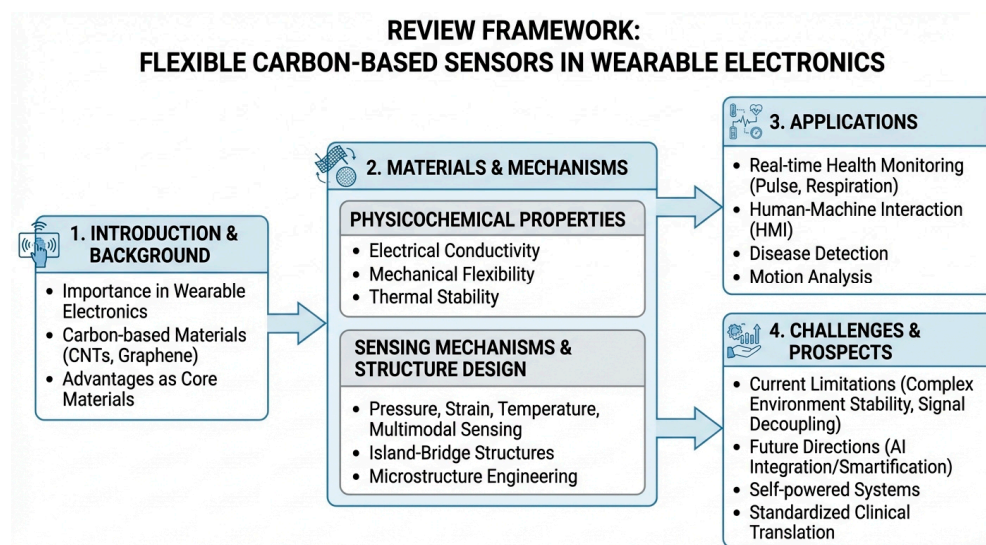
This paper will elaborate on the following aspects:

First, we focus on carbon-based materials used in flexible sensors. Carbon-based materials—represented by graphite and carbon nanotubes—possess suitable flexibility and favorable electrical properties, making them highly appropriate as core components of flexible sensors [7–13]. This section outlines the key performance metrics of carbon-based materials to demonstrate their advantages as fundamental materials for flexible sensing applications.

Second, we turn our attention to the major sensing mechanisms currently in use, including capacitive sensors [14,15], piezoresistive sensors [16–20], triboelectric sensors [1,21], piezocapacitive sensors [22], piezoelectric sensors, and energy-efficient self-powered sensors [23–28]. These categories broadly represent the mainstream mechanisms of contemporary sensors and indicate potential directions for future development.

Meanwhile, flexible sensors have been widely applied across numerous fields, with human health monitoring being the most representative [1,29,30]. This review focuses on the applications of flexible sensors in the health domain, including the monitoring of sleep [2,31], body temperature [32], skin surface pressure [33], breath, limb movements [34,35], DNA [36], and even the detection of viruses and infectious diseases [37]. Meanwhile, a type of skin-conformal flexible sensor known as electronic skin (E-skin) has been applied in most of the aforementioned fields.

This paper will provide a summary and outlook on the aforementioned aspects. The framework structure can be seen in Figure 1.



