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Wearable biosensors incorporating nanocomposites: Advancements, applications, and future directions

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ABSTRACT

Wearable sensors have emerged as transformative tools, enabling real-time monitoring of human health and activities. Within this field, miniaturized and flexible devices have attracted significant attention due to their compact size, ease of use, and non-invasive operation. These sensors function by detecting biological activities and converting bio-signals such as electrophysiological, mechanical, and biochemical information into quantifiable data. Such data can be obtained through various sensing approaches, including the detection of electrolytes, ions, and gases. In many cases, wearable sensors are fabricated by integrating the sensing element into a polymer matrix, with nanomaterials playing a particularly important role in enhancing performance. Health monitoring remains the primary application area for these devices. Emerging technologies, including AI-assisted sensing and cloud-based data processing, are expected to drive future advancements, while also introducing challenges related to data privacy. Looking ahead, key areas of development for nanomaterial-based wearable sensors include non-contact monitoring, textile-integrated devices, and improvements in security and regulatory frameworks.

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1. Introduction

Recent advances in wearable technologies have focused on the development of miniaturized and compact sensors capable of tracking various physiological and biochemical parameters [1-3]. These wearable devices serve dual purposes, including diagnostics and continuous monitoring across multiple domains. Their current capabilities include detecting physiological signals, biochemical markers, and motion-related data [4]. These sensors are central to health monitoring, environmental tracking, and fitness management [5].

A wearable sensor should be small, light, and as unobtrusive as possible [6]. Moreover, they must exhibit high stretchability, exceptional sensitivity, and long-term durability without any degradation in performance to operate with consistent reliability in practical use, particularly as wearable strain sensors [7]. The ongoing miniaturization of these devices not only boosts user comfort but also facilitates seamless integration into daily life. Despite the progress, most existing diagnostic tools remain non-wearable and reliant on invasive methods like blood draws and conventional bench-top assays. This situation conveys a critical challenge in the field, which is the need for wearable sensors to develop beyond basic health monitoring and to reliably and continuously detect clinically relevant physiological events in real time [1].

Emerging use cases include non-invasively confirming fetal health through motion detection in the womb, distinguishing epileptic seizures from vigorous activity, warning of dehydration in athletes or workers, tracking individual glucose responses to food, and even monitoring and controlling the spread of infectious diseases before symptoms arise. Addressing these challenges requires sensors that are not only miniaturized and durable but also capable of collecting multimodal or multiplexed data continuously and in real time [1].

Next-generation wearable sensors designed for simultaneous physical and biochemical analysis have the potential to develop diagnostics. They could enable high-resolution, time-stamped health data collection, empowering individuals and clinicians alike with real-time insights into personal health [8].

A notable innovation driving this miniaturization and performance enhancement in biosensors is the incorporation of nanocomposites, advanced materials possessing exceptional mechanical, electrical, and chemical properties [9]. These nanocomposites markedly enhance sensor sensitivity, flexibility, and durability, making them highly suitable for next-generation wearable platforms [10, 11].

As such, this review explores recent advancements in miniaturized and wearable biosensors incorporating nanocomposite materials, with a focus on their wide-ranging applications and future directions.

2. Fundamentals of biosensors

2.1. Definition and types of biosensors

A sensor is an analytical device that detects physical quantities and converts them into readable and measurable signals. It is often used to identify analytes such as metal ions, electrolytes, or bioactive compounds. A biosensor, on the other hand, is a specialized type of sensor that incorporates a biological element such as an enzyme, antibody, or nucleic acid combined with a physicochemical detector to specifically analyze biological molecules or processes [12].

Biosensors are classified based on the designated sensing mechanism, including pressure, strain, electrochemical, optoelectronic, and temperature-based sensors, among others [13]. Additionally, depending on their application, they fall into three categories: (a) in vitro diagnostic biosensors, which analyze samples such as blood, saliva, or urine [14]; (b) continuous monitoring biosensors (CMBs), which provide real-time data collection over extended periods [15, 16]; and (c) wearable biosensors, designed for non-invasive, on-the-go health monitoring [17, 18].

Recent advancements have introduced innovative technologies, including clustered regularly interspaced short palindromic repeats (CRISPR) and CRISPR associated proteins (Cas) biosensing platforms, improved lateral flow assays, and miniaturized formats such as microfluidic and paper-based analytical devices [15].

