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Review Article

ADVANCEMENTS IN BIOSENSOR TECHNOLOGIES: FROM NANOBIOSENSORS TO BIOCOMPATIBLE AND OPTICAL SYSTEMS FOR CLINICAL AND ENVIRONMENTAL APPLICATIONS

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ABSTRACT:
Biosensor technology has progressed enormously over the past few years, mainly due to the merger of advanced materials, nanotechnology, and design strategies. This systematic review aims to provide a broad synthesis of the current research landscape, spanning an array of studies addressing the advances and applied aspects of biosensors in a variety of sectors. Biosensors with their unique ability to detect biological analytes with high sensitivity and specificity have become indispensable in clinical diagnostics, where fast and accurate detection of diseases, biomarkers, and pathogens is crucial. For environmental monitoring, biosensors are indispensable in the detection of pollutants, toxins, and pathogens, thus allowing real-time monitoring of air, water, and soil quality. On the other hand, wearable biosensors have changed the paradigm for personal health management by continuously monitoring vital signs, glucose levels, and other parameters. This review discusses material innovations including graphene, nanomaterials, and molecular imprinted polymers, as well as design innovations like miniaturization, wireless capabilities, and integration with AI for enhanced data processing. By synthesizing developments across these diverse applications, this review aims to identify trends, challenges, and future prospects in this ever-changing field of biosensor technology.

Keywords: Biosensors, Clinical diagnostics, Environmental monitoring, Personal health management, Nanotechnology, Wearable sensors.

INTRODUCTION

In recent years, the increasing demand for rapid, versatile, and precise approaches for the detection of biological and environmental substances has set the field of biosensors on a technological fast track. As asserted by Kulkarni (2022) [1], biosensors are important analytical instruments that couple biological sensing elements with transducers, converting biological signals to measurable electrical signals. This technology has immensely benefited a multitude of fields, predominantly in healthcare, by enabling the accurate assay of diseased organisms, pathogens, and biomarkers. These advances stem from the integration of modern materials, nanotechnology, and novel design strategies. The importance of biosensors goes beyond clinical applications; they are also being used for environmental monitoring and personal health management, showcasing their disruptive impact on multiple domains.
The biosensor technologies keep on evolving in the need of enhanced sensitivity and specificity in the detection of the analytes. Chadha (2022) [2]has documented many advances within the last decade that the biosensor has made possible in the detection of innumerable substances-from enzymes to biomarkers to viruses. The very incorporation of nanotechnology has not only enhanced biosensor viability but also dramatically altered their

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application scenario- making them the revered tools in both health care diagnostics and environmental monitoring (Ramesh, 2022) [3]. New material discoveries in light of recent progress, especially those pertaining to the application of two-dimensional materials like MXenes, have surmounted the liabilities of classical biosensor design and have acted positively toward improvement in stability and selectivity (Ramesh, 2022) [3].
Biosensors have huge implications for industries ranging from molecular biology to automotive and intelligent textiles. There arises a need to comprehend the emerging potentials, implementational forms, and technological advances for biosensor utilization, given the sheer breadth of applicability.
Many biosensors' applications are explored pertaining to the fields of medical science. The main objectives of this study are:

- To study biosensors and their applications in both healthcare and medical services;
- To study on the utmost critical biosensor advancements in the field of medicine;
- To recognize newer biomarkers of biosensors for future applications in the medical field by (Bhatia D, 2024)[4].

Central to the current situation under biosensor research is the rise of wearable biosensors, which facilitate non-invasive continuous monitoring of vital signs and other physiological parameters, along with convenience for health management (Polat, 2022)[5]. These are highly desirable under the increased focus on personalized healthcare and the need for patients to monitor their health status in real time. Such wearable devices, supplemented by state-of-the-art transducers, are engaged in effective signal transduction and data acquisition, thus potentially marking the beginning of a new chapter in personal health management (Polat, 2022) [5].

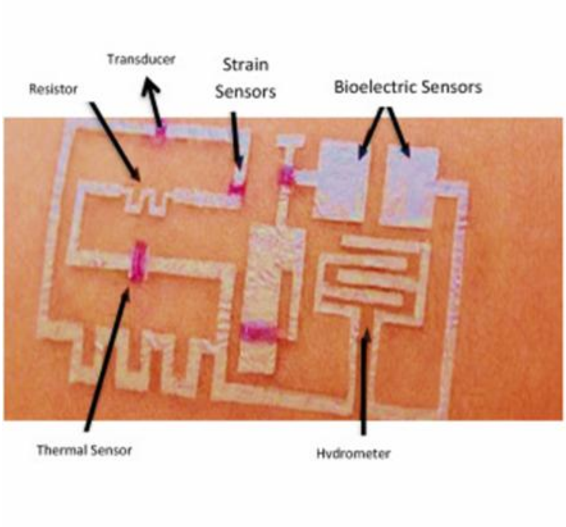

Figure 1 (a)

Figure 1 (b)

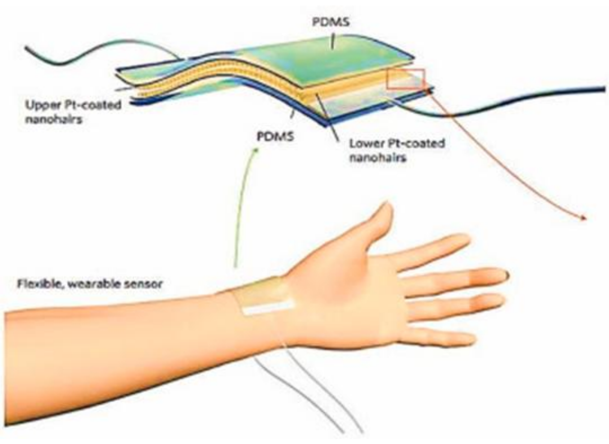

Figure 1 (c)

Figure 1. Representative examples of wearable biosensor systems for physiological monitoring. (a) A multifunctional epidermal electronic system illustrating integrated components including thermal sensor, strain sensor, hydrometer, resistor, transducer, and bioelectric sensors for comprehensive on-skin diagnostics. (b) A flexible, wearable electronic patch with embedded circuitry, demonstrating high-performance, skin-conformal health monitoring capabilities. (c) Schematic illustration of a stretchable wearable sensor based on platinum (Pt)-coated nanohairs embedded in polydimethylsiloxane (PDMS), showing the multilayer structure and its placement on the forearm for real-time biosignal acquisition.

Integration of artificial intelligence (AI) and machine-learning algorithms in biosensor technology is another scope of advancement for the enhancement of biosensors. In the words of Hassan (2024) [6], AI-supported biosensors enable complex data processing and interpretation, thereby achieving maximum analytical accuracy and optimizing diagnostic workflows. The intersection of nanotechnology with AI in biosensor design will alter several healthcare paradigms, facilitating more efficient and personalized medical interventions.
The genesis of biosensor technology dates back to the pioneering work of Leland Clark Jr. during the 1960s, who set grounds for combining biological recognition elements with transducers (Wu, 2023)[7]. Such combined design allowed conversion of biological responses into quantifiable measures. As described by Cammann (1969), these developments opened a pathway to novel applications encompassing a variety of fields. In particular, electrochemical biosensors may hold special relevance for portable diagnostics due to the possibility of downsizing and easy interfacing (Wu J, 2023)[7]. These devices are of course going to address the fast-growing need for medical diagnostics, which will also improve patient care by promoting real-time monitoring of health parameters.
It presents recent developments in nanophotonic biosensors based on plasmonic and dielectric nanostructures that could contribute to the realization of this vision. We focus on label-free optical biosensors based on biomolecular recognition and the measurement of refractive index changes, as well as the measurement of infrared absorption or Raman scattering using surface-enhanced optical spectroscopies. Their features and benefits will be described, and the major challenges for their development and application will be discussed. (Altug H, 2022)[8].

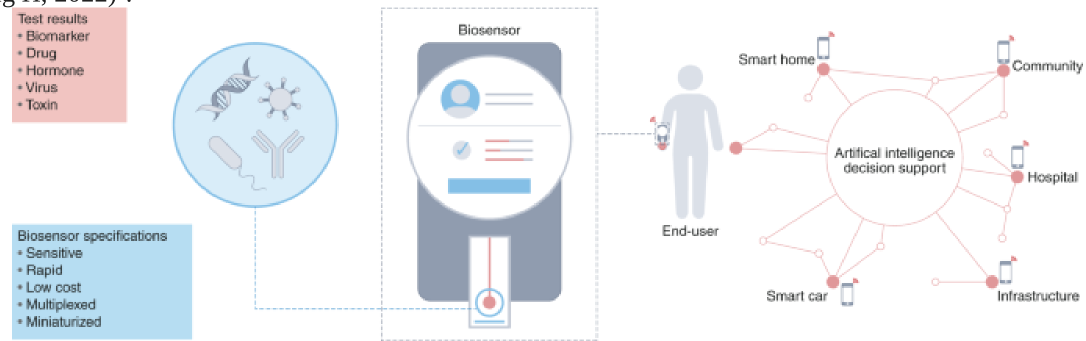

Figure 2. Schematic representation of a smart biosensing ecosystem integrated with artificial intelligence (AI) decision support. The biosensor detects diverse test targets including biomarkers, drugs, hormones, viruses, and toxins with key specifications such as sensitivity, rapid response, low cost, multiplexing capability, and miniaturization. The acquired biosensor data is transmitted from the end-user device to a cloud-based AI platform, enabling real-time decision-making across interconnected domains including hospitals, communities, smart homes, infrastructure, and smart vehicles for personalized healthcare management.
This elaborated how the researchers stated that NMs-based biosensors may be acting as signal transducers or recognition agents to control current flow. For this purpose, electroactive tags were employed to mark the presence of analytes. The team devoted itself to perfecting the sensor's competence for varied chemicals present in the ecosystem (like water, air, and food) and biological matrices (like blood, urine, and saliva) under constant monitoring. They then derived that these NM-based biosensors comply with all important parameters concerning precision, efficiency, sensitivity, selectivity, reproducibility, and stability in analyzing and detecting EPs in any assigned sampleHerein, CuS NMs are synthesized through a hydrothermal approach, where its crystal configuration, geometry, composition, and topographical evaluation were studied quite thoroughly. For the sensing of HQE, a broad linear range for CuS/GCE (the GCE stands for glassy carbon electrode) was achieved, which stretches from 1 to 2287 mM, and the LODs were enhanced (0.135 mM). Henceforth, the CuS nano-globule-based electrochemical sensor is highly recommended for real-time HQE investigation and can be further utilized as a strong contender for the detection of several other EPs.
This review article critically reviews the essential role of NMs based biosensing in detecting and sensing different pollutants, commonly referred to as emerging pollutants (EPs), such as fertilizers, pesticides, dyes, pharmaceutical wastes, heavy metals, etc. The emphasis on the various forms of NMs based biosensors in EP's

detection has been discussed in deep along with its detection mechanism and future perspectives by (Thakur A, 2022)[9].