**Figure 1.** Framework figure.

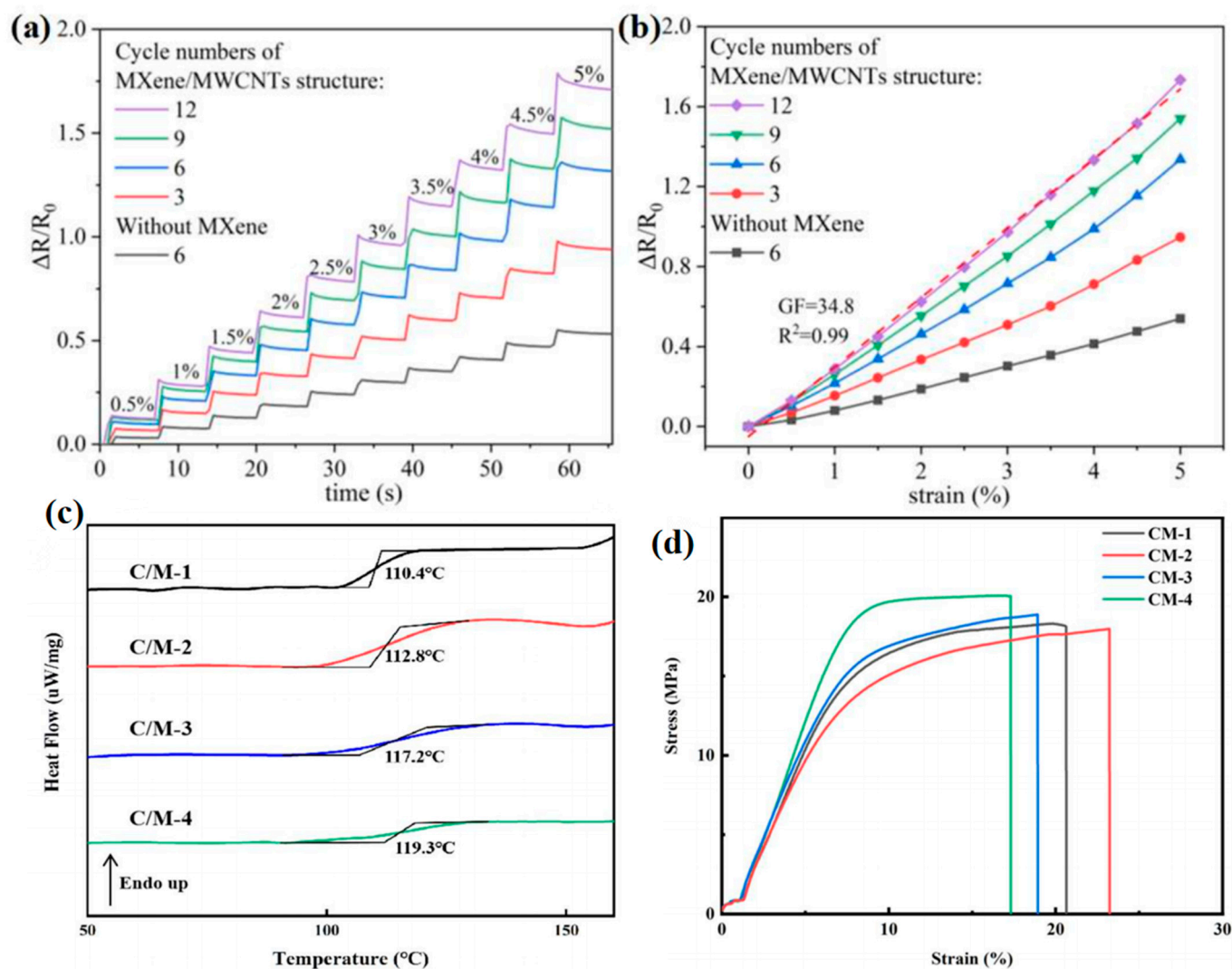
## 2. Application and Development of Carbon-Based Materials in Flexible Sensors

### 2.1. The Development and Applications of Carbon Nanotube Structures

Carbon nanotubes significantly enhance flexible strain sensor performance due to their unique structural attributes. Their high aspect ratio enables superior electrical conductivity and mechanical flexibility, while their nanoscale dimensions facilitate sensitive strain detection [38]. These properties make carbon nanotubes ideal for developing advanced strain sensors in flexible electronics [39–43].

Although carbon-based materials such as carbon nanotubes have attracted considerable attention due to their exceptional electrical conductivity and mechanical flexibility, their single-component forms often struggle to simultaneously achieve high sensitivity and a broad detection range [44,45]. To address this limitation, some researchers have focused on constructing composite microstructures combining carbon nanotubes with materials such as MXenes. By establishing an “island-bridge” sliding conductive network, these composites can substantially enhance the overall performance of the sensors [46]. An MXene/MWCNT composite structure can be constructed via a self-assembly approach, wherein MXene functions as the “islands” enveloped and interconnected by dense MWCNT “bridges,” forming a distinctive sliding conductive network. This architecture endows the sensor with exceptional performance: under small strains, micro-sliding within the network induces stable resistance changes, while under large strains (20–40%), separation of the bridges leads to a sharp increase in resistance. Consequently, the sensor achieves ultrahigh sensitivity over a wide strain range of up to 40% (with a gauge factor, GF, reaching 646), along with rapid response (280 ms) and excellent stability over 1800 cycles [46]. The MXene (“island”) and multi-walled carbon nanotube (MWCNT, “bridge”) self-assembled sliding network developed in this study operates based on a synergistic mechanism that is key to overcoming performance limitations. Under small strains, the network undergoes reversible sliding, enabling stable responses. In contrast, under large strains (20–40%), the separation of MWCNT bridges and the sharp reduction in contact between the MXene “islands” collectively trigger a sudden change in conductivity. This results in a strain gauge factor (GF) of up to 646 over an exceptionally wide detection range (0.05–40%). This design cleverly balances sensitivity and measurement range, providing a reliable sensing solution for precise capture of full-scale human signals, from micro-pulse (0.05%) to large joint bending (40%) [46]. Carbon nanotubes (CNTs), functioning as one-dimensional fillers with diameters of approximately 10–20 nm, form hybrid filler systems when combined with two-dimensional MXene. This architecture also exerts a pronounced influence on the macroscopic electromagnetic properties of the material: The CNTs serve as interconnects between MXene nanosheets, enabling the construction of a three-dimensional conductive network that significantly enhances the mechanical properties of the composite (e.g., a tensile strength of 20.0 MPa for C/M-4) as well as its electromagnetic shielding effectiveness (reaching up to 10.6 dB) [47]. The results can be seen in Figure 2.