2.2. Key components of biosensors

Key components of a biosensor are the biorecognition element, the transducer, and the signal processing unit as can be seen from Fig. 1 [19].

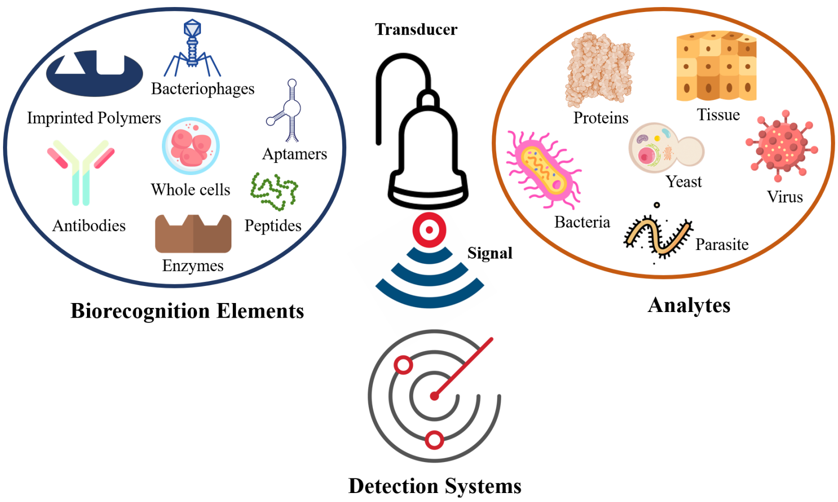

Fig. 1. Schematic representation of the main components of a biosensor, including analyte, biorecognition element, and transducer.

The biorecognition element functions to selectively identify the target analyte and can include enzymes, antibodies, nucleic acids, aptamers, or living cells [19, 20]. The transducer is able to convert the biological interaction into a quantifiable signal, depending on the system design [21, 22]. Moreover, the signal processing unit amplifies, filters, and translates this signal into a readable output. Together, these components enable sensitive, specific, and real-time detection [23, 24].

2.3. Working principles of biosensors

The operation of a biosensor involves a sequence of connected processes that convert a biological interaction into a measurable signal. At the outset, the biorecognition component is affixed to the sensor's surface using physical or chemical methods to ensure selective interaction with the target analyte. Upon exposure, the analyte binds to the biorecognition element, leading to a specific biochemical reaction such as antigen-antibody binding or enzyme-substrate conversion, which generates changes in electrons, ions (e.g., H^+), gases (e.g., O_2), or heat [25-27]. These biochemical events are then transformed by the transducer into a measurable physical signal, often involving changes in electrical signals [28] (such as current, voltage, potential, impedance), optical absorption, piezoelectric, thermal or mechanical properties [29, 30]. The resulting raw signal is typically weak and requires amplification and filtering to eliminate noise, after which it is processed and displayed as a user-friendly output in numeric, graphical, or digital form [31, 32]. For example, in an electrochemical biosensor, enzymatic activity may result in the generation or consumption of electrons, leading to changes in current that are detected using electrodes (working, reference, and counter), and the resulting current intensity is directly proportional to the concentration of the analyte [33-35].

3. Nanocomposites in sensor development

Over the past years, the adoption of a wide range of advanced functional materials into wearable sensors has emerged, which significantly enhances the performance and versatility of sensors [6]. Among these, nanocomposites have emerged as a promising platform for sensing technologies, particularly in the healthcare sector [7].

3.1. Overview of nanocomposites

Nanocomposites are engineered materials composed of two or more components, with at least one dimension in the nanoscale range (typically <100 nm) [36, 37]. Their high surface-area-to-volume ratio increases the interaction between the sensor and the analyte, leading to greater sensitivity. For instance, in a study by Ruecha et al., graphene-based polyaniline (G/PANI) nanocomposites used as electrode modifiers in electrochemical sensors demonstrated that their high surface-area-to-volume ratio provides increased interaction sites with heavy metal ions such as Zn(II), Cd(II), and Pb(II). This enhanced interaction led to improved sensitivity and lower detection limits, enabling effective trace metal analysis in complex biological samples like human serum [38]. Furthermore, nanocomposites made with conductive materials can transmit signals more rapidly and efficiently [39]. For instance, Jiang et al. [40] developed Ag nanoparticles/Nitrogen-doped graphene (NG) nanocomposites that exhibit enhanced electrical conductivity and a larger surface area, which facilitates more effective electron transfer. This increased electron transfer efficiency enabled the creation of a highly sensitive biosensing platform for acetamiprid detection, achieving a remarkably low detection limit of 3.3×10^{-14} M. This example emphasizes how conductive nanocomposites can improve signal transmission in sensing applications. Moreover, the tunable mechanical flexibility and biocompatibility of these nanocomposites make them ideal for integration into wearable devices [41, 42]. For example, Han et al. [43] developed a nanocomposite film made from cellulose nanofibers and graphene nanoplatelets that exhibited high electrical conductivity, mechanical robustness, and excellent flexibility. This nanocomposite functioned effectively as a wearable strain sensor, demonstrating rapid response and durability over thousands of cycles, making it ideal for integration into flexible and wearable health-monitoring devices. Overall, their tunable physical and chemical properties make nanocomposites particularly suitable for next-generation biosensors, improving sensitivity, selectivity, and response time in both clinical and environmental applications [44, 45].

3.2. Types and composition of nanocomposites

Nanocomposites can be categorized based on their composition into metal-based, carbon-based, and polymer-based types [46, 47]. Metal-based nanocomposites, such as those containing gold (Au) or silver (Ag) nanoparticles, offer high electrical conductivity and catalytic efficiency [48, 49]. Carbon-based nanocomposites, including graphene, graphene oxide, and carbon nanotubes (CNTs), exhibit excellent mechanical strength along with superior electrical conductivity [50, 51]. Polymer-based nanocomposites are fabricated by integrating inorganic nanomaterials into organic polymer matrices, thereby improving flexibility, stretchability, and sensitivity [52-54].

These materials are typically synthesized using methods such as sol-gel processing, chemical vapor deposition (CVD), electrospinning, or wet chemical techniques, depending on the desired structure and functionality [55-57].

The type of polymer matrix and the incorporated nanofiller material greatly influence the overall performance of nanocomposite-based sensors [58]. The polymers utilized in such systems may be classified as non-elastic, hydrogels, chemically crosslinked elastomers, or physically crosslinked elastomers. Soft, stretchable nanocomposites have addressed a critical challenge in wearable electronics, namely, the mechanical mismatch between rigid devices and soft biological tissues. Compared with conventional rigid electronics, nanocomposite-based sensors conform more naturally to the body, enabling long-term, high-reliability biosignal recording with minimal discomfort [59, 60]. Conductive hydrogels, which combine flexible hydrophilic networks with conductive fillers, offer excellent elasticity, mechanical robustness, and multifunctional sensing capabilities, making them highly suitable for wearable applications [59, 61]. For instance, Liu et al. [62] developed a transparent, tissue-like ionogel-based wearable sensor reinforced with silver nanowires. The resulting P(AAm-co-AA)/Ag NW composite achieved a stretchability of up to 605% and a fracture stress of approximately 377 kPa. It exhibited sensitivity to both temperature fluctuations and electrostatic fields. To reduce skin irritation and improve conformability, the nanocomposite was encapsulated in a transparent polyurethane dressing, enabling multidirectional stretch and effective skin adherence. The sensor showed high sensitivity, stability, and repeatability, making it ideal for long-term strain sensing applications.

Nanofillers can be derived from carbon-based nanomaterials, polymers, metallic nanoparticles (such as Ag and Au), liquid metals, and a class of emerging two-dimensional (2D) materials like MXenes [58, 59, 61]. Nanofillers are responsible for mediating electrical conductivity, signal stability, and biocompatibility [59, 61]. Among the most promising nanofillers are MXenes, a class of two-dimensional transition metal carbides and nitrides known for their unique physicochemical properties. These materials exhibit a tunable bandgap, excellent photocurrent generation capability, and high electrical conductivity. Their layered structure facilitates efficient ion transport, while their hydrophilicity, biocompatibility, and ease of functionalization further enhance their suitability for sensor applications. Additionally, MXenes have minimal diffusion barriers, making them highly attractive for use in bioanalytical devices and wearable biosensors [13, 63]. Their ability to retain the biological activity of immobilized molecules while providing excellent electrical interfacing has made MXenes suitable for both electrochemical and optical biosensors [64]. The layered architecture facilitates signal transduction, while its conductivity supports highly sensitive and real-time biomolecule detection [65]. For example, Huang et al. [66] fabricated a biosensor based on surface functionalized MXene ($Ti_3C_2T_x$) for sensitive enzymatic glucose detection. They enhanced the surface of MXene by generating defects and increasing hydroxyl groups to serve as binding sites for bioreceptor immobilization. The functionalized MXene's excellent electrical conductivity and abundant active sites facilitated electron transfer during the redox reaction between glucose oxidase and glucose. The sensor demonstrated a high sensitivity of up to 5.1 A/A for 10 mM glucose and was integrated into a cloud-based data collection system, ensuring detection errors within 10%. Moreover, Chen et al. [67] developed a noninvasive, wearable sensor for the sensitive and selective detection of uric acid (UA) in human sweat. They functionalized $Ti_3C_2T_x$ MXene with 1,3,6,8-pyrene tetrasulfonic acid sodium salt (PyTS) via π–π conjugation to create a bifunctional electrocatalyst. This PyTS@Ti_3C_2Tx composite provided multiple active sites, enhancing the electrocatalytic oxidation of UA. The sensor demonstrated high sensitivity within a range of 5 μM to 100 μM and achieved a low detection limit of 0.48 μM, outperforming traditional uricase-based sensors. Integrated with flexible microfluidic sampling and wireless electronics, the sensor enabled real-time monitoring of UA levels during exercise, facilitating personalized health management and disease prevention. Furthermore, Wang et al. [68] constructed a dual-mode aptasensor combining electrochemical and colorimetric detection for rapid on-site identification of Vibrio parahaemolyticus (V.P.) in seafood. A PBA-Fc@Pt@MXenes was developed as a nanoprobe, utilizing MXenes modified with phenylboronic acid and ferrocene, which exhibited peroxidase-like activity and specific recognition. The aptasensor, featuring a V.P.-specific aptamer and the nanocomposite, achieved a detection limit as low as 5 CFU/mL via electrochemical detection and 30 CFU/mL via colorimetric methods. The synergistic catalytic and conductive effects of Pt and MXenes significantly amplified signals, enabling high sensitivity and mutual verification for accurate pathogen detection.

Chaudhari et al. [69] described a carbon-nanocomposite textile sensor embedded in a compression sleeve, capable of piezoresistive sensing to quantify elbow-range motion during upper-limb VR rehabilitation. Their demonstrations, including a Kinarm validation and a VR task, show a strong, proportional relationship between joint angle and sensor resistance, with over 90% accuracy for at-home measurements using a Meta Quest 2 VR system. Fig. 2 presents participant performing a commercial stretching exercise available on Oculus Quest. A CNT sensor integrated into the sleeve monitors the sleeve resistance variations across three stretch types. Arrows in the figure show the peaks and troughs in the resistance curve, along with the corresponding arm positions during Stretch 2.

Multiple investigations have emphasized the practical utility of nanocomposites in wearable sensor design. Table 1 shows a summary of different nanocomposite-based wearable sensors.

3.3. Other advancements in wearable biosensors

Textile-based wearable sensors have also attracted growing interest, particularly for their potential in healthcare applications. Smart textiles integrate sensors, actuators, communication units, computing, and electronic systems, all of which are either textile-based or compatible with textile embedding. This integration enables the discreet and comfortable monitoring of physiological signals. To embed sensing elements into garments, both conventional fabric manufacturing methods, such as weaving, and advanced techniques, including inkjet printing, coating, lithography, and CVD, are employed. These methods help achieve high performance in terms of signal quality and sensitivity. Examples of such innovations include textile electrodes, temperature sensors integrated into fabrics, and textile-based activity monitors [79]. One of the most promising applications of textile-based sensors is the development of dry, flexible textile electrodes for monitoring biopotential signals such as electrocardiography (ECG) and electromyography (EMG) [80]. Unlike conventional gel-based electrodes, which may cause skin irritation and are disposable, textile electrodes offer enhanced comfort, washability, and long-term usability for both clinical and fitness-related monitoring [81]. Gel-based electrodes also tend to dry out over prolonged use, leading to increased impedance and signal degradation. In contrast, dry textile electrodes eliminate the need for conductive gels and maintain stable signal quality, making them highly suitable for continuous biopotential sensing in wearable systems [82, 83]. These electrodes are often fabricated using conductive yarns [84, 85] or coated with nanomaterials such as PEDOT:PSS [86], graphene [87, 88], or MXenes [89] to achieve high conductivity, low skin–electrode impedance, and signal stability during movement. Fig. 3 illustrates a schematic representation of a wearable biosensor system designed for continuous monitoring of physiological and movement data. Embedded sensors in such systems enable the recording of ECG signals through various electrode configurations, as well as the collection of EMG data [4]. Based on this concept, Mahmud et al. [90] developed a novel wearable ring sensor capable of continuously monitoring electrodermal activity, heart rate, skin temperature, and locomotion. Their system was tested on volunteers across diverse emotional states, demonstrating accurate, real-time data collection. This approach highlights how miniaturized, multi-modal biosensors can improve comfort, reliability, and accuracy in wearable health monitoring, addressing key challenges in emotional and physiological state measurement. Additionally, Siddharth et al. [91] developed a wearable multi-modal biosensing system capable of synchronously recording EEG, photoplethysmogram (PPG), eye-gaze, and body motion data outside laboratory settings. Their integrated platform minimizes motion noise, supports real-time data transmission, and can be extended to include other biosensors. This system demonstrates how multi-modal, research-grade sensors can be readily applied in practical applications, advancing wearable biosensing for affective computing and health monitoring. Advancements in additive manufacturing (AM), commonly known as 3D printing, have opened new possibilities for enhancing accessibility and affordability in diagnostic technologies [92, 93]. AM enables the low-cost fabrication of customized, flexible, and wearable bioelectronic patches capable of monitoring multiple electrolytes in an individual's sweat [93]. These 3D-printed devices interact noninvasively enabling continuous, real-time tracking of physiological metrics [94]. For instance, Yi et al. [95] introduced an innovative microengineered pressure sensor fabricated by a multi-material, multilayer all-3D-printed nanocomposite-based (M2A3DNC) designed to record multiple physiological signals with high sensitivity in real time.

Table 1

Summary of different nanocomposite-based wearable sensors.

Nanocomposite material	Fabrication method	Application	Ref.
CNT coated knit fabric (polyester, nylon, elastane fibers)	Coating of fabric with a thin CNT composite	Wearable piezoresistive sensor for real-time measurements in virtual reality-based upper-extremity rehabilitation	[69]
FD-BTO/PVDF	3D printing	Self-powered sports monitoring, pressure pattern recognition	[70]
S-CNF-Ag NPs/AA	Photocrosslinked hydrogel	Sweat metabolite detection (urea, uric acid), real-time pH monitoring	[71]
GO/PVA/PDA	Hydrogel	ECG signal acquisition through self-adhesive electrodes	[72]
MWNT/PDMS	Extrusion-based 3D printing	Flexible strain sensor for mechanical motion	[73]
MoO_3/V_2CT_x	Wet chemical synthesis	Detection of acetone and alcohol-based sanitizers	[74]
PVA-based ionogel with $[C_4mim][I]$	Ionogel composite	Temperature-tolerant, high-performance wearable sensor	[75]
Ag@Cu/gelatin/ Na_2SO_4	—	Bionic skin and flexible electronic sensors	[76]
PVA/PANI/TEGO	Hydrogel	Motion and glucose monitoring	[77]
Graphene/AuNPs/chitosan nanocomposite	Simple casting method	Electrochemical biosensing of glucose in blood samples	[78]

* Functionalized barium titanate (FD-BTO)/polyvinylidene fluoride (PVDF), sulfonated cellulose silver nanocomposites (S-CNF-Ag NPs)/ acrylic acid (AA), graphene oxide (GO), polyvinyl alcohol (PVA) and polydopamine (PDA), electrocardiography (ECG), multi-walled carbon nanotube (MWNT)/polydimethylsiloxane (PDMS), 1-butyl-3-methylimidazolium iodide ($[C_4mim][I]$), silver coated copper (Ag@Cu), gold nanoparticles (AuNPs), Carbon nanotube (CNT).

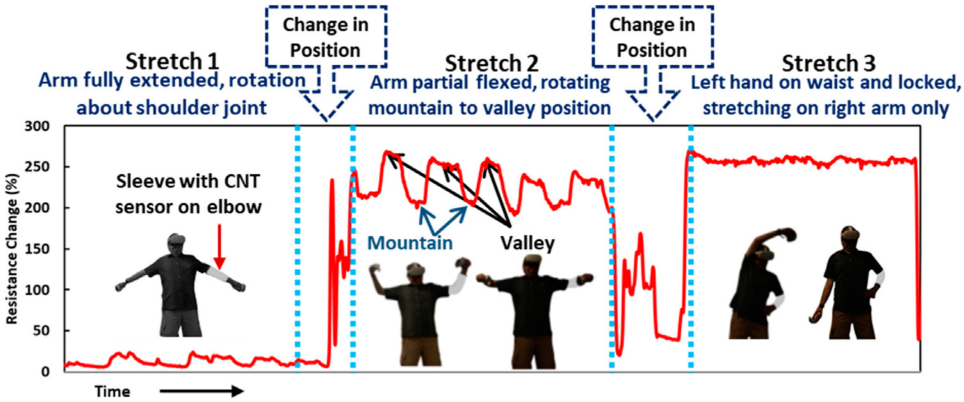

Fig. 2. Participant testing with a commercial Oculus Quest stretching exercise; a CNT sensor is attached to the sleeve on one arm. The plot shows the sleeve's percent change in resistance for three stretch types, with arrows marking the peaks/troughs and the corresponding arm positions during Stretch 2 [69].

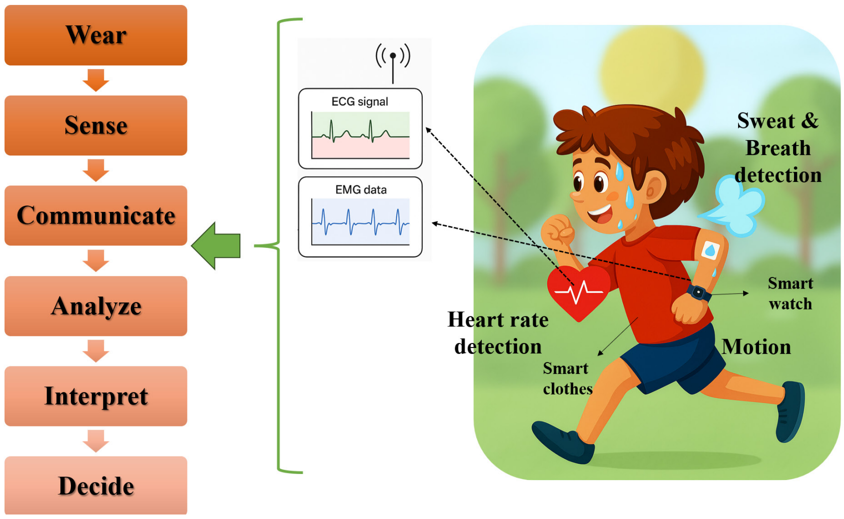

Fig. 3. Schematic representation of a wearable biosensor system designed for continuous monitoring of physiological and movement data.

Using the intrinsic advantages of extrusion 3D printing, they directly printed the conductive layers and micro-structured dielectric layers by optimizing the nozzle's path, resulting in air voids that enhanced the compressibility of the active layer. This approach exhibits the production of sensors with very low detection limits, rapid response times, and mechanical properties matching those of human skin, ensuring comfortable and sustained contact. Based on the versatility of 3D printing, NajafiKhoshnoo et al. [96] developed a fully integrated, miniaturized, and wireless pH sensor system called WB2F3D, fabricated entirely through 3D printing on skin-like flexible substrates. This innovative approach enabled the multimaterial and multilayer printing of sensor components, including electronic circuitry and antennas, in a low-cost, time-efficient manner. The 3D-printed, battery-free system demonstrated high sensitivity, specificity, and excellent mechanical flexibility, ensuring continuous and real-time monitoring of pH levels relevant to wound healing and disease detection. Moreover, another notable example from Kim et al. [97] illustrates the development of multiplex, low-cost, and mechanically flexible all-inclusive integrated wearable (AIIW) patches created using 3D-printing technology. These patches incorporate flexible sensors and microfluidic sample handling units, enabling simultaneous, noninvasive, and continuous measurement of multiple electrolyte levels in sweat. This approach demonstrates the potential for personalized health monitoring and paves the way for scalable, reliable, and affordable platforms for large-scale health assessments. Furthermore, recent innovations in sensor design have led to the development of highly sensitive and selective wearable biosensors. The incorporation of nanocomposites has served as a key driver of these developments, boosting device sensitivity, accelerating response times, and facilitating the simultaneous detection of multiple biomarkers [17, 94].

4. Applications of wearable biosensors

Miniaturized wearable biosensors have a broad and diverse range of applications. Among these, health monitoring stands out as one of the most prominent. These devices are increasingly employed to track physical activity, physiological metrics, and environmental conditions in real time [6].

In medical practices, such sensors provide continuous glucose monitoring for diabetic patients, heart rate tracking via ECG, assessment of respiratory rate, blood pressure, and oxygen saturation, measurement of muscle activity, and controlled drug delivery. The data obtained from these measurements provide valuable insights into a person's health and hold significant diagnostic potential [4].

Such capabilities support early disease diagnosis, for example, congestive heart failure detection, help in the prevention of chronic conditions like diabetes, and improve the clinical management of neurodegenerative diseases such as Parkinson's. Moreover, wearable sensors facilitate rapid response to emergencies like seizures in epilepsy patients and cardiac events in individuals under cardiovascular monitoring [98]. For example, Li et al. [99] utilized portable biosensors to monitor physiological changes in individuals during daily activities, recording over 250,000 measurements from 43 people. Their data revealed circadian variations and responses to environmental factors like high-altitude flights, highlighting the sensors' ability to detect early signs of illnesses such as Lyme disease and differentiate between insulin-sensitive and -resistant individuals. This demonstrates how portable biosensors can support personalized health monitoring and early disease detection outside clinical settings.

Moreover, textile-based dry electrodes have demonstrated high performance in wearable healthcare systems for long-term biopotential monitoring. These flexible sensors, embedded directly into garments, allow continuous ECG and EMG tracking, which is essential for early detection of cardiac anomalies in elderly patients and real-time assessment of muscle activity during rehabilitation or athletic performance [100]. Their seamless integration into everyday clothing enables discreet, non-invasive monitoring, thereby enhancing user compliance.

Moreover, recent advances in wireless communication and low-power electronics facilitate the real-time transmission of high-fidelity biosignals to mobile devices, supporting remote patient management and AI-assisted clinical decision-making [101]. Such systems play a vital role in reducing hospitalization and enabling proactive, personalized care [102].

Beyond healthcare, wearable sensors are also used in environmental monitoring to detect air pollutants and assess water quality by identifying contaminants [103, 104]. In the fields of sports and fitness, wearable sensors offer real-time feedback on physical activity and biometrics [105], while in industrial environments, they serve in safety monitoring and equipment diagnostics [106]. A specific application is gait analysis using motion sensors placed on parts of the body, such as the feet or waist. These sensors, which include accelerometers, gyroscopes, force sensors, strain gauges, inclinometers, and goniometers, can assess multiple gait characteristics, providing a detailed picture of movement dynamics [107].

5. Challenges and limitations

Despite major advances in miniaturized wearable biosensors, several challenges persist. Technical difficulties in fabrication and integration can lead to variability in device performance, and limitations in sensitivity and selectivity can hinder the precise detection of specific biomarkers [108]. Additionally, ensuring biocompatibility remains a critical concern for safe and prolonged use on the human body [109]. Data privacy and security also pose serious issues, as these devices often collect sensitive personal information [110].

Among different sensing approaches, non-invasive chemical sensing modalities face particularly difficult barriers to commercialization. Furthermore, significant fundamental improvements are still needed across mechanical, electrical, and optical sensing platforms, particularly to enhance detection specificity. These challenges are partially rooted in the biological interface itself: human skin acts more as a protective barrier than an information-rich medium, limiting signal access and accuracy [1, 111].

Another persistent limitation involves the bulkiness and rigidity of many wearable sensors, which can lead to user discomfort, motion artifacts, and inaccurate data. This has spurred intensive global research into the development of next-generation, ultra-lightweight, soft, and flexible materials suitable for wearable devices [112]. Consequently, further efforts are needed to optimize signal processing and transmission units that are lightweight, compact, energy-efficient, and seamlessly integrated into the overall sensor design [13].

Electromagnetic tracking systems (ETSs) also face limitations, including restricted capture volumes and susceptibility to magnetic interference from nearby metal objects. Once these drawbacks are resolved, ETSs can potentially provide positional and orientation data with accuracy comparable to that of image-based tracking systems [107].

Regarding sensors incorporating nanocomposites, mass production of 2D nanomaterials remains both technically challenging and cost-prohibitive [13]. In addition, interactions between these materials and biological fluids like sweat or saliva can degrade sensor performance. Environmental instability of some 2D materials further restricts their practical use unless adequately addressed without compromising sensor sensitivity.

Despite continued progress, wearable sensors still face limitations in data accuracy, disease-specific detection, and early diagnostic capability [113]. Overcoming these limitations will require breakthroughs in materials, system integration, and signal interpretation technologies.

6. Future directions

Emerging trends in nanocomposite research hold great promise for advancing sensor technologies. Interdisciplinary collaboration among materials scientists, engineers, and biologists is expected to yield novel solutions that further enhance sensor sensitivity, durability, and biocompatibility [114]. At the same time, regulatory frameworks must evolve to address ethical concerns related to data privacy and the widespread deployment of wearable biosensors [110].

Ongoing innovations in sensing materials, embedded electronics, wireless communication, nanotechnologies, and device miniaturization now make it feasible to build smart systems capable of continuously monitoring human activity. These wearable systems can detect abnormal or emergency conditions by tracking physiological signals and other contextual parameters, enabling timely interventions [115]. Wearable and remote health monitoring systems are also poised to reduce the healthcare access gap between urban and rural populations by extending the reach of medical expertise [4]. Although numerous existing sensors are designed to monitor basic physical parameters such as pressure, temperature, and movement, and analyzing complex biological fluids (e.g., sweat, interstitial fluid, urine, or breath) requires integrated and more sophisticated sensor platforms [6]. An ideal wearable sensor should be compact and unobtrusive. Although miniaturizing the sensing unit is often achievable, downsizing the power source remains a major challenge. One promising strategy involves harvesting and storing energy from the user or environment using thermoelectric materials [6]. Future directions also include developments in wearable energy systems, multicomponent integration, and wireless communication technologies [112]. These features are essential for fully autonomous and connected health monitoring platforms. Wireless and wearable sensors are expected to play a central role in personalized healthcare, offering remote, non-contact, and continuous monitoring without disrupting daily routines [116]. However, since these devices handle personal health data and connect to networks, robust cybersecurity measures must be developed to protect patient privacy and prevent unauthorized data access [110].

Textile-based dry electrodes are also expected to undergo substantial innovation as part of next-generation e-textile systems. Future developments may focus on improving their washability, durability, and long-term skin adhesion without compromising comfort or signal fidelity. Integrating such electrodes with AI-driven platforms can enable intelligent interpretation of biopotential signals such as ECG and EMG, supporting early diagnosis and continuous monitoring. Moreover, hybrid designs that combine textile flexibility with nanomaterials and energy-harvesting capabilities could lead to fully autonomous and self-powered wearable systems for healthcare. These advancements will help overcome current limitations and broaden their real-world applicability beyond clinical settings [100, 117].

Although many studies have demonstrated the potential of wireless monitoring technologies in the lab, scaling these solutions for real-world, industrial, or large-scale deployment remains a major hurdle [13]. Multifunctional sensors that integrate both mechanical and electrochemical sensing elements offer a promising path toward more comprehensive health assessments [13]. Additionally, improving diagnostic accuracy and early disease detection will likely require combining advanced sensor architectures with artificial intelligence (AI). AI-powered wearable sensors can help extract meaningful signals and support clinical decision-making by delivering precise, actionable insights [113].

7. Conclusion

In summary, this review has highlighted the rapid evolution of wearable sensors and the integration of emerging technologies such as nanomaterials towards the development of cutting-edge, skin-like devices. Advances in data processing and improved integration with textiles have also been discussed. These developments have significantly influenced fields such as healthcare by reshaping the role of biosensors, enabling greater accessibility, and reducing the need for invasive analyses. Nevertheless, the progression of wearable sensor technology introduces new challenges, including ensuring data privacy and security, enhancing durability, and achieving seamless incorporation into textiles and clothing. Future research should focus on scalable fabrication methods, the establishment of robust regulatory frameworks, and improved system integration. Continued interdisciplinary collaboration is expected to drive further advancements, positioning wearable sensors as indispensable tools in personal healthcare and paving the way for deeper integration with emerging technologies.

Author contributions

Nadia Banitorfi Hoveizavi: Conceptualization, Investigation, Writing – original draft, Writing – review & editing; **Mina Laghaei:** Investigation, Writing – original draft, Writing – review & editing; **Shima Tavakoli:** Conceptualization, Writing – review & editing. **Behrouz Javanmardi:** Writing – original draft, Writing – review & editing.

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Conflict of interest

The authors declare no conflict of interest.

Data availability

No data is available.

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