Field-effect transistor-based biosensors (bio-FETs) represent one of the most promising classes among biosensors using the electrochemical transduction system, being widely used and able to combine the advantageous electronic characteristics of field-effect transistors, i.e., the signal amplification implied by the working principle of the transistors, and the high selectivity towards the analyte of interest, ensured by the presence of a suitable recognition element. This review will give an account of the state of the art and future perspectives of bio-FETs applied to environmental and agricultural plant monitoring. It will primarily cover Section 2 with the bio-FET technology, working principles, most common FET configurations, electronic materials, and fabrication and functionalization methods. Section 3 will focus on the literature analyzed on environmental monitoring application of bio-FETs, while Section 4 will focus on agricultural plant monitoring. The state of the art will then be discussed in Section 5, and conclusions and future perspectives made in section 6.(Elli G, 2022)[10].

With growing industrialization, the urgent need to detect toxic metal(loid)s has become ever clearer (Chauhan, 2022) [11]. In monitoring heavy metal contamination, biosensors have confirmed to be extremely fast in detecting hazardous substances and reliable in those detections. The recent upsurge in the review of Chauhan (2022) [11] reports on an up-to-date review of mechanism and materials for biosensing in order to give adequate directions to the future research undertakings in this urgent area.

Williams (2024) [12] further concurs with this notion while he inputs the progress of biosensor technology including using nanomaterials and electrochemical techniques, emphasizing the great importance of these technologies in both medical diagnostics and environmental applications.

This systematic review seeks to encapsulate the current research landscape concerning biosensor technologies advancement-from nanobiosensors to biocompatible and optical systems-with emphasis on their application in clinical and environmental areas. Novel materials and advancements in sensing mechanics and disruptive technologies will lay bare the multitude of applications and consequences that these biosensors hold for future scientific and technological developments. The intent of this review is to analyze the extensive landscape of research and opinions in the area by deriving a bouquet, showing not only the advancements made so far but also directing future research for possibly mapping ground breaking advancements in biosensor technologies.

To sum up, biosensors have grown to be vital aides in healthcare and environmental monitoring due to their accurate detection and fast analysis. The implementation of new materials, modern design approaches, and interdisciplinary collaboration would be advantageous to these technologies' enhancement. In parallel developments, there is a need to grab these new techniques and work toward addressing contemporary health care and environmental sustainability challenges. This will be a comprehensive review intending to throw more light on future pathways and possibilities in the ever-evolving field of biosensor technology, paving the way for effective solutions to diagnostic, environmental, and personal health management problems.

2. Biosensors

2.1 Nanobiosensors and 2D Materials

Mature and most promising field of biosensor technology, where applications of nanomaterials have considerably enhanced sensitivity and selectivity in these devices. In recent studies, nanomaterials such as nanoparticles, nanowires, and carbon nanotubes (CNTs) have been used to optimally design biosensors. Naresh (2021) [13] highlighted the use of noble metal nanoparticles and metal oxide nanomaterials fabricated both by chemical and physical methods in improving the detection capabilities. This paves the way for evaluation of different material configurations and fabrication techniques across various studies.

Singh (2023) [14] added to the reservoir of knowledge by adding the interesting qualities of two-dimensional (2D) materials to nanobiosensor fabrication. These include graphene oxide, black phosphorus, and MXenes. The high surface area of these materials along with exceptional electrical properties facilitates sensitivity in disease diagnostics. These specific materials pointed out a trend of preference towards nanostructures that could provide more bioreceptor loading and much faster electron transfer rates, which is likely to give better biosensor performance.

Huang (2021) [15] presented traditional nanostructures such as the introduction of nanoparticles, nanotubes, and nanowires into systems that have increased the efficacy of electrochemical biosensors. As stated in this study, these nanomaterials can create a nanoscale interface between biological elements and electrodes, leading to better detection performance of biomolecules. Huang mentioned drawbacks with respect to stability and reproducibility of the results and suggested optimizations to be made in these two aspects for real-life applications.

Moreover, Ramesh (2022) [16] spoke about the promise of different classes of nanomaterials-from nanoparticles to nanowires, CNTs, and quantum dots (QDs)-for nano-biosensors. All these nanomaterials have high surface area and excellent thermal and electrical conduction, which strengthen the case for using these materials as core constituents of very high sensitivity biosensors. Quantum dots have been studied especially as they mark an addition in research into the nanomaterial types being investigated since they have a very unique photoluminescent property providing another detection mode.

Krishna (2023) [17] further contributed an application to the work by using the 2D ZnO nanostructure exclusively for nanosheets and nanoribbons. The high isoelectric point combined with the significant surface-to-volume ratio of these nanostructures demonstrated how these nanostructures served as matrix layers by enhancing the binding of biomolecules and ultimately improving the sensitivity of detection.

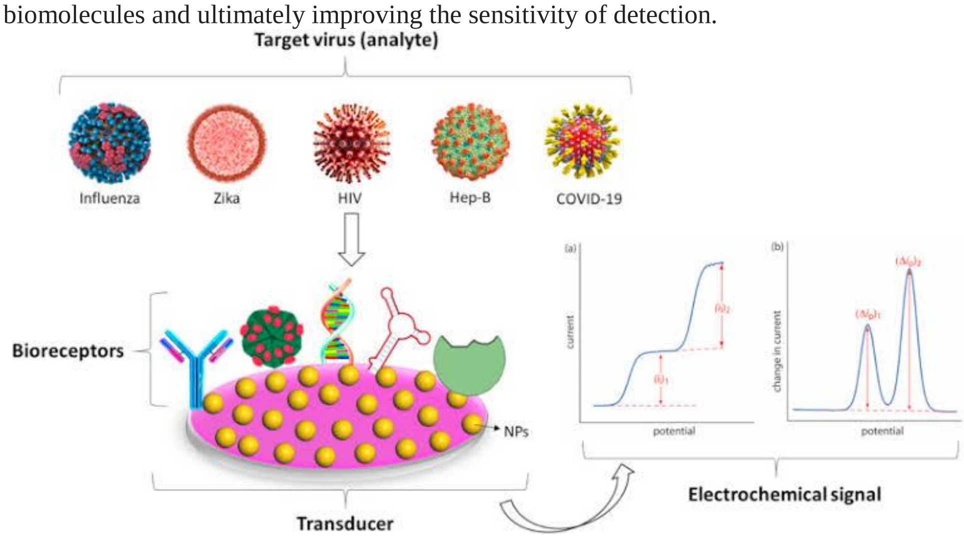

Figure 3. Schematic illustration of an electrochemical biosensing platform for virus detection. The system employs specific bioreceptors (e.g., antibodies, nucleic acids, enzymes) immobilized on a nanostructured transducer surface containing nanoparticles (NPs) to selectively capture target viral analytes including Influenza, Zika, HIV, Hepatitis B, and SARS-CoV-2 (COVID-19). Upon binding of the viral analyte, the biorecognition event is transduced into a measurable electrochemical signal, reflected as changes in current or potential in voltammetric profiles, enabling highly sensitive and specific detection for diagnostic applications.

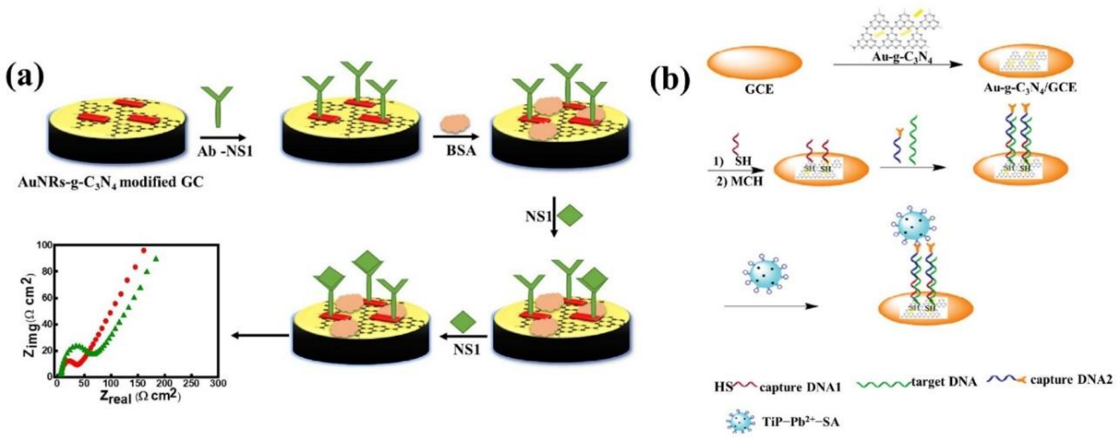

Figure 4. Design and working mechanism of AuNRs–g-C3N4 nanocomposite-based electrochemical biosensors. (a) Schematic representation of an immunosensor constructed on a glassy carbon electrode (GCE) modified with gold nanorods (AuNRs) and graphitic carbon nitride (g-C3N4), where antibodies against NS1 antigen are immobilized for specific detection, followed by BSA blocking and analyte binding. The Nyquist plot (inset) shows impedance changes upon NS1 interaction. (b) Construction of a DNA-based electrochemical biosensor employing Au–g-C3N4/GCE as a platform for sequential assembly of thiolated capture DNA, blocking with MCH, hybridization with target DNA, and signal amplification using a TiP–Pb2+–SA nanoprobe complex.

Abdel-Karim (2024) [18] built on these methods with nanoparticles, nanowires, CNTs, nanorods, and QDs used in achieving nanobiosensors. This text clearly shows the multidimensionality of biosensor design in utilizing various nanomaterials in detecting a certain analyte. The research also highlights having a highly surface area and stability for allowing more sensitive detections.

Mukherjee (2024) [19] is narrower in scope, concentrating on graphene-derived nanostructures for electrochemical biosensors for cancer biomarker detection. It adds significant value to the application of nanomaterials for oncological diagnostics, underlining the attributes of their high electrical conductivity and adsorption capacity along with the functional groups facilitating bioreceptor immobilization.

Table 1 Nanomaterial-integrated biosensors for clinical and environmental applications

Theme	Key Insights	Authors Contributing
Sensor Platforms Reviewed	Electrochemical, optical, piezoelectric, and wearable biosensors dominate the literature. Integration with flexible electronics and skin-mountable devices is emerging.	Naresh (2021), Huang (2021), Krishna (2023), Mukherjee (2024)
Nanomaterials Used	Graphene and its derivatives (GO, rGO), ZnO nanostructures, QDs, CNTs, and 2D materials like g-C_3N_4 are commonly reviewed. Their surface area, conductivity, and biocompatibility make them ideal for sensitive biosensing.	Singh (2023), Ramesh (2022), Krishna (2023), Mukherjee (2024)
Biomedical Applications	Strong emphasis on disease diagnostics, especially infectious diseases (e.g., COVID-19) and cancer. Biosensors are used for biomarker, pathogen, and metabolic monitoring.	Singh (2023), Krishna (2023), Mukherjee (2024), Abdel-Karim (2024)
Environmental Monitoring	Fewer studies focus on pollution/toxin detection, although some reviews emphasize dual-utility sensors for both health and environmental diagnostics.	Ramesh (2022), Naresh (2021)
Design & Functional Enhancements	Nanomaterials enhance signal transduction, detection limits, and real-time response. Miniaturization, integration with wireless and AI technologies, and flexible substrates improve portability and user-friendliness.	Naresh (2021), Ramesh (2022), Abdel-Karim (2024), Mukherjee (2024)
Methodology of Reviews	All are literature-based reviews; no meta-analysis. Scope ranges from material science to clinical integration. Some include application-specific perspectives (e.g., cancer, COVID-19).	All studies
Challenges Identified	Scalability, reproducibility of nanomaterial synthesis, batch variation, biocompatibility in vivo, and lack of large-scale clinical validation.	Naresh (2021), Singh (2023), Huang (2021), Mukherjee (2024)
Future Recommendations	Suggested directions include AI and IoT integration, real-time wearable biosensors, improved deposition techniques, regulatory validation, and expansion to in vivo and point-of-care diagnostics.	Ramesh (2022), Krishna (2023), Abdel-Karim (2024), Mukherjee (2024)

2.2 Electrochemical and Smart Biosensors

Electrochemical sensors have been discovered to be remarkably valuable in analytical chemistry, having their application in a wide range of fields, such as environmental monitoring, clinic analysis, and so on. Such significance is the result of possible developments in nanotechnology, which enhance the sensors' sensitivity, selectivity, and applicability. This review collects recent studies that enlighten the progress, performance, and future prospect of electrochemical sensors in view of the incorporation of nanomaterials. The review critically assesses efforts from various recent investigations in order to portray the ambivalent nature of electrochemical sensors and their potential impacts on the scientific and industrial multidisciplinary landscapes.

2.2.1 Foundational Techniques and Innovations

Baranwal (2022) [20] provides a comprehensive overview of electrochemical techniques, including voltammetry, amperometry, and potentiometry. These methods are foundational for sensor development, enabling the precise quantification of analytes in various matrices. The study emphasizes that the performance of electrochemical sensors can be significantly enhanced through the incorporation of nanomaterials such as carbon nanotubes, graphene, and metal nanoparticles. These materials not only increase the surface area available for analyte interaction but also improve the electron transfer kinetics, leading to faster response times and higher sensitivity. In particular, Baranwal’s review highlights the growing trend towards the integration of smart technologies in biosensing devices, facilitating real-time data analysis and remote monitoring. This capability is especially crucial in applications such as health monitoring, where timely data can inform critical decisions. The implications of this integration are profound, potentially transforming patient care and environmental monitoring practices by enabling continuous, real-time assessments.

Shanbhag (2023) [21] builds on this foundation by delving into the role of bioreceptors in bio-electrochemical sensors. The study categorizes various bioreceptors, including enzymes, antibodies, and nucleic acids, and discusses their interactions with transducer materials. Shanbhag emphasizes the importance of selecting appropriate electrode materials and immobilization strategies to optimize sensor performance. For instance, the use of gold nanoparticles can enhance the loading capacity of enzymes, thereby increasing the overall sensitivity of the sensor.

2.2.2 Application in Environmental Monitoring

This work delves into the use of electrochemical biosensors and their application in monitoring of water quality, with an exposition by Hui (2022) [22]. This study attempts to look into alternative sensor configurations, detection methods, and surface modifications that are important in the detection of inorganic and organic pollutants. Hui discusses some of the serious challenges in the way of monitoring the environment, particularly the need for sensitive and selective sensors in a complex matrix such as water. The integration of nanomaterials as a means of overcoming these challenges, enhancing electrochemical activity and stability, under a varying environmental condition will go a long way as discussed in Baranwal.

The implications of Hui's findings are in sync with Baranwal's argument for integration of nanomaterials, which in turn supports how innovations in sensor technology are poised to offer better approaches to environmental monitoring. Timely water quality assessments will allow timely responses and therefore play a vital role in the promotion of public health as well as the protection of the environment.

Umapathi (2022) [23] moves the discussion forward into agriculture, showing the success of portable biosensors for detecting pesticide residues in food products. Further, Umapathi also explores the view mentioned by Hui, stressing the need for appropriate solutions for monitoring, and that user-friendly devices are essentially needed to be developed for use in the field. The use of smartphone technology for real-time data collection forms the crux of this advancement in food safety. This will not only protect consumers but empower farmers and other stakeholders to make informed decisions about pesticide usage, thereby promoting sustainable agriculture.

2.2.3 Innovations in Clinical Diagnostics

Li (2022) [24] goes in-depth to discuss the two-dimensional materials (2DMs) such as graphene and MXenes, elaborating on their synthesis techniques and unusual surface chemistry. Their responsive properties are crucial for enhancing the performance of electrochemical sensors and foster innovations in wider applications beyond clinical diagnostics. An example would be that with high conductivity and large surface area, graphene stands to be a good candidate for fabricating sensitive biosensors capable of detecting very low levels of biomarkers from various body fluids.

The necessity for the combination of nanomaterials with personal use devices that promote disease diagnosis and therapeutic monitoring is, therefore, insisted on by Zhang (2022) [25]. Basically owing to the lots of ongoing global health threats, Zhang underscores the need for such rapid and accurate testing in the clinical setting. The impact of Zhang's work displays that once electrochemical sensors were used, timely medical intervention could be taken on, thus highlighting their transformational potential within contemporary health care.

Kulkarni (2022) [26] goes further into the study of microfluidic-based biosensors and their applications in point-of-care testing. The research delves into the design considerations and fluid dynamics that influence sensor performance, thereby demonstrating through microfluidics how the usability and practicality of biosensors can be improved. Microfluidic technology also allows for the downsizing of these sensors, thus making them suitable for use in underdeveloped worlds. This point plays a key role in countries where access to advanced diagnostic facilities is usually scarce.

Kumar (2022) [27] places emphasis on the urgency to adopt rapid detection methods in response to the COVID-19 pandemic. The paper examines the latest developments in electrochemical sensors reported with the ability to detect SARS-CoV-2 and outlines the key role of rapid diagnostics in managing health crises. Kumar's observations highlight the influence of electrochemical sensors on public health surveillance, enabling more rapid outbreak responses and improving health outcomes.

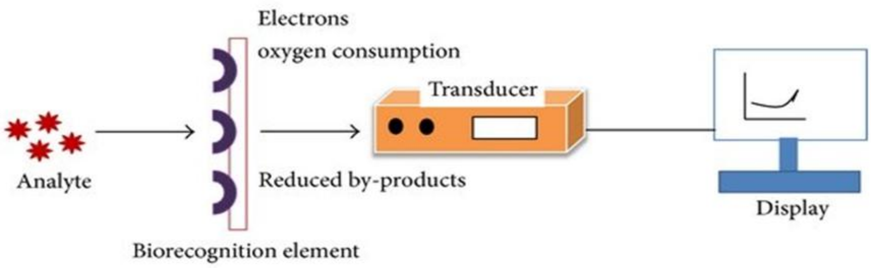

Figure 5. Schematic representation of a biosensor signal transduction pathway. The diagram illustrates the core working principle of a biosensor, where an analyte interacts with a biorecognition element, triggering oxygen consumption and electron release. These biochemical events generate reduced by-products, which are detected by a transducer and converted into an electrical signal. The resulting data is processed and displayed

for analytical interpretation, enabling sensitive and specific detection of target analytes in biomedical applications.

2.2.4 Expanding Applicability Across Sectors

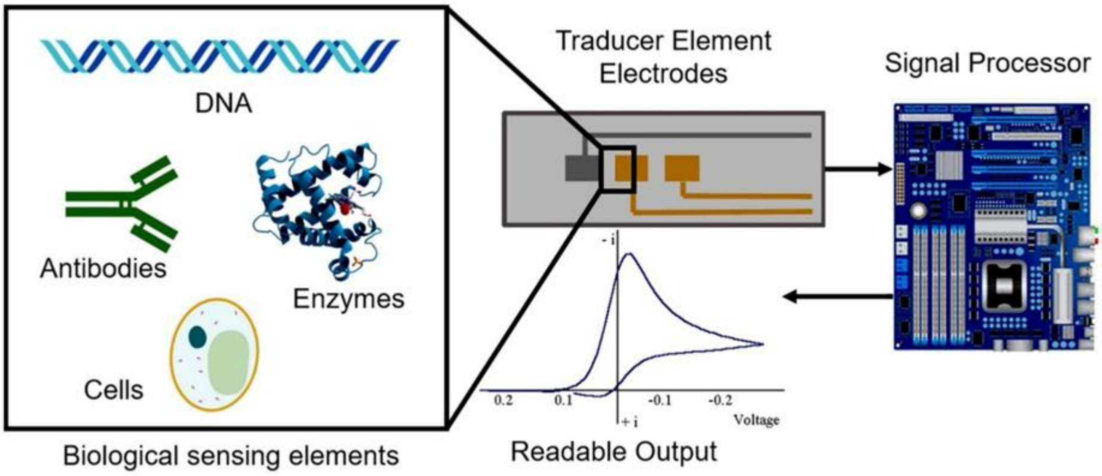

Figure 6. Schematic illustration of biosensor architecture integrating biological sensing elements, transducer, and signal processing components. The diagram depicts the essential components of a biosensor system. Biological recognition elements such as DNA, antibodies, enzymes, and cells detect specific analytes and initiate signal generation. The interaction is translated by transducer elements with integrated electrodes into electrical signals. These signals are then processed by a microelectronic signal processor to yield a readable output, enabling accurate, real-time biomedical analysis.

Thakur's work exemplifies the continuum of innovation within the field and urges for constant research into novel materials and methods that can significantly augment sensor performance.

Curulli (2023) [33] focuses on the incorporation of functional nanomaterials in electrochemical biosensors for rapid viral diagnosis. Curulli explores various biosensor types and electrochemical techniques and outlines the promise of these technologies to meet public health emergencies through real-time monitoring. This study conveys the need for rapid diagnostic

Gold nanomaterial-based sensors for detecting phenolic antioxidants have been evaluated for versatility within electrochemical sensor systems in many fields-ranging from food to cosmetics- by Petrucci (2022) [28]. Since these types of sensors are multifunctional in nature, their applications in diverse analytical contexts legitimize the versatility given. The sensors' sensitivity toward low concentrations of phenolic compounds relevant to the assessment of quality and safety of food products is enhanced upon the addition of gold nanoparticles.

Reddy (2022) [29] examines the advantages of graphene and graphene-based nanocomposites in enhancing detection sensitivity and stability for environmental monitoring. The work describes how the extraordinary properties of graphene can be put to use in developing sensors that are highly sensitive and yet robust enough to function under extreme environmental conditions. This research also appears to contribute to the greater narrative of the employment of novel materials for enhanced sensor performance, both environmentally and clinically.

Zambry (2022) [30] presents clinical applications, including the detection of SARS-CoV-2, discussing electrode materials and biorecognition strategies. The inclusion of microfluidic technology in electrochemical sensing capabilities demonstrates the potential for translating interdisciplinary expertise into health improvement. The potential of electrochemical sensors to respond to new health threats emphasizes the relevance of Zambry's findings in current and future public health interventions.

Chadha (2022) [31] gives a much wider scope by surveying different biosensor types and focusing on the integration of advanced biological methods with advanced instrumentation. Such a broad overview demonstrates the interdisciplinary nature of biosensor developments, pointing out the importance of collaborative efforts in pushing the frontiers of this field. As Chadha pointedly analyzes the convergence of various sensing technologies, he opens doors toward developing next-generation biosensors that can address ultimate challenges in analytical work.

Thakur (2022) [32] supported this narrative, discussing advances in nanomaterials-based biosensor technologies in monitoring environmental pollutants. The need for advanced nano bioconjugation methods to enhance sensor sensitivity across applications is underscored.

tools for managing viral outbreaks, thereby highlighting the importance of electrochemical sensing in public health.

Sumitha (2023) [34] engages with cancer biomarkers to show that electrochemical biosensors provide extremely high sensitivity and selectivity, which are crucial not only for early detection but also for monitoring of cancer. Sumitha further contributes to the overall theory establishing electrochemical sensors as critical health diagnostics, accentuating the necessity of innovative remarkers in oncology. Should these sensors, therefore, ever find their way into early intervention, the consequence for the patient could be significant, warranting their being considered within clinical practice.
Irkham (2023) [35] narrates how the combined properties of graphene nanostructures and nanoparticles can enhance clinical diagnostics. The work discusses the incorporation of Internet of Medical Things (IoMT) and Artificial Intelligence (AI) for such technologies, indicating future directions in the development of sensors. Such amalgamations of technology and healthcare hold great promise for smart healthcare solutions, enabling real-time health monitoring and analytics that can easily direct approaches in personalized medicine.
Hassan (2022) [36] outlines the development of biosensors from their classical forms into more applications of wearable and stretchable technologies, signifying a direction towards continuous health monitoring. That notion revitalizes the importance of interdisciplinary collaboration toward the successful manufacture of point-of-care devices. Continuous health monitoring would revolutionize patient care, especially in collaborative control of chronic diseases, whereby timely interventions would avert complications.
Bhatia (2024) [37] explores the advancements in biosensor technology, particularly with respect to cardiovascular diseases, discussing the ongoing attempts to use innovative technologies to improve diagnostics and health monitoring. The review presents a wide portfolio of potential biosensing methods and materials to provide greater sensitivity and specificity to cardiovascular diagnostics, thus making a call for such a device in clinical practice where it is required the most.
Mukherjee (2024) [38] has discussed the design of electrochemical biosensors for cancer biomarkers, thereby demonstrating the improvement of sensor performance on the large-scale by graphene-derived nanostructures. The importance of translating nanotechnology into clinical diagnostic solutions is now gaining prominence, especially in cancer diagnosis; it can be turning point in successful treatment when early clues are found.
The integration of intelligent and efficient wearable sensors with well-optimized wound dressing bandages holds a technological transformative era wherein contactless chronic skin monitoring can be established. However, this approach is still in its infancy and lacks systematic research to marry various components such as sensing, machine-skin interfacing, and most importantly, rapid data analytics. In this direction, the present review elucidates the merging of the two interrelated fields of wearable sensor technology and wound dressings, presenting an all-inclusive review of their joint potentialities in the continuous monitoring of chronic wounds. That being said, our review extends beyond conventional wound care in that it incorporates sensors seated within these dressings to facilitate the real-time evaluation of wound parameters. Blending the sensor data pertaining to signs of life, biochemical markers, and environmental conditions will offer a real-time, non-invasive picture of the wound's condition. In addition, the corresponding artificial intelligence algorithms harvest this dataset towards the prediction and optimization of tissue regeneration trajectories. The review covers the design considerations, the sensor technologies, and biomarker identification that can fuel the development of these intelligent solutions for wound care. In addition, it reviews the recent works targeting the implementation of AI models that predict wound healing based on sensed data. This review serves as a great guide for researchers in the multidisciplinary area of sensors and wound dressings, for the advancement of contactless chronic skin monitoring and predictive tissue regeneration by (Prakashan D,2024) [39].

Table 2. Nanomaterials-based electrochemical biosensors: innovations, gaps, and future trajectories.

Thematic Cluster	Synthesis of Evidence and Contributions	Key Contributing Authors (Year)
Sensor Types & Design Evolution	Electrochemical biosensors dominate, incorporating voltammetry, amperometry, potentiometry, and microfluidics. Portable and wearable formats are emphasized for real-time diagnostics and point-of-care testing. Integrated smartphone and microfluidic interfaces increase usability in field conditions and low-resource settings.	Baranwal (2022); Umapathi (2022); Kulkarni (2022); Prakashan D (2024)
Nanomaterial Utilization	Nanomaterials (CNTs, graphene, MXenes, metal NPs, ZnO) enhance sensitivity, selectivity, and signal transduction. 2D materials, especially graphene derivatives and MXenes, have demonstrated promise in early diagnostics. Gold nanostructures enhance conductivity and biomolecule immobilization.	Baranwal (2022); Li (2022); Petrucci (2022); Mukherjee (2024)
Biofunctional Components	Use of bioreceptors—enzymes, antibodies, nucleic acids—is critical. Gold nanoparticles facilitate effective immobilization and enhance recognition efficiency.	Shanbhag (2023); Mukherjee (2024); Thakur (2022)

	Immobilization chemistry and surface optimization remain essential in improving bio-affinity and signal amplification.	
Clinical & Health Monitoring Applications	Sensors are being developed for rapid diagnosis of SARS-CoV-2, cancer biomarkers, antioxidants, and wound biomarkers. Real-time, non-invasive monitoring (e.g., chronic wounds) is emerging through integration with wearable dressings and AI algorithms. Early detection and personalized diagnostics are core priorities.	Kumar (2022); Mukherjee (2024); Petrucci (2022); Prakashan D (2024)
Environmental & Food Safety Monitoring	Electrochemical sensors show strong applicability in detecting water pollutants, pesticide residues, and food antioxidants. Integration with portable and smartphone platforms enhances their real-world usability. Cost-effectiveness and sensor stability under harsh conditions remain concerns.	Hui (2022); Umapathi (2022); Petrucci (2022); Thakur (2022)
Performance Gains & Methodologies	Across studies, nanomaterials consistently demonstrate improved detection limits, faster response times, and higher reproducibility. Key methodologies include voltammetry, amperometry, surface modification, and electrochemical signal processing. Standardization of protocols remains a challenge.	Baranwal (2022); Shanbhag (2023); Li (2022); Zhang (2022)
Research Gaps Identified	Core challenges include: (1) lack of clinical validation, (2) insufficient long-term stability data, (3) challenges in real-time and large-scale deployment, (4) bioreceptor degradation, (5) environmental toxicity of nanomaterials, and (6) cost barriers to commercial scalability.	Multiple (see above)
Future Perspectives & Recommendations	Future directions emphasize AI and IoT integration, triboelectric energy harvesting, skin–sensor interfacing, sustainable nanomaterials, and clinically validated, miniaturized, low-cost devices. A shift toward multifunctional, intelligent biosensing platforms is envisioned for both health and environmental sectors.	Kumar (2022); Prakashan D (2024); Zhang (2022); Mukherjee (2024)

2.3 Biocompatible and Wearable Sensor Materials

Wearable technology is becoming a growing force in health care. Such growth in wearables has raised the need for creating advanced materials which meet the two requirements of biocompatibility and proper functioning in diverse environments. The major improvement that materials science added to the functionality of wearable sensors is user-friendliness. This progress opened new applications in the fields of health applications and diagnostics. This review assembles and unifies important recent findings on biocompatible materials and their usage in wearable sensors, emphasizing all concomitant efforts relating to such development in this emerging field.

Khan (2024) [40] investigated self-healing hydrogels and conductive polymers, which emerge as excellent biocompatible materials suitable for use in wearable sensors. Their flexible, yet durable performances are essential in an on-body application, notwithstanding mechanical strain that most devices will undergo while in use. However, these materials would provide benefits, especially for their self-healing properties which help prolong the active life of devices without significant deterioration in performance. The materials' resilience and performance would therefore be a significant focal point in the development of wearable health technology.

In a complementary study, Alam (2024) [41] examined specifically biodegradable materials developed for implantable biosensors. This focus is critical in improving the longevity of devices while also minimizing immune response. Development of self-healing polymers and bioresorbable metals stands in the middle of this work by Alam, which demonstrates taking that material science route towards biological compatibility without a reduction in performance. It was specifically mentioned in Alam (2024) that biodegradable sensors reduce the need for surgical removal after implantation, thereby improving patient comfort and compliance.

De Marzo (2024) [42] expands this discussion further to include green biomaterials like natural polymers among the various environments in which they exist with low environmental impact, in addition to their biocompatibility and biodegradability. This would reflect the continuing trend of sustainably developing healthcare technologies, making sure that health monitoring solutions will not only be effective but also be environmentally responsible.

2.3.1 Mechanisms and Strategies in Sensor Development

Research into biointerfaced materials, as analyzed by Zohar (2021) [43], indicates that maintaining stable interactions between the sensors and biological systems—i.e., tissues and cells—is critical to effective monitoring-of-the latter. This focal point in the design of the material requires meticulous calculation of the interactive chemical, structural, and mechanical properties in such a way that they can withstand a biological environment without any functional loss. Zohar's work raised the demand for sensor-design strategies that support harmonious integration with biological entities.

Then came Han (2021) [44], who researched ultrathin soft materials conformable to the skin. These bioresorbable and self-healing materials are expected to improve biosafety and reliability for wearable and implantable devices. Han's results emphasize the view that developments in material science truly enhance the functionality of health-monitoring devices, here especially focusing on the need for soft materials to minimize discomfort for long-term use.

Transducer behavior in biosensors was reviewed by Polat (2022) [45], who emphasized that advanced materials play a key role in transducing biological signals into detectable outputs. This transduction is what equips wearable devices for real-time health monitoring and, thus, Polat's comments brought attention to the vital importance of integration of bio-receptors with electronic components to achieve the desired sensitivity and specificity for health monitoring applications.

2.3.2 Material Selection and Performance Optimization

Karthikeyan (2024) [46] provided critical insights into the fabrication of biomedical antennas, emphasizing substrate characteristics that optimize performance for non-invasive applications such as breast cancer detection. The material selection process is pivotal; it determines the antenna's efficiency, which directly affects diagnosis accuracy.

Verma (2022) [47] expanded on the integration of IoT technologies with wearable devices and their role in enhancing patient treatment, monitoring, and disease detection. The interplay between advanced materials and connectivity solutions, particularly 5G technology, transforms traditional health monitoring into a more responsive and proactive approach.

Yang (2022) [48] focused on the characteristics of biocompatible sensors, emphasizing their importance in long-term physiological monitoring and the detection of vital indicators. The materials used must not only provide reliability but also accommodate various physiological signals, enhancing the sensor’s diagnostic capabilities. Yang's work illustrates a comprehensive understanding of how materials fundamentally influence the effectiveness of wearable devices.

2.3.3 Selection of Materials and Optimization of Performance

Karthikeyan (2024) [46] directs an investigation of substrate features crucial to biomedical antenna construction, which increases efficiency in non-invasive applications such as breast cancer detection. Material selection determines the efficiency of the antenna, which further translates to diagnosis accuracy.

Verma (2022) [47] built on the combination of IoT technologies with wearable devices and their role in elevating patient treatment, monitoring, and disease detection. The combination of advanced materials with connectivity solutions, such as 5G technology, makes health monitoring instant and proactive than what it used to be.

Yang (2022) [48] studied the characteristics of biocompatible sensors that need to be used in long-term physiological monitoring and that check main vital indicators. To ensure reliability, the materials selected must accommodate all physiological signals, enhancing the diagnostic potential of the sensor. Hence, Yang's research shows holistic understanding of basically how materials influence effectiveness of wearable devices.

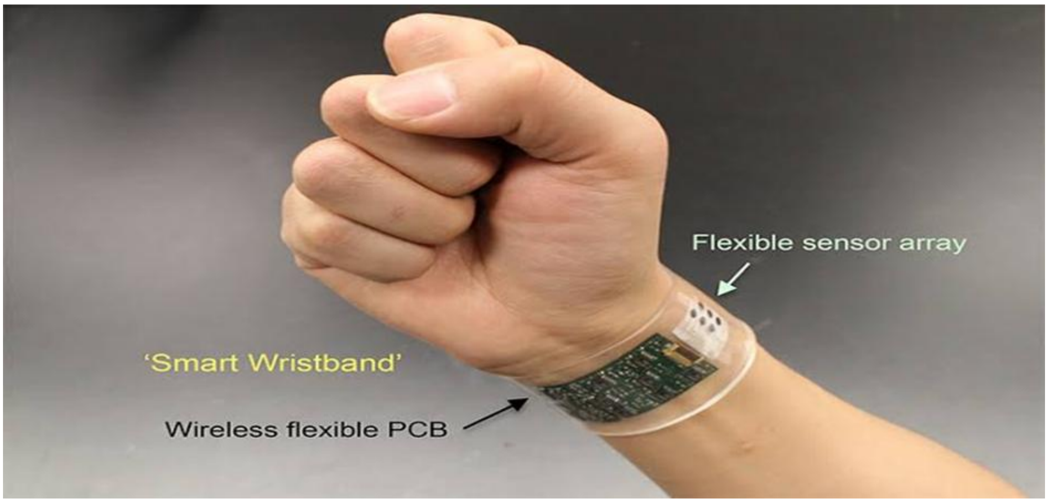

Figure 7. Functional schematic of a biosensor system comprising biological sensing elements, a transducer with integrated electrodes, and a signal processing unit. This figure illustrates the workflow of a biosensing platform. Biological recognition elements—including DNA, antibodies, enzymes, and whole cells—serve as the

primary interface for analyte interaction. These biological events are converted into measurable electrical signals by a transducer element outfitted with precision electrodes. The resulting signal, depicted here as a cyclic voltammogram, is processed and interpreted by a microelectronic signal processing unit to produce a readable output, enabling sensitive and specific biochemical analysis.

2.3.4 Advanced Applications and Technological Integration

Electrochemical biosensors consist of a recognition component and an electronic transducer that detect body fluids with high accuracy. More importantly, they provide timely results of the corresponding physiological parameters, and can be integrated into portable, wearable, and implantable devices, valuable for point-of-care-diagnostic scenarios. Personal glucose meters, in particular, greatly aid diabetes management within the comfort of patients' homes. The study further discusses the integration of biosensors into wearable, portable, and implantable systems. Another approach is to tackle critical engineering challenges for improving sensing accuracy, enabling multiplexing, and one-step protocols; and thus, mediate the integration of electrochemical biosensing devices into digital healthcare scenarios by (Razvan Bocu, 2024) [49].

Based on the advantages observed for bio-based polymers, focused studies regarding the fabrication of natural-based wearable sensors have been discussed. Particularly focused on cellulose, chitosan, silk, and gelatin in terms of their roles in sensing functionality. Thus, this review has opened a window toward wearable sensors based on natural polymers. It is hoped that the next generation of sensors will be launched by integrating newly achieved results from the use of sustainable and green components and miniaturized sensor structures by (Seyedeh Nooshin Banitaba, 2023) [50].

The smart wearable sensor has tremendous potential and is becoming increasingly popular in the biochemical and biological research fields, assuming an important role in the non-invasive monitoring of human health through continuous screening of specific biomarkers trapped in biological analytes compared to the conventional hospital-centered system in real time as a diagnostic tool to generate timely information. These smart wearable sensors provide an innovative option for assessing and investigating human health by integrating some recent advancement in technology and engineering, which can significantly enhance real-time point-of-care testing capabilities. These smart wearable sensors have developed progressively on a crossroad of multiplexed biosensing, microfluidic sampling, and data acquisition systems comprised of flexible substrate and bodily attachments for making them enhance wearability, portability, and reliability presents critical viewpoints on the latest happenings in the world of wearable sensors in the impending smart digital health monitoring in real-time scenarios. In addition, increased discussions have been witnessed over the last few years regarding materials selection, design optimization, fabrication techniques, and data processing units, along with their continuous monitoring and tracking strategies in a system-level integration such as Internet of Things, cyber-physical systems, and machine learning algorithms by (madhusudan b.kulkarni, 2024) [51].

Owing to the worldwide popularity of smartphones, these have been used for sensor readout, wireless data transfer, data processing, and storage, result display and finally cloud server communication leading to the development of smartphone-based biosensing systems. Recent advances show great promise for the healthcare system with scaling data processing powers, transfer efficiencies, and storage capacity with diversifying functionalities by (yihan Zhang, 2023) [52].

Faham (2024) [53] underscored the nanomaterial promise in optical sensors for continuous biomarker detection, where mechanical robustness and high sensitivity are advantageous. This shows that nanotechnology plays an important role in enhancing functional capabilities of wearable devices, to the extent that they could provide accurate readings in real-time.

Zheng Lou(2020) [54] discussed how advances in the field of material science are laying the foundation for novel wearable healthcare technologies. His work demonstrates the promising ability to monitor several biological signals, in a non-invasive way, such as through skin sweat and other biofluids and proposes the vision where continuous health monitoring becomes part of daily living.

Thanks to the advantages afforded by these wearable biosensors, a non-invasive analysis of various analytes can be performed, sensitive and selective, with wireless systems. The process has no long, laborious steps. A real-time monitoring scenario exists for physiological signals everywhere ranging from physical bio-signals such as temperature, pulse, and blood pressure to biochemical parameters such as glucose, dopamine, ions, and many more biomarkers present in human biofluids such as sweat, saliva, interstitial fluid, and tears. Continuous monitoring of physiological and personal parameters by means of wearable sensors, it impacts the definition of an individual user concerning their state of well-being, comfort, and health for people of all ages in indoor and outdoor life environments. Thus, in recent times, research sciences and biomedical communities are making use of wearable biosensors to assess precise health diagnosis outline the most recent notable accomplishments achieved within the domain of wearable sensors for biomedical and healthcare applications, involving bio-multifunctional smart wearable sensors, wearable devices, decision-making units, existing state of the market, challenges, and upcoming patterns of wearable devices by (Arzum Erdem,2023) [55].

Outline the development of precise, adaptable sensors enabled by nanomaterials, emphasizing their crucial role in augmenting the specificity and sensitivity of a sensor-requirement for efficient disease management, for gout

and kidney diseases. This technological revolution stands to align personal health monitoring with wearable devices, which bodes well for the future of noninvasive medical diagnostics by (Chong-Bo Ma,2024) [56].
Diabetes and its complications are serious threats to the health and well-being of millions of people. Glucose levels are critical indicators of the health status of diabetics. Over the past decade, concerted efforts in every field have facilitated enormous advances in glucose monitoring technology. Unfortunately, the applications of minimally invasive electrochemical CGM sensors still remain limited, mainly due to the following aspects: i) invasiveness, ii) lifespan, iii) biocompatibility, and iv) calibration and prediction. In the past few years, the performance of minimally invasive electrochemical CGM systems has marked improvement due to spectacular advancements seen in new materials and relevant technologies. In this review, we summarize the history of commercial CGMSs, development of sensing principles, and research progress of minimally invasive electrochemical CGM sensors in reducing invasiveness of implanted probes, maintaining enzyme activity, and improving sensor interface biocompatibility. Furthermore, this review introduces calibration algorithms and prediction algorithms applied to CGMSs and provides an overview of machine learning algorithms applied for glucose prediction by (Yuanyuan Zou, 2023)[57].
The classification of PGNs based on the structural derivatives of graphene (such as graphene sheets, graphene oxide, reduced graphene oxide, and graphene quantum dots) and the strain sensing mechanisms (such as resistive and capacitive) were introduced. With that, we told the fabrication approaches which are PGN-based strain sensors such be solution processing, melt blending, in situ polymerization, spinning, printing, and coating. After that, the present article highlighted functional PGN-based strain sensors based on different polymers and their applications in the monitoring of both minute and significant physiological signals. The challenges, in the end, identified were present and future perspectives of PGN-based wearable strain sensors for precise and trustworthy monitoring of physiological signals. This review presents a comprehensive overview on the current state-of-the-art of PGN-based wearable strain sensor to inspire further research in the field by (Suvrajyoti Mishra,2024) [58].
Biosensors have great potential in medical diagnostics due to their easy use, scalability, and efficient manufacturing. Smart wearables facilitate harmonious health monitoring for older adults, thereby bridging self-care and professional healthcare. Such exchanges of medical information diminish the need for hospital visits while opening several avenues of wellness, fitness, and athletics for consumers and commercial business sectors.
the advancements in Biosensors technology and their promising benefits in medicine, focusing on cardiovascular diseases and using informative diagrams. It examines fourteen key applications of Biosensors in the medical field, highlighting the integration of biomedical devices, apps, firmware, and advanced algorithms. These developments pave the way for innovative medical therapies, real-time evidence-based insights, customized solutions, and informed guidance, shaping a bright future for healthcare by (Dinesh Bhatia,2024) [59].

Table 3. Functional integration of emerging biomaterials and platforms for wearable and implantable biosensors

Thematic Domain	Core Innovations & Comparative Insights	Contributing Authors (Year)
Material Systems for Wearability	Flexible, self-healing, biodegradable, and eco-friendly polymers (e.g., hydrogels, silk, gelatin, cellulose) are central to improving device longevity, user comfort, and sustainability. Conductive polymers and soft substrates enhance signal reliability in dynamic environments.	Khan (2024); Alam (2024); Han (2021); De Marzo (2024); Yang (2022)
Biodegradability & Biosafety	Bioresorbable metals and biopolymers reduce the need for surgical retrieval of implanted devices. Ultrathin and biocompatible materials minimize immune response and mechanical irritation during long-term deployment.	Alam (2024); Han (2021); Yang (2022); Zohar (2021)
Sustainable & Eco-Friendly Design	Natural polymers (e.g., silk, cellulose, gelatin) are proposed for both biosensing and environmental safety. Emphasis is placed on green fabrication, eco-conscious sourcing, and reducing e-waste in healthcare electronics.	De Marzo (2024); Khan (2024); Alam (2024)
Biointerfaces & Tissue Integration	Studies stress improved mechanical compliance, surface chemistry, and biostability of materials interfacing with skin or internal tissue. Enhanced biointerfacing ensures stable signal acquisition over prolonged periods and minimizes foreign-body responses.	Zohar (2021); Han (2021); Khan (2024); Yang (2022)
	Advanced materials such as conductive polymers, hybrid nanocomposites, and bioreceptors are optimized for	Polat (2022); Faham (2024); Karthikeyan

Signal Transduction Enhancement	improved electrical and optical signal conversion. Materials like graphene, MXenes, and gold nanoparticles enable high sensitivity for real-time monitoring.	(2024); Yang (2022)
Wireless Communication & IoT	Biosensors are increasingly paired with wireless modules and IoT systems for continuous monitoring. 5G and Bluetooth protocols improve response time and remote diagnostics. Antenna materials are optimized for signal clarity, miniaturization, and long-range communication.	Verma (2022); Karthikeyan (2024); Prakashan D (2024)
Diagnostic Functionality & Use Cases	Applications span glucose monitoring, cancer detection, blood pressure, antioxidant sensing, chronic wound healing, and pollutant exposure. Focus is shifting toward multiplexed detection and real-time analytics.	Mukherjee (2024); Faham (2024); Petrucci (2022); Prakashan D (2024)
AI & Smart Analytics Integration	Integration of AI and machine learning into wearable devices enables predictive diagnostics, tissue regeneration assessment, and anomaly detection. Emphasis is placed on combining sensor output with advanced analytics for personalized healthcare.	Prakashan D (2024); Verma (2022); Yang (2022)
Outstanding Challenges	Limitations across studies include: (i) insufficient clinical trials, (ii) lack of long-term mechanical and biointerface testing, (iii) challenges in scale-up manufacturing, (iv) poor multi-analyte detection performance, and (v) underdeveloped cybersecurity frameworks for IoT-enabled biosensors.	All studies
Strategic Research Recommendations	Future directions call for: (i) design of hybrid biodegradable–self-healing materials, (ii) standardization of biointerface test protocols, (iii) AI-enabled wearable ecosystems, (iv) green electronics manufacturing, and (v) enhancing secure, cloud-integrated biosensing networks for point-of-care deployment.	Khan (2024); Alam (2024); Verma (2022); Faham (2024); Zohar (2021)

2.4 Optial & Field Effect Transistor Biosensors

Present-day biosensors are important instruments in medicine and environmental monitoring due to their speedy, sensitive, and specific detection of analytes. Field-Effect Transistor (FET) biosensors among all biotechnologies are very prominent because of their excellent performance characteristics. This review presents the collection and synthesis of all efforts made recently concerning improvement, ongoing issues, and future directions in FET biosensors. Specific areas include sensitivity optimization, technological integration enhancement, and application enhancements in the real world, all critical to the public adoption of these advanced technologies.

Optofluidic sensors integrate photonics with micro/nanofluidics in a compact device that can realize label-free detection of molecules and monitoring of binding events on surfaces in real time with very high specificity, ultrahigh sensitivity, low detection limit, and multiplexing capability. Nanophotonic structures made up of metallic and/or dielectric building blocks excel at focusing light into ultrasmall volumes, creating enhanced electromagnetic near-fields ideal for amplifying the molecular signal readout so that authors now draw attention to current trends in nanophotonics-enabled optofluidic biosensors for applications in life sciences while providing a detailed perspective on how these approaches can synergistically amplify the optical signal readout and achieve real-time dynamic monitoring, which is critically important in biomedical assays and clinical diagnostics by (Wang J,2022) [60].

They could, in turn, amplify the effectiveness of plasmonic phase biosensing but with hyper-sensitive transducers having detection limits at the single molecule level (<1 fg mm^{-2}) whereby the possibility of detecting analytes in concentrations orders of magnitude lower than what has been recently reported in literature becomes realistic. Also, these outputs put together the new arrangements based on dielectric nanomaterials-bound states in continuum and exceptional points. (Kabashin AV,2023) [61].

Optical biosensors have many advantages over traditional analytical methods. They enable the identification of several biological and chemical compounds directly, instantly, and without the need of labels. Some of the benefits include excellent specificity, sensitivity, compactness, and low cost. There are main topics the review discusses, which includes optical biosensor technologies based on nucleic acid. The review covers colorimetric, fluorescence, surface plasmon resonance (SPR), Evanescent-Wave Optical, Fiber optic, and bioluminescent optical fiber biosensors. The core principles of each type of biosensor are explained briefly, emphasizing the achievements of the last decade in the area of diagnosing infectious viral diseases. Concluding remarks concerning the perspectives of further developments are discussed by (Eksin E,2023) [62].

We highlight prospects for sensor performance enhancements and added functionalities through nanostructures as well as on-chip and optoelectronic integration with microfluidics, biochemistry, and data science toolkits. We also discuss open challenges in nanophotonic biosensing, such as reducing the overall cost and handling of complex biological samples, and provide an outlook on future opportunities to improve these technologies and expand their impact on improving health and safety by (Altug H,2022) [63].

Portable optical biosensors have emerged as revolutionary tools for the new-age diagnostics using point-of-care. With these sensors, point-of-care medical diagnostic testing has been revolutionized through the advances in the development of new portable optical sensors. All the possible ways of classifying optical sensors on the basis of the underlying transduction mechanism are addressed, including challenges such as sensitivity, specificity, miniaturization, cost, and regulatory approvals associated with portable optical biosensors for use in point-of-care diagnostics; possible solutions to these challenges are also examined. The minituarization strategies and the necessity of using innovative materials and substrates while designing point-of-care diagnostic devices will be seen. Moreover, the review considers the recent advances in the miniaturization, which have allowed portable optical devices to be developed for some of their latest applications in rapid point-of-care diagnostics focusing on the detection of bioanalytes linked to different health conditions. Portable optical biosensors can change health care by offering quicker, more precise, and personalized diagnoses, thereby improving disease management, health outcomes, and access to diagnostics around the world through tech advances by (Rasheed S,2024) [64].

The active microfluidic devices designed by the above authors, as well as non-paper- or paper-based lateral flow assays for in vitro diagnostics, are another topic discussed in this paper. Strategies for developing in vivo near-infrared fluorescence and surface-enhanced Raman scattering bio-imaging platforms to monitor physiological processes and disease progression in living cells and tissues were discussed within the article. Finally, applications for POCT and bio-imaging in diagnosing toxins, heavy metals, illegal drugs, cancers, traumatic brain injuries, and infectious diseases such as COVID-19, influenza, HIV, and sepsis have been highlighted by (Hang Y,2022) [65].

Most popular optical and impedance spectroscopy techniques absorption, fluorescence, surface plasmon resonance, Raman scattering, interferometry, and also newly emerging photonics trends are revised. The challenges in materials selection, surface modification in microfluidic structures, sensitivity enhancement, and miniaturization of biosensor systems are discussed. The review gives a good background for current advances and future trends in microfluidics integrated technologies for the label-free detection of protein biomarkers and discusses existing challenges and a way toward novel solutions by (Konoplev G,2022) [66].

Thanks to rapid advances in wearable biosensors, continuous health monitoring has become possible through non-invasive screening. Of all the possible sensing techniques, field-effect transistor (FET)-based wearable biosensors are getting increased attention because of their unique advantages, including label-free detection, rapid response, simple operation, and potential for integration. This review gives a comprehensive overview of the transformative impact the FET-based wearable biosensor could have for health care monitoring. By providing multidimensional insight on device design, fabrication, functionalization, and application, it is expected to serve as an important reference for researchers in biosensing technology and personalized health care by (Nguyen TT,2023) [67].

This biosensor chip successfully prevents any direct contact between the device and solution and uses independent signal readouts based on two different response mechanisms to circumvent the limitations faced with conventional transistor biosensors. The selective detection of cytokines (e.g., interferon-γ, IFN-γ) was accomplished using both the FET sensing mode (0.1-4000 pg mL-1, with a limit of detection of 24.1 fg mL-1) and the EC sensing mode (0.4-2000 ng mL-1) at different concentration ranges. The application of the EC-FET dual-mode biosensor for the analysis of real samples was demonstrated by detection of salivary levels of IFN-γ. The combination of EC and FET sensing modes provides not only high sensitivity and a wide dynamic detection range (seven orders of magnitude) for various biological matrices but also the enhanced confidence of detection results, showing promising applications in biological analysis and early disease diagnosis by (Ouyang J,2024)[68].

Portable point-of-care biosensors represent the future of medical diagnostics with the intention to improve health care through reduced costs, improved access, and increased quality, termed the 'triple aim.' Moreover, ere developing myriad point-of-care sensors with sufficiently high sensitivity to detect multiple analytes in a real-time mode will draw all medical diagnostics within the reach of human beings. Biochemical field-effect-transistor (FET)-based biosensors are characterized by ultrahigh sensitivity, label-free and amplification-free detection, low cost and low complexity, portability, and large-scale multiplexability. It is being thought of embedding these biosensors in wearable or implantable devices which provide a way for real-time monitoring of analytes in vivo and hence detect early disease biomarkers for diagnosis and management. The review discusses the recent advances concerning the development of the sensitivity, parallelization, and reuse of the FET biosensors; establishes the benchmark limit of detection of currently available FET biosensors; elaborates on the challenges confronted, and summarizes the opportunities available for the FET biosensors focusing on future health care applications by (Chen S,2023) [69].

The ultrasensitive recognition of biomarkers enables a very precise diagnosis of diseases. Graphene-based field-effect transistors (GFET) are considered the key promising devices among next-generation biosensors. Ultimately, GFET biosensors possess unique advantages such as being label-free, easier to integrate and operate, and the ability to directly detect biomarkers in liquid environments. That includes coming up with various disease biomarker detection sensitivity enhancement strategies (e.g., cancer, cardiovascular diseases, neurodegenerative disorders, infectious viruses, etc.) as incorporated in microfluidics. At the conclusion will be the discussed issues and challenges that the GFET biosensors strategies for modulation of biosensing interfaces face in biomarker detection by (Zhao W,2024) [70].

In medicine, these sensors have made it easier to diagnose diseases, discover drugs, and create point-of-care devices; in environment monitoring, they have been used to assess air, water, and soil quality and ensure food safety. Nevertheless, there is still a great deal of work to be done, despite impressive advances having been made. This review article presents the latest modifications in micro- and nanotechnology-enabled sensors for the biomedical and environmental challenges, giving special emphasis to improvement of the basic sensing techniques with the help of micro/nanotechnology. The different fields and applications of these sensors in solving the present-day problems in both biomedical and environmental sectors have been dealt with. The paper discussed the future scope of the study in expansion toward expanding the detection capabilities of sensors/devices, increasing the sensitivity and selectivity, integrating wireless communication and energy-harvesting technologies, and finally optimizing sample preparation, material selection, and automation in design, fabrication, and characterization of sensors by (Tovar-Lopez FJ, 2023) [71].

The paper has dealt with the biosensors made possible by organic electronics-that include electro-chemical, optical, piezoelectric, and thermal sensors. Their diversity in detecting biomolecules, pathogens, and environmental contaminates has been illustrated in the light of these biosensors. It also deals with the integration of organic biosensors into the wearables and the Internet of Things (IoT) ecosystem, whereby they can provide almost real-time remote and individualized health-monitoring solutions. The review also deals with the present challenges and the future of organic biosensing with emphasis on the potential of breakthroughs towards personalized medicine, environmental sustainability, and advancement in human health and well-being as far by (Kaushal JB,2023) [72].

Early detection of cancers is a prime factor in getting a successful diagnosis, which may substantially lower rates of death and increase chances for survival among patients. Cancer biomarkers are helpful in detecting the different stages of cancer cells, following their growth, and judging the patient's response to treatment. Cancer detection using traditional methods is quite complicated due to the long steps, such as nucleic acid amplification, target detection, and a long treatment process that may not be applicable for rapid screening. Biosensors appear to be prospective tools for the diagnosis of cancer which can be used to detect cancers and which, because of their unique electrical and mechanical properties, show great promise in developing carbon nanotube (CNT)- and graphene-based transistor biosensors. These biosensors allow a highly sensitive and selective rapid detection of cancer biomarkers, usually at very low concentrations. This review article will present recent developments in the area of CNT- and graphene-based transistor biosensors for detecting cancers by (Sengupta J,2023) [73].

There came a paradigm shift in the healthcare monitoring system with the wide application of wearable biosensors, which screen with a non-invasive and continuous method. Among the many sensing techniques, more attention is being paid to field-effect transistor (FET)-based wearable biosensors, as they bring advantages in detection, including label-free, fast response, easy operation, and capability of integration. This particular background is significant in exploring some of the specific designs of an FET-based biosensor, like enzyme, antibody, and nanobody, aptamer, as well as ion-sensitive membrane sensors. The next section investigates how biomarkers present in the physiological fluids of sweat, tears, saliva, and skin interstitial fluid (ISF) are monitored using an FET-based sensor technology. It concludes with discussions of various challenges, technical issues, and opportunities related to applications using FET-based biosensors. Overall, this review demonstrates the transformative potential of FET-based wearable biosensors in healthcare monitoring. By giving a well-defined perspective on device design, fabrication, functionalization, and applications, this paper aims to serve as an important reference for researchers in the field of biosensing technology and personalized healthcare by (Nguyen TT,2023) [74].

Integrating organic biosensors into those wearable devices and into the whole Internet of Things (IoT) ecosystem is also discussed-as these would provide real-time, remote, and personalized monitoring solutions. The review further discusses the present challenges and future prospects of organic biosensing, hence emphasizing the promise of breakthroughs in personalized medicine, sustainability at the environmental level, and progress in human health and well-being by (Kaushal JB,2023) [75].

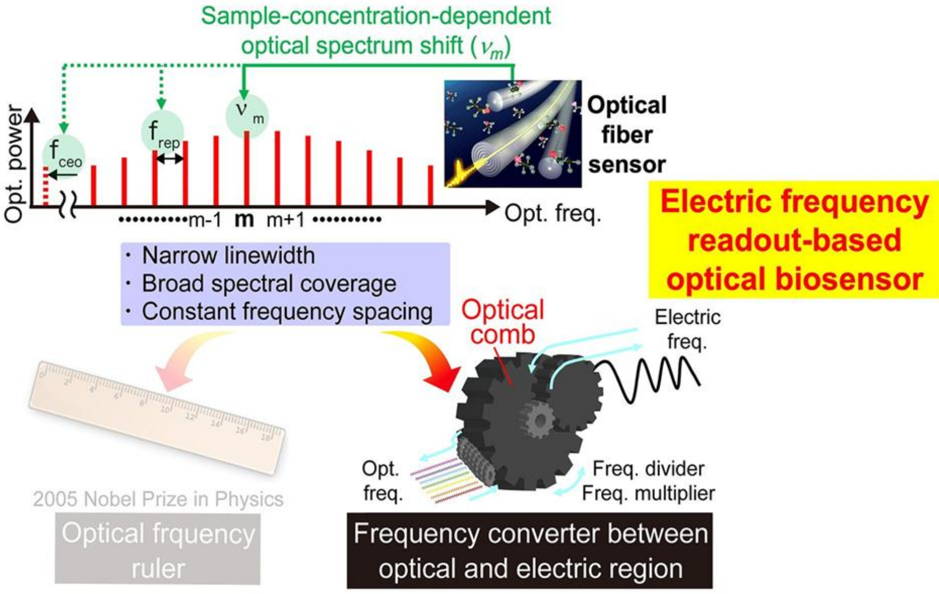

Figure 7. Functional schematic of a biosensor system comprising biological sensing elements, a transducer with integrated electrodes, and a signal processing unit.

This figure illustrates the workflow of a biosensing platform. Biological recognition elements—including DNA, antibodies, enzymes, and whole cells—serve as the primary interface for analyte interaction. These biological events are converted into measurable electrical signals by a transducer element outfitted with precision electrodes. The resulting signal, depicted here as a cyclic voltammogram, is processed and interpreted by a microelectronic signal processing unit to produce a readable output, enabling sensitive and specific biochemical analysis.

In fields of biomarker detection platforms, FET biosensors are very potentially responsible as they respond very fast, and miniaturization and integration can easily be arranged for high-throughput screening, unlike traditional clinical diagnostic modes. Beginning from this perspective, the review then concentrates on those immunoassays developed upon a single biosensor for disease diagnosis; efficient integrations of FET biosensors with a large-area array, where multiplexing allows estimation into the main testing options useful for high-throughput diagnosis; and the integrations of the FET biosensors with microfluidics majorly aiding the rapid evolution of lab-on-chip (LOC) sensing platforms, aiding biosensor integration with various sensor types for multifunctional applications. Lastly, we summarize the long-term projection of commercialization of the FET sensing systems from (Hao R, Liu L,2023) [76].

An innovative one-dimensional semiconductor nanomaterial, silicon nanowires (SiNWs) are extremely promising in the area of biomedical sensing. SiNWs have outstanding electronic properties for enhancing the detection sensitivity of biosensors. When SiNWs are combined with field-effect transistors (FET), that special biosensor shows real-time and label-free high sensitivity and target selectivity to a signal. Of late, there have been increased interests on biomedical detections using SINC-FETs. In this review, we critically present a survey of the SiNW-FETs with special emphasis on reversible surface modification methods. In addition, applications of SiNW-FETs in the detection of DNA, protein, and microorganisms are summarized. With that, we will discuss the working principles and technical methods related to them. This review will discuss the prospects and challenges to be addressed by SiNW-FETs in their future developments (Li H, Li D, Chen H,2023) [77].

Biosensor is a biorecognition element device that measures biological reactions via physical and chemical sensing. Biorecognition elements can include enzymes, antibodies, nucleic acids, proteins, receptor molecules, or any other biological agent that acts as input, recognizes, and transfers signals and outputs as digitalization, color, absorbance, or odor. Biosensors undoubtedly play a significant role in the clinical and biomedical sectors that save time during diagnosis, generate results in quick time, can be rapidly transported to any place where an emergency or natural disaster arises, are pocket-size, economically viable, and have high sensitivity, specificity with a low limit of detection. By 2036, the clinical biosensors market is expected to cross 36.7 billion dollars, even as the scope of the biosensor application became extremely large during the COVID-19 pandemic. This chapter will be about biosensors and their clinical applications by (Parameswari R,2024) [78].

Nano-biosensors consisting of recognition molecules and nanomaterials have been widely applied in disease diagnosis, health monitoring, and environmental monitoring. Molecular specificity field-effect transistor (FET) biosensors as a kind of nano-biosensors do show amplified signals with many advantages such as rapid response time, easy miniaturization, and integration, securing their exceptional sensitivity toward the detection and identification of molecules. Because of inherent properties such as tunability in structure and high stability, aptamers have emerged to be most widely applied biological recognition entities in the FET sensing domain. This review aims to summarize significant advances in the area of FET biosensors based on aptamer functionalized nanomaterials related to their applications for medical diagnostics and environmental monitoring. The comprehensive summary covers the structure, sensing mechanisms, fabrication techniques, and functionalization strategies of aptamer-modified FET biosensors. In this review, the authors also analyzed the relations between structure and sensing performance of FET biosensors. The authors will also focus on the challenges and futuristic views so that support might be given for future development of efficient healthcare management and environmental monitoring devices (Chen D,2023) [79].

Table 4. Materials, modalities, and diagnostic functionality across optical and transistor-based platforms

Thematic Focus	Technologies & Materials	Diagnostic Applications	Key Advancements	Limitations & Research Gaps	Future Perspectives	Representative Studies (Author, Year)
Nanophotonic and Plasmonic Sensors	Nanophotonic structures, dielectric nanomaterials, plasmonic phase biosensors	Real-time biosensing, single-molecule detection	Ultra-sensitive, label-free detection using plasmonic and nanophotonic coupling; improved specificity in optical signal enhancement	Device miniaturization, complexity of real-world sample handling, and cost remain concerns	Integration with optoelectronics, machine learning, and continuum states for biosensor optimization	Wang J (2022); Kabashin AV (2023); Altug H (2022)
Optical Biosensors for POC Diagnostics	Colorimetric, fluorescence, SPR sensors; portable optical platforms	Infectious disease diagnostics, viral detection, decentralized healthcare	Portable and highly sensitive biosensors allow rapid point-of-care testing; colorimetric and SPR-based sensors optimized for viral RNA/DNA detection	Challenges in scalability, affordability, and long-term reusability in field conditions	Miniaturization and cost-efficient substrates for wide-scale deployment	Eksin E (2023); Rasheed S (2024)
Dual-mode and FET Biosensing Systems	EC-FET hybrid biosensors, graphene FETs, silicon and wearable FET platforms	Cytokine profiling, cancer biomarker detection, real-time physiological monitoring	High-performance, dual-mode biosensors with wide dynamic range; wearable FETs support real-time monitoring of sweat, tears, saliva, and ISF	Multiplexing limitations, signal drift, and challenges in wearable platform integration	Scalable fabrication of FET-based sensors with improved stability for chronic disease monitoring	Ouyang J (2024); Nguyen TT (2023); Chen S (2023); Zhao W (2024)
Organic	Organic polymer-based biosensors;	Personalized medicine, environmental exposure	Versatile detection capabilities with remote	Integration challenges, limited durability of	Organic biosensors as sustainable solutions for	Kaushal JB (2023); Verma (2022)

and IoT-integrated Platforms	wearable + IoT-enabled sensors	assessment	connectivity; seamless integration into wearables and IoT for decentralized health tracking	organic biosensors under long-term physiological conditions	personalized healthcare and environmental sustainability	
Carbon Nanomaterial Transducers	CNTs, graphene nanocomposites, GFETs	Cancer biomarker detection, neurodegenerative disease screening	Exceptional electrical properties of CNTs and graphene improve sensitivity and reduce noise in signal transduction platforms	Reproducibility and cost-effective fabrication remain technical hurdles	Enhancing large-scale reproducibility and hybrid composite-based carbon biosensors	Sengupta J (2023); Zhao W (2024)
Micro/Nano-enabled Sensing Systems	Microfluidic devices, nanostructured materials	Biomedical and environmental biosensing	Nanotechnology platforms enable miniaturized, multi-modal sensing with enhanced sensitivity in both biological and ecological monitoring scenarios	Limited interdisciplinary standardization for dual biomedical-environmental validation		

3. CONCLUSION

The advances made recently in Sensor technologies such as nanobiosensors, electrochemical sensors, wearable sensors, and Field-Effect Transistor (FET) biosensors have shown extraordinary promise for the forthcoming improvements in diagnostic capabilities using medicine and environmental monitoring. Nanobiosensors utilize materials such as carbon nanotubes, quantum dots, and graphene to result in enhanced sensitivity and efficiency, enabling real-time diagnostics for infectious diseases as well as personalized medicine. The integration of nanomaterials has improved detection limits and response times so that single biomolecules can be detected and the unique catalytic roles of nanostructures in biochemical interactions are exposed. Electrochemical sensors are very important in analytical chemistry. In this field, nanotechnology has benefited by developing its foundations on techniques such as voltammetry that have been improved with incorporation of nanomaterials in increased surface area and improvement of electron transfer efficiency in use. These sensors are also important in terms of various applications like clinical tests and environmental monitoring, making it important to have increased sensitivity in detecting pollutants even in highly complex matrices. These sensors can also be used in clinical applications that are very promising, especially with portable devices: less time for testing during public health situations, for example, COVID-19. As such, they come toward becoming more wearables, though some of the challenges may include durability in the long term; power management of such devices; data security; and scalability of sustainable biomaterials, which would have to be considered for reducing the inefficiencies in clinical integration. FET biosensors have been crucial tools designed as rapid and sensitive analyzers for detecting analytes. The emphasis on enhanced sensitivity essentially assists early disease diagnostics as well as boosts functionality when integrated with microfluidics for concurrent analysis of multiple biomarkers. While these advancements are very promising, there are still challenges like optimizing biosensing interfaces and controlling costs. The explosion in trend toward multifunctionality, further coupled with the incorporation of optical techniques within these sensors, enriches the diagnostics processes with its intensity and specificity.

Overall, challenges and research gaps on these sensor technologies should be addressed for real-world applications, requiring convergent efforts and ingenuity to realize these technologies' full potential contribution to improved public health and environmental sustainability.

The collective advances in sensor technologies include nanobiosensors, electrochemical sensors, wearable sensors, and FET biosensors, which together lead towards a new transformative era in their potential applications across healthcare, environmental monitoring, and food safety. Such improvements using nanomaterials include innovations in design strategies and with new materials such as graphene or other 2D materials. Sensor performance has improved greatly in terms of their sensitivity, selectivity, and even being able to provide real-time diagnostics. Improvement of electron transfer efficacy, enhanced immobilization in bioreceptors, and multifunctionality are improvements making these sensors best for disease diagnostics, personal health monitoring, and environmental sustainability.

However, notwithstanding those invaluable progress developments, challenges such as instability, irreproducibility, scalability, and overall reliability still exist. To achieve optimal performance and move from laboratory to real-world applications, these gaps must be addressed. Future work must optimize material synthesis, multi-analyte capabilities, and begin integrating advanced technologies like artificial intelligence and the Internet of Medical Things. Cross-disciplinary efforts would prove beneficial in overcoming these obstacles.

By driving innovation and aligning the strengths of novel materials with high-tech tools, these sensor technologies hold the promise of transforming personal health monitoring and environmental sustainability. There is excitement in the prospects of what collaborative research, next-generation designs, and advanced materials will do in the next decade. All of these efforts will ultimately lead to smarter, more effective healthcare solutions, and in the end, positively influence public health outcomes and life quality.

4. Future perspectives

The future is expected to see major advances in biosensor developments using 2D materials, artificial intelligence (AI), and advanced data analytics. Because of their intrinsic properties, the use of materials like graphene is predicted to boost the efficiency and scalability of nanobiosensors at a time when the demand for real-time wearable health diagnostics to support proactive health management is increasing. New forms of miniaturization and the convergence of nanostructures with innovative electrochemical methodologies will lead to the birth of portable diagnostic devices that are personalized, which also forms an integral aspect of today's health care. There is a strong drive to integrate nanomaterials with AI systems to significantly enhance the real-time monitoring capability from health into industrial applications. From literature, research proposes commercially viable strategies for the large-scale production of these sensors so that they are user-friendly for point-of-care applications.

In the field of electrochemical biosensors, rapid onboard testing for viral and cancer-related ailments is underscored, demonstrating the relevance of these devices in public health management. There is a clear trend away from traditional to wearable technologies, which correlates with the idea of continuous health monitoring as a requirement for chronic disease management and upliftment of patient outcomes. Cardiovascular diagnostic advancements reiterate the critical demand for the practical, accessible testing tools in clinical practice while on-going investigation of the ways nanotechnology can improve the performance of sensors.

Furthermore, in the research so far, there are considerable gaps that must be addressed to include wearable sensors into electronic health systems: the optimization of designs of the sensors; improving biocompatibility; improving inaccuracy. Therefore, the future of the research must include development of novel materials, IoT architecture for wearables, and sustainable alternatives like bio-based polymers to mitigate existing drawbacks. Dramatically, ensuring the credibility of FET biosensors in different biological matrices, together with grappling with different regulatory torts, would be another binding step toward the realistic advancement of these sensors. Thus, a synergic approach would be key to innovating biosensor technology by harmonizing knowledge from varied fields in making healthcare proactive and personalized.

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