Overall, carbon nanotubes [48,49], through self-assembly, form flexible conductive networks that combine high sensitivity with a wide strain range, providing an ideal sensing platform for intelligent health monitoring. Due to their high aspect ratio and fibrous structure, one-dimensional carbon nanotubes easily form flexible conductive networks, exhibiting excellent electrical conductivity ( $10^7$  S/m) and mechanical strength. This allows flexible sensors to maintain even higher responsiveness ( $GF > 1000$ ) while operating stably over a wide temperature range from  $-196$  °C to  $300$  °C and in corrosive environments [48].



**Figure 2.** (a,b) show the response and sensitivity under gradually increasing micro-strain of 0–5%. (c) shows the DSC curves of composites with increasing MXene content Reproduced from [47], MDPI, 2025. (d) shows the stress–strain curves of composites with increasing MXene content Reproduced from [47], MDPI, 2025.

Meanwhile, carbon nanotubes (CNTs), as one-dimensional nanomaterials [49], are generally classified into single-walled carbon nanotubes (SWCNTs) and multi-walled carbon nanotubes (MWCNTs). Their synthesis and functionalization are often coupled with cyclodextrins (CDs). For instance, pyrene-modified cyclodextrins (pyrene-CDs) can be assembled onto SWCNTs through noncovalent interactions, while aminated cyclodextrins can be covalently grafted onto SWCNT surfaces pre-functionalized with 3,4,9,10-perylenetetracarboxylic acid (PTCA). These composite systems are frequently employed for electrode modification, where the incorporation of CNTs markedly enhances electron-transfer performance—for example, functionalizing carbon electrodes with SWCNTs prior to gold nanoparticle deposition to improve conductivity. In the context of flexible sensors, CNTs serve as excellent conductive substrates or nanocomposite components due to their high electrical conductivity and large specific surface area. When combined with cyclodextrins, CNT-based composites exhibit improved electron-transport efficiency and greater adsorption capacity toward target molecules [49]. This synergistic enhancement provides a highly sensitive sensing platform for detecting phenolic compounds, pharmaceuticals, and other organic analytes.

Carbon black (CB) features a hierarchical structure composed of spherical primary particles that form complex, branched aggregates. These aggregates provide a high surface-area-to-volume ratio and exceptional electrical conductivity, which are essential sensing parameters. The primary advantages of CB as a sensor material include its ability to facilitate rapid electron transfer and increase the electroactive surface area, thereby significantly enhancing sensitivity and lowering detection limits for analytes like Sunset Yellow. Furthermore, CB is more cost-effective and chemically stable than other carbon nanomaterials like graphene, making it a highly practical choice for developing robust and affordable electrochemical sensors.

## 2.2. Performance and Applications of Graphene-Based Carbon Materials in Flexible Sensors

Graphene's unique structure and exceptional properties make it a promising material for advancing flexible sensors in applications like electronic skin and health monitoring [50].

Some researchers have developed noble-metal nanoparticle/graphene composite structures by anchoring Pd, Pt, and other nanoparticles—precisely controlled at the nanometer scale—onto graphene surfaces via solution-based methods [7]. Experimental results show that Pd nanocube/graphene sensors achieve a hydrogen detection range of 10–10,000 ppm with a response time of approximately 30 s, while Pt/Pd core-shell/graphene structures exhibit a response of 36% to 1% hydrogen at room temperature. This architecture leverages the catalytic activity of noble metals (e.g., Pd facilitating hydrogen molecule dissociation) together with the high electrical conductivity of graphene (carrier mobility  $> 10,000 \text{ cm}^2/\text{V}\cdot\text{s}$ ) and its ultrahigh specific surface area (theoretical value of  $2630 \text{ m}^2/\text{g}$ ), generating a synergistic effect that enables high-sensitivity detection without compromising material flexibility. Consequently, the composite structure allows flexible gas sensors to achieve high sensitivity at room temperature (detection limit down to  $0.025\% \text{ H}_2$ ), rapid response ( $\sim 30 \text{ s}$ ), and excellent stability ( $> 1000$  cycles), thereby providing a material foundation for the development of low-power, wearable hydrogen-monitoring devices [7].

Graphene oxide (GO) has also been widely utilized in flexible sensing applications. As a representative two-dimensional material with a single-layer thickness of approximately 1 nm, GO possesses abundant oxygen-containing functional groups—such as hydroxyl and epoxy groups—that serve as effective adsorption sites for water molecules [51]. GO synthesized via a modified Hummers method and subsequently subjected to partial deoxygenation in a KOH alkaline solution can achieve moderately enhanced electrical conductivity while maintaining a high density of oxygen functionalities. In terms of sensing performance, this material exhibits high sensitivity and rapid response–recovery behavior within a relative humidity range of 15–70%, with a recovery time of approximately 40 s. Its resistance decreases markedly as humidity increases. Moreover, the intrinsic flexibility, low density, and biocompatibility of GO allow it to be easily integrated with flexible substrates (e.g., polyester) through simple deposition techniques such as drop-casting, thereby providing a crucial material foundation for the development of wearable humidity sensors [51]. Beyond graphene oxide, additional material possibilities have been explored. Using commercial silk as a substrate, a simple dipping process followed by thermal reduction at  $400^\circ\text{C}$  yields a reduced-graphene-oxide-coated silk (rGOS) material. This composite preserves the woven structure of natural silk (with a single-layer thickness of approximately  $349.6 \mu\text{m}$ ) while gaining excellent electrical conductivity through the uniform rGO coating. A seven-layer pressure sensor fabricated from this material achieves a high sensitivity of  $2.58 \times 10^3 \text{ kPa}^{-1}$  in the low-pressure regime ( $0.2\text{--}72.3 \text{ kPa}$ ). Additionally, strain sensors constructed from rGOS yarn exhibit a gauge factor of 0.307, demonstrating notable flexibility and strong capability for detecting human motion [52].

### 3. Mechanisms and Performance of Carbon-Based Flexible Sensors

#### 3.1. Mechanisms and Performance of Common Flexible Sensors

This section provides an overview of commonly employed sensing mechanisms, focusing primarily on capacitive and piezoelectric sensors, along with their corresponding performance metrics.

The carbon-based material foundations of capacitive flexible sensors primarily consist of composites formed by conductive fillers—such as carbon nanotubes and graphene—and polymer matrices including PDMS or silicone rubber [53,54]. Their high electrical conductivity and tunable dielectric properties provide essential material support for sensor performance optimization. The operating principle follows the parallel-plate capacitor model: under applied pressure, the compression of the dielectric layer and the corresponding changes in the internal conductive network of the composite jointly increase the effective dielectric constant, thereby converting mechanical stimuli into variations in capacitance [14,15]. In terms of performance metrics, carefully engineered dielectric-layer architectures can significantly enhance overall sensing performance. Studies have shown that employing a composite dielectric configuration combining double-sided hemispherical microstructures with an internal porous structure enables sensitivities as high as  $3.15 \text{ kPa}^{-1}$  across a wide pressure range of 0–200 kPa, with a minimum detectable pressure of 27 Pa. The sensor also exhibits response and recovery times of 120 ms and maintains stable output during continuous testing at 1.5 kPa for 2500 s. Other work has focused on tailoring the morphology of CNT fillers, demonstrating that CNTs with aspect ratios of 1250–3750 at a loading of 3.75 wt.% can raise the relative permittivity of the composite dielectric from 13.3 (unloaded) to 198.92 under 35 kPa, representing a 14.95-fold increase. This enhancement enables a high sensitivity of  $2.90 \text{ kPa}^{-1}$  in the low-pressure range of 0–450 Pa. The underlying mechanism of this performance improvement lies in the synergy between structural and material effects: microstructured surfaces enlarge the initial deformation space, while porous networks allow continued deformation under higher pressures. Simultaneously, CNT redistribution under compression and strengthened interfacial polarization amplify the pressure responsiveness of the dielectric constant. Together, these mechanisms produce a dual enhancement arising from both structural deformation and intrinsic material characteristics. As a result, such capacitive sensors exhibit unique advantages in flexible electronics and health-monitoring applications requiring high-precision pressure detection [14,15].

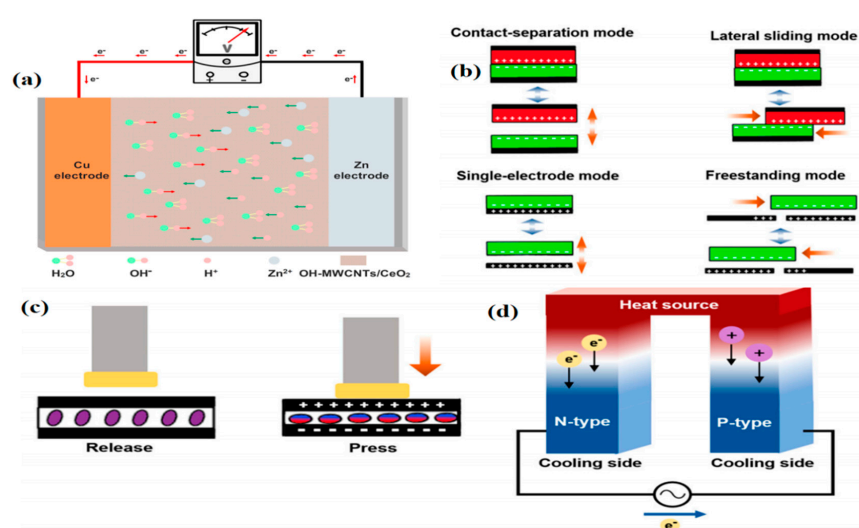
Piezoelectric sensors, on the other hand, employ the piezoelectric effect of materials such as poly-L-lactic acid (PLLA) or poly(vinylidene fluoride) (PVDF) to convert mechanical deformation directly into electrical signals. Their fundamental mechanism is based on the generation of charge separation in non-centrosymmetric crystals or polar polymer chains when subjected to external stress. Such sensors offer high sensitivity (e.g., PLLA-based braided fibers achieving >95% accuracy in detecting bruxism), rapid response (PVDF-based sensors with response times as short as 31 ms), and self-powered operation. These advantages make piezoelectric sensors highly promising in wearable health monitoring and biomedical applications [23,24].

In addition, piezoresistive sensors also present notable application advantages [16–18]. Piezoresistive sensors operate by detecting external pressure through changes in electrical resistance. Their core mechanism involves uniformly dispersing carbon-based conductive fillers—such as multi-walled carbon nanotubes (MWCNTs)—within a flexible polymer matrix (e.g., PDMS) to form a conductive network. When external pressure is applied, the inter-filler distance decreases, leading to a pronounced reduction in resistance due to the quantum tunneling effect [17].

### 3.2. New Designs and Mechanisms of Flexible Sensors

As academic and commercial sectors impose increasingly stringent requirements on the power consumption of wearable devices, self-powered sensors have emerged as an important technological direction. The following section introduces the mechanisms, performance metrics, and advantages of these categories.

The performance enhancement of self-powered sensors is closely tied to the critical role of carbon-based materials (e.g., carbon nanotubes), whose high electrical conductivity and tunable surface properties provide the foundation for efficient energy conversion and signal amplification. These sensors harvest and convert ambient energy through various mechanisms, including electrochemical, triboelectric, piezoelectric, and thermoelectric processes [25,27]. In electrochemical systems, humidity can trigger redox reactions that generate electrical power. For example, a humidity sensor based on hydroxylated MWCNT-modified  $\text{CeO}_2$  can output 0.711 V and  $0.376 \mu\text{W}$  at 91.5% relative humidity, with response and recovery times of 18.6 s and 6.9 s, respectively [28]. Triboelectric mechanisms rely on charge generation during contact–separation events; CNT–PDMS composite foams, for instance, produce a linear decrease in output current from  $2.9 \mu\text{A}$  to  $1.6 \mu\text{A}$  as humidity increases from 30% to 80%. Piezoelectric systems generate electric potential under mechanical deformation, as demonstrated by CNT/ $\text{BaTiO}_3$ /PVDF-TrFE composite sensors that deliver voltages up to 5.2 V under stress and have been successfully applied to fluoride ion detection with a limit of  $2.9 \mu\text{M}$ . Thermoelectric mechanisms utilize the Seebeck effect, and CNT–epoxy composites can produce measurable voltages even when the temperature gradient is less than  $1^\circ\text{C}$  [27]. These self-powered sensors offer significant advantages in environmental and biomedical monitoring: they enable long-term, continuous operation without external power sources, supporting applications such as respiratory monitoring, ocean wave detection, and human motion sensing. Some devices can even drive low-power electronics; for example, connecting three sensors in series allows charging a capacitor to 2.2 V, sufficient to light an LED. Therefore, self-powered sensors not only enhance the energy autonomy and integration of sensing systems but also provide robust technological support for practical applications in the Internet of Things, smart wearables, and implantable medical devices [27,55]. The sensing mechanisms described above can be seen in Figure 3. Table 1 shows some principles and key points of 3 basic different mechanisms.



**Figure 3.** (a) shows the mechanism of the humidity sensor based on hydroxylated multi-walled carbon nanotube-modified  $\text{CeO}_2$ . Reproduced from [28], MDPI, 2025. (b–d), respectively, illustrate the working mechanisms of triboelectric, piezoelectric, and thermoelectric sensors. Reproduced from [27], MDPI, 2025.

**Table 1.** Some principles and key points of 3 basic different mechanisms.

| Sensing Mechanism                  | Core Principle and Materials                                        | Key Performance Highlights                                                                     |
|------------------------------------|---------------------------------------------------------------------|------------------------------------------------------------------------------------------------|
| Capacitive and Piezoresistive      | Displacement or tunneling effect in CNT/Graphene-polymer composites | High sensitivity ( $3.15 \text{ kPa}^{-1}$ ), low detection limit (27 Pa), and high stability. |
| Piezoelectric and Triboelectric    | Mechanical-to-electrical conversion via PVDF, PLLA, or CNT foams    | Self-powered, ultra-fast response (31 ms), and high accuracy (>95%).                           |
| Electrochemical and Thermoelectric | Redox reactions or Seebeck effect using modified MWCNTs/hybrids     | High energy autonomy (0.711 V output) and sub-degree (<1 °C) thermal resolution.               |

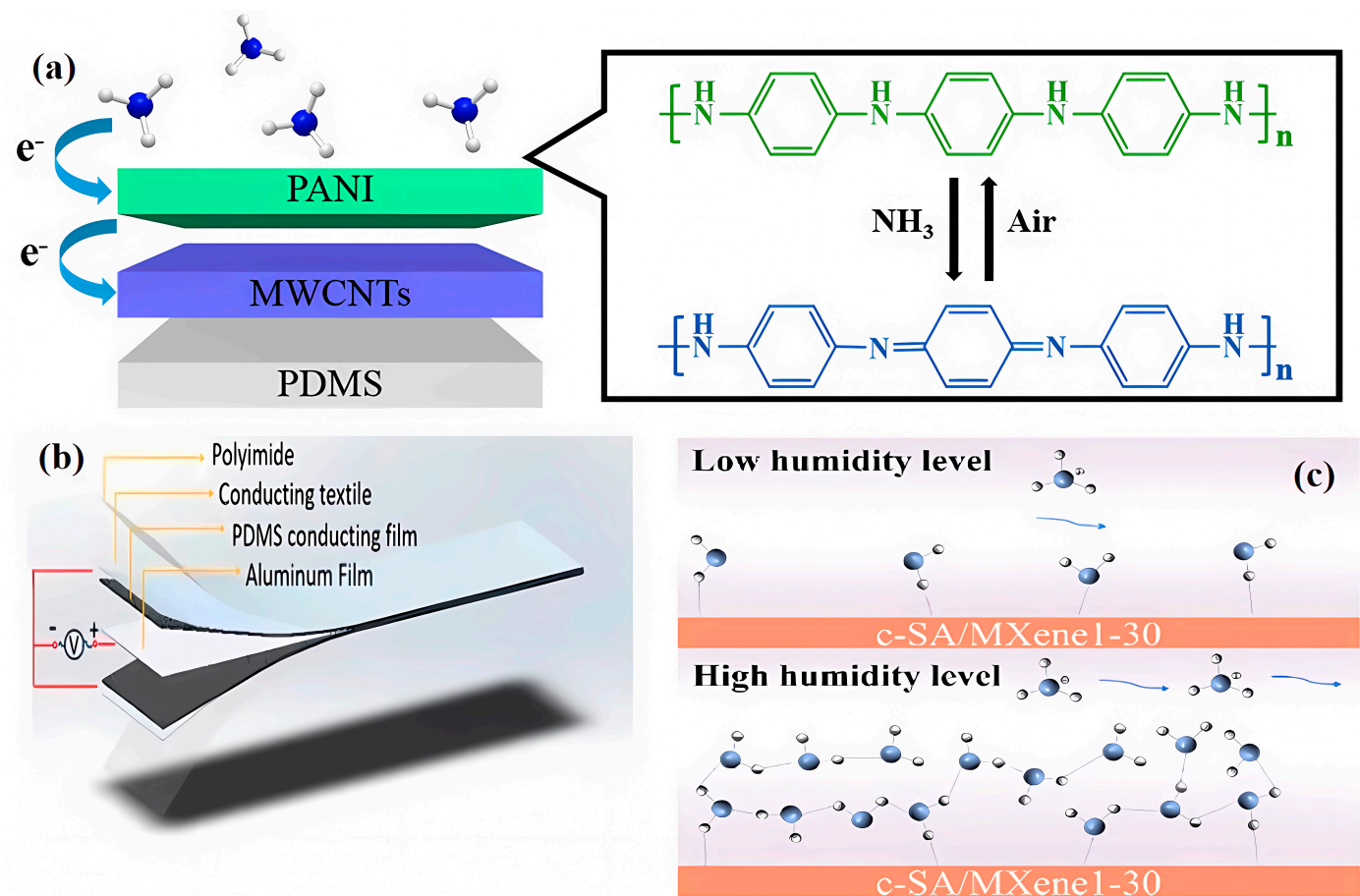
## 4. Applications and Developments of Carbon-Based Material Sensors in the Health Sector

### 4.1. Sensor Applications in the Monitoring of Fundamental Physiological Parameters

Fundamental physiological parameters include body temperature, skin pressure, blood pressure, and various indicators associated with sleep and respiration. This section presents the applications and advancements of carbon-based flexible sensors in monitoring these physiological parameters.

The discussion begins with sensor applications in human sleep monitoring. Flexible sensors used for sleep monitoring operate by converting subtle physiological activities during sleep into quantifiable electrical signals, and carbon-based materials, with their excellent electrical conductivity, mechanical flexibility, and skin conformity, play a particularly important role in this scenario [24,31]. Their working mechanisms mainly rely on the efficient transduction of minute mechanical stimuli: triboelectric (TENG) devices generate charge transfer through the periodic contact–separation of two materials, enabling simultaneous detection of body movements, breathing rhythms and turning events during sleep; piezoelectric (PENG) sensors output electrical signals through polarization changes under periodic micro-pressure, allowing the recording of eye movements, facial micro-motions and even slight pharyngeal vibrations. In terms of performance, the key lies in the precise differentiation of physiological signals and the suppression of noise. For example, TENG-based wearable systems can clearly distinguish the inhalation ( $\approx 2 \text{ s}$ ) and exhalation ( $\approx 5 \text{ s}$ ) phases of respiration, and they can resolve arterial and venous peaks in heartbeat waveforms separated by only about 0.12 s, a level of temporal precision essential for apnea detection and heart-rate-variability analysis [2]. Meanwhile, maintaining long-term wearing comfort, signal stability, and resistance to motion artifacts—such as turning, pillow pressure changes, or environmental vibrations—remains a major challenge. Carbon-based materials (e.g., CNTs, graphene, MXene) provide an ideal material platform for constructing thin, lightweight sensor units that adapt to skin deformation while offering high signal-to-noise conductive pathways, granting them broad potential in future high-precision sleep-monitoring systems, including smart mattresses, smart bedding, and facial micro-motion detection [2]. Complementing sleep monitoring is the assessment of respiratory activity. Carbon-based flexible sensors play an important role in respiratory monitoring by detecting specific exhaled gases (such as  $\text{NH}_3$ ) or humidity variations [56,57]. Their operating mechanisms vary across material systems: for instance, PANI-MWCNTs/PDMS sensors rely on the dedoping reaction between  $\text{NH}_3$  and polyaniline, coupled with  $\pi$ – $\pi$  conjugation interactions with carbon nanotubes, achieving a response of 11.8 toward 40 ppm  $\text{NH}_3$  and a detection limit as low as 10 ppb. Meanwhile, SA/MXene sensors exploit the high surface area of MXene and the hydrophilic functional groups of sodium alginate to adsorb water molecules, leading to pronounced ionic conductivity changes; they exhibit an

impedance variation of two orders of magnitude across 10–90% RH, response and recovery times of 4 s and 11 s, respectively, and maintain stable performance for 24 h even at 98% RH. Despite these advances, significant challenges remain, including performance degradation under high humidity, complex interfering species present in real exhaled breath, and the need for long-term wearability, stability, and user comfort [56,57]. The mechanisms of these sensors can be seen in Figure 4. Table 2 shows some physiological parameters and their performance.



**Figure 4.** (a) shows the gas sensing mechanism of PANI-MWCNTs/PDMS sensor. Reproduced from [57], MDPI, 2023. (b) shows the structure of TENG belt. Reproduced from [2], MDPI, 2024. (c) the diagram of the proposed mechanism of SA/MXene–based sensor. Reproduced from [56], MDPI, 2024.

**Table 2.** Some physiological parameters and their performance.

| Physiological Parameter | Key Materials and Mechanisms           | Application and Performance Highlights                                                    |
|-------------------------|----------------------------------------|-------------------------------------------------------------------------------------------|
| Sleep Monitoring        | TENG/PENG (CNTs, Graphene, MXene)      | Detects eye/facial micro-motions and pharyngeal vibrations with high conformity.          |
| Respiratory Activity    | PANI-MWCNTs (Gas); SA/MXene (Humidity) | Resolves $NH_3$ (10 ppb LOD) and humidity (10–90% RH) with rapid 4 s response.            |
| Vital Signs and Motion  | High-precision TENG/Carbon-composites  | Resolves heartbeat peaks (0.12 s interval) for heart-rate-variability and apnea analysis. |

In the domain of body-temperature and skin-surface pressure monitoring, flexible sensors have achieved remarkable progress in recent years [58,59]. Temperature-sensing

devices typically rely on thermoresistive or thermoelectric mechanisms, employing carbon-based materials such as CNT/graphene composites with a temperature coefficient of resistance of  $-0.17\%$  per  $^{\circ}\text{C}$ , or graphene-nanowall/PDMS systems with coefficients reaching  $0.214$  per  $^{\circ}\text{C}$ , enabling highly accurate detection across a broad temperature range from  $12.5^{\circ}\text{C}$  to  $93.7^{\circ}\text{C}$ . Pressure sensing is mainly realized through piezoresistive, capacitive, or piezoelectric transduction. For instance, a TPU/EMIM/boron-nitride ion-gel-based piezoresistive sensor exhibits an ultrahigh sensitivity of  $804.27\text{ kPa}^{-1}$ , a rapid response time of  $17\text{ ms}$ , and a detection limit extending up to  $50\text{ kPa}$  [32,60]; meanwhile, graphene field-effect transistor arrays incorporating an air-gap dielectric layer can operate across an exceptionally wide range from  $250\text{ Pa}$  to  $3\text{ MPa}$  [32]. Carbon-based materials, due to their superior electrical conductivity, tunable microstructure, and biocompatibility, serve as key components in both electrodes and active sensing layers. Nevertheless, challenges remain in balancing sensitivity and detection range, suppressing interference from coupled multi-physical stimuli, and ensuring long-term wearability, stability, and comfort. These aspects define critical development directions for next-generation electronic skin and wearable biomedical devices [32,61].

#### 4.2. Detection of Non-Traditional Physiological Parameters

Post-COVID-19, carbon-based flexible sensors have attracted escalating attention for DNA and viral pathogen detection.

These platforms exhibit pronounced advantages in nucleic-acid assays, as corroborated by the following quantitative metrics [36,62]. Sensitivity is exemplified by a carbon-black/poly(azure A) architecture that furnishes a limit of detection (LOD) of  $0.03\text{ pM}$  for doxorubicin, with a linear dynamic range spanning  $0.1\text{ pM}$ – $100\text{ nM}$  (eight orders of magnitude). Inter-sensor reproducibility is evidenced by a relative standard deviation (RSD) of  $4.5\%$  at  $1.0\text{ nM}$  analyte. Economical fabrication is enabled by single-use screen-printed carbon electrodes that streamline manufacturing and minimize per-test expenditure. Operational robustness is demonstrated by  $\geq 30$ -day stability at  $4^{\circ}\text{C}$  and reliable quantification in minimally pretreated biofluids (e.g., 5-fold-diluted urine or serum), underscoring superior anti-interference capacity [62]. These performance indices collectively substantiate the translational potential of carbon-based flexible sensors for rapid clinical diagnostics and therapeutic-drug monitoring [50].

Flexible biosensors transduce viral signatures via the selective recognition of pathogen-specific moieties—nucleic acids or proteins—into quantifiable electronic readouts [37]. Representative performance benchmarks include an electrochemical DNA sensor exploiting nucleic-acid hybridization that attains a limit of detection (LOD) of  $200\text{ copies mL}^{-1}$  for SARS-CoV-2 RNA with a diagnostic sensitivity of  $85.5\%$  and a molecularly imprinted polymer (MIP)-based platform that furnishes an LOD of  $15\text{ fM}$  for the SARS-CoV-2 nucleocapsid (N) protein. These architectures concurrently offer high sensitivity, rapid kinetics ( $<30\text{ s}$  for reactive oxygen species, ROS), and mechanical conformability, rendering them ideally suited for point-of-care deployment. Notwithstanding, their analytical robustness is undermined by matrix effects in complex clinical specimens, limited long-term operational stability, and unresolved challenges in scalable manufacturing and assay standardization [37].

## 5. Conclusions and Challenges

Carbon-based materials, including carbon nanotubes, graphene, and their diverse composite systems, have established themselves as the essential hardware foundation for high-performance flexible sensors due to their exceptional electrical conductivity, mechanical flexibility, and structural tunability. Recent advancements in microstructural engineering and the emergence of innovative sensing mechanisms, such as triboelectric and piezoelec-

tric transduction, have significantly enhanced sensitivity, response speeds, and operational stability. These breakthroughs have enabled the transition of flexible sensors from simple laboratory prototypes to sophisticated platforms capable of real-time health monitoring, sleep analysis, and the detection of viral pathogens with high diagnostic sensitivity.

However, a significant “miss” in nowadays research remains the lack of long-term operational robustness and signal reliability under the complex, multi-stimuli environments of daily life. While laboratory results show high sensitivity, many current devices struggle to maintain signal stability when exposed to sweat, humidity, and the mechanical fatigue of thousands of cycles. Furthermore, research has yet to fully solve the problem of signal cross-talk in multi-parameter sensing; current sensors often fail to differentiate between simultaneous mechanical and thermal inputs without relying on heavy external data processing. Additionally, the gap between high-performance single-unit sensors and the scalable, low-cost manufacturing of high-density integrated arrays remains a major barrier to the practical commercialization of electronic skin and wearable medical devices.

Looking ahead, future research should aim for the development of fully integrated, intelligent sensing systems that move beyond simple signal acquisition. The outlook for the field lies in the convergence of carbon-based sensing units with “sense-and-process” architectures, where AI-driven calibration and on-site signal processing can suppress interference and improve diagnostic accuracy in complex biofluids. Research must also prioritize energy autonomy by optimizing self-powered mechanisms, such as harvesting ambient energy via thermoelectric or triboelectric processes, to support continuous monitoring in the Internet of Things and implantable electronics. Ultimately, the next generation of flexible sensors must focus on sustainable material platforms and universal testing standards to ensure both environmental compatibility and reliable clinical translation in the global healthcare sector.

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