Bi–Quarterly
Volume 3, Issue 1, Spring & Summer 2026
GHALIB MEDICAL JOURNAL
(MJ)
Journal Homepage: https://www.mj.ghalib.edu.af
ISSN
P: 3105-0786
E: 3006-094X
OPEN ACCESS
Publisher: Ghalib University-Herat
https://doi.org/10.58342/MJ.V.3.I.1.14

Biosensors in Medicine: A Biochemical Perspective on Principles, Applications, and Future Trends

Mohammad Ehsan Salehi[1, 2*], Baryaly Atarpoor[3]

[*1.] Paraclinical Department, Faculty of Curative Medicine, Ghalib University, Herat, Afghanistan.
(Corresponding author Email: Salehi313@alumni.um.ac.ir)
[2.] Research Center and Scientific Journals, Ghalib University-Herat, Herat, Afghanistan
[3.] Clinical Department, Faculty of Curative Medicine, Ghalib University, Herat, Afghanistan. (dr.attarpoor@ghalib.edu.af)

Article Info

Article type: Review

pp: 223- 244

Received: 15/01/2026
Accepted: 17/03/2026
Published: 21/03/2026

ABSTRACT

Background and Objective: Biosensors have emerged as essential tools in modern medicine due to their ability to provide rapid, sensitive, and specific detection of biological analytes. This review aims to present a comprehensive biochemical perspective on the principles, classification, clinical applications, and future directions of biosensors in healthcare.

Method: A narrative review approach was employed to analyze and synthesize existing literature on biosensor technologies. Key aspects including fundamental biochemical mechanisms (enzyme–substrate interactions, antigen–antibody binding, and nucleic acid hybridization), classification based on biorecognition elements, and signal transduction systems were systematically examined.

Findings/ Result: Biosensors were categorized into major groups such as electrochemical, optical, and piezoelectric systems, each with distinct analytical advantages. Clinical applications were identified across multiple domains, including metabolic disorders, cancer diagnosis, infectious diseases, and cardiovascular monitoring. The findings highlight the growing importance of biosensors in point-of-care testing and personalized medicine. However, several limitations were noted, including challenges related to stability, reproducibility, biofouling, and scalability, despite advancements driven by nanotechnology, materials science, and synthetic biology.

Conclusion: Biosensors represent a rapidly evolving field with significant potential to transform diagnostic and therapeutic strategies in modern healthcare. Future developments, particularly in wearable devices, artificial intelligence integration, and lab-on-a-chip technologies, are expected to enhance their clinical applicability and

performance.
Keywords: Biosensors; Enzyme-based biosensors; Point-of-care testing; Signal transduction.

Cite this article: M. E. Salehi, B. Atarpoor. Biosensors in Medicine: A Biochemical Perspective on Principles, Applications, and Future Trends. *Ghalib Medical Journal*. [Internet]. Publication date. 21.03.2026; 3 (1): 223-244: https://doi.org/10.58342/MJ.V.3.I.1.14

دوفصل‌نامه
دورهٔ ۳، شمارهٔ ۱، بهار و تابستان ١٤٠٥

مجلهٔ علوم طبی غالب
(MJ)

صفحهٔ اصلی مجله: https://www.mj.ghalib.edu.af

ISSN
P: 3105-0786
E: 3006-094X

OPEN ACCESS

https://doi.org/10.58342/MJ.V.3.I.1.14

ناشر: پوهنتون/ دانش‌گاه غالب – هرات

بیوسنسورها در پزشکی: بررسی بیوشیمیایی مبانی، کاربردها و تحولات آینده

محمداحسان صالحی[1*]، بریالی عطارپور[2]

[*1]. دیپارتمنت پاراکلینیک، پوهنحی/دانشکده طب معالجوی، پوهنتون/ دانشگاه غالبِ هرات، هرات، افغانستان. (Salehi313@alumni.um.ac.ir)
[2]. مرکز تحقیقات و مجلات علمی، پوهنتون/ دانشگاه غالبِ هرات، هرات، افغانستان
[3]. دیپارتمنت کلینیک، پوهنحی/دانشکده طب معالجوی، پوهنتون/ دانشگاه غالبِ هرات، هرات، افغانستان (ایمیل: dr.attarpoor@ghalib.edu.af)

اطلاعات مقاله

نوع مقاله:
مروری

صص: ۲۲۳-۲۴۴
تاریخ دریافت:
۱۴۰۴/ ۱۰/ ۲۵
تاریخ پذیرش:
۱۴۰۴/ ۱۲/ ۲۶
تاریخ نشر:
۱۴۰۵/ ۰۱/ ۰۱

چکیده

زمینه و هدف: زیست‌حسگرها به‌دلیل توانایی در فراهم‌سازی شناسایی سریع، حساس و اختصاصی آنالیت‌های زیستی، به ابزارهایی اساسی در پزشکی نوین تبدیل شده‌اند. این مقاله مروری با هدف ارائه یک دیدگاه جامع بیوشیمیایی در خصوص اصول، طبقه‌بندی، کاربردهای بالینی و جهت‌گیری‌های آینده زیست‌حسگرها در حوزه سلامت تدوین شده است.

روش: در این مطالعه از رویکرد مروری روایتی به‌منظور تحلیل و تلفیق مطالعات موجود در زمینه فناوری‌های زیست‌حسگری استفاده شد. جنبه‌های کلیدی شامل مکانیسم‌های بنیادی بیوشیمیایی (نظیر برهم‌کنش آنزیم–سوبسترا، اتصال آنتی‌ژن–آنتی‌بادی و هیبریداسیون اسیدهای نوکلئیک)، طبقه بندی بر اساس عناصر شناسایی زیستی و سامانه‌های انتقال سیگنال به‌صورت نظام‌مند مورد بررسی قرار گرفتند.

یافته‌ها: زیست‌حسگرها به گروه‌های اصلی مانند سامانه‌های الکتروشیمیایی، نوری و پیزوالکتریک طبقه‌بندی شدند که هر یک دارای مزایای تحلیلی متمایزی هستند. کاربردهای بالینی آن‌ها در حوزه‌های متعددی از جمله اختلالات متابولیک، تشخیص سرطان، بیماری‌های عفونی و پایش قلبی–عروقی شناسایی گردید. یافته‌ها نشان‌دهنده اهمیت روزافزون زیست‌حسگرها در آزمون‌های تشخیص در محل ارائه خدمت (Point-of-Care) و پزشکی شخصی‌سازی‌شده است. با این حال، علی‌رغم پیشرفت‌های حاصل از فناوری نانو، علم مواد و زیست‌شناسی سنتزی، چالش‌هایی همچون پایداری، تکرارپذیری، بیوفولینگ و مقیاس‌پذیری همچنان وجود دارد.

نتیجه‌گیری: زیست‌حسگرها حوزه‌ای با رشد سریع هستند که ظرفیت قابل‌توجهی برای تحول در راهبردهای تشخیصی و درمانی در نظام سلامت مدرن دارند. پیشرفت‌های آینده، به‌ویژه در زمینه ابزارهای پوشیدنی، ادغام با هوش مصنوعی و فناوری‌های آزمایشگاه روی تراشه (Lab-on-a-Chip)، انتظار می‌رود کارایی و کاربردپذیری بالینی آن‌ها را به‌طور چشمگیری ارتقا دهد.

کلیدواژه‌ها: زیست‌حسگرها؛ زیست‌حسگرهای مبتنی بر آنزیم؛ تشخیص در محل ارائه خدمت؛ انتقال سیگنال.

ارجاع به این مقاله: صالحی م. ا، عطارپور ب. بیوسنسورها در پزشکی: بررسی بیوشیمیایی مبانی، کاربردها و تحولات آینده. *مجلهٔ علوم طبی غالب*. [اینترنت]. ۰۱/ ۰۱/ ۱۴۰۵. [تاریخ برداشت]؛ ۳(۱): ۲۲۳-۲۴۴. https://doi.org/10.58342/MJ.V.3.I.1.14

1. Introduction

Biosensors have emerged as pivotal tools in modern medicine, enabling the rapid, highly sensitive, and often real-time detection of a wide range of biological analytes. Broadly defined, a biosensor is an analytical device that integrates a specific biological recognition element with a physicochemical transducer to generate a quantifiable signal proportional to the concentration of a target analyte.

Since the seminal development of the first glucose biosensor by Clark and Lyons in 1962, biosensing technologies have undergone remarkable evolution. Early systems, primarily based on enzyme–substrate interactions, have progressively advanced into sophisticated platforms incorporating diverse biorecognition elements, including enzymes, antibodies, nucleic acids, and even whole cells. This evolution has significantly enhanced the specificity, sensitivity, and versatility of biosensors in clinical diagnostics and broader biomedical applications [1, 2].

From a biochemical standpoint, the operation of biosensors is fundamentally governed by the specificity and binding affinity of molecular interactions. Key recognition mechanisms, such as enzyme, substrate interactions, antigen-antibody binding, and nucleic acid hybridization, serve as the primary determinants of selectivity in these systems. These molecular events, which are regulated by thermodynamic and kinetic principles, play a decisive role in defining the sensitivity, response time, and overall analytical performance of biosensors. Consequently, a thorough understanding of these biochemical mechanisms is crucial not only for accurate data interpretation but also for the informed design and development of advanced biosensing platforms with enhanced accuracy, stability, and reliability [3, 4].

In clinical settings, the demand for rapid, accurate, and minimally invasive diagnostic technologies has increased markedly, driven by the rising prevalence of chronic diseases, recurrent infectious outbreaks, and the growing emphasis on personalized medicine. Biosensors have effectively responded to these needs by facilitating point-of-care testing, real-time monitoring, and early-stage disease detection. For instance, glucose biosensors have transformed diabetes management, while next-generation platforms are being developed to detect cancer biomarkers, cardiac indicators, and infectious agents [5, 6].

Collectively, these applications underscore the pivotal role of biosensors in bridging the gap between laboratory-based research and bedside clinical decision-making.

Recent advances in nanotechnology, materials science, and molecular biology have substantially expanded the functional capabilities of biosensors. The integration of nanomaterials, such as gold nanoparticles, graphene, and quantum dots, has markedly enhanced signal amplification and lowered detection limits. Concurrently, progress in biochemistry, particularly in protein engineering and synthetic biology, has facilitated the development of highly specific, stable, and tunable biorecognition elements. These interdisciplinary advances highlight the central role of biochemistry as a key driver in the continued evolution of biosensing technologies [7, 8].

Despite these developments, several challenges persist, including limitations in stability, reproducibility, cost-effectiveness, and seamless integration into clinical workflows. Overcoming these barriers requires not only technological innovation but also a deeper biochemical understanding of molecular recognition processes and signal transduction mechanisms. Accordingly, a comprehensive and clinically oriented overview of biosensors, grounded in biochemical principles, is essential for healthcare professionals aiming to effectively implement these technologies in practice.

The present review seeks to provide such an overview by examining the biochemical foundations of biosensors, their principal clinical applications, and emerging future directions. By presenting complex concepts in an accessible yet scientifically rigorous manner, this article aims to enhance physicians' understanding of biosensor technologies and to emphasize their growing importance in modern medicine.

Materials and Methods

This study was conducted as a narrative review aimed at providing a comprehensive biochemical overview of biosensors in medicine. Relevant scientific literature was identified through systematic searches of major electronic databases, including PubMed, Scopus, and Web of Science. Keywords such as "biosensors," "biochemical principles," "medical diagnostics," "enzyme-based biosensors," "immunosensors," and "nanobiosensors" were used in various combinations.

Articles published in English, with a focus on biomedical and biochemical aspects of biosensors, were included. Both classical foundational studies (e.g., early biosensor development) and recent advances in nanotechnology, synthetic biology, and clinical applications were considered to ensure a balanced and up to date perspective.

Studies were screened based on relevance to the biochemical mechanisms, clinical utility, and technological advancements of biosensors. Priority was given to peer-reviewed articles, review papers, and seminal works. Data were extracted and synthesized qualitatively, with emphasis on biochemical interactions, sensor design principles, and clinical applicability.

Biochemical Principles Underlying Biosensors

Biosensors are fundamentally based on biochemical interactions that enable the selective recognition of target analytes in complex biological matrices. A typical biosensor consists of three integrated components: a biorecognition element, a transducer, and a signal processing or readout unit. Among these, the biochemical characteristics of the biorecognition element are the primary determinants of the biosensor's selectivity, sensitivity, and overall analytical reliability [9].

Biorecognition Mechanisms

Biorecognition is mediated by highly specific molecular interactions that generally occur under physiological or near-physiological conditions. The most widely used recognition mechanisms include enzyme–substrate interactions, antigen–antibody binding, and nucleic acid hybridization. The specificity of these interactions arises from structural complementarity and a combination of non-covalent forces, including hydrogen bonding, electrostatic interactions, van der Waals forces, and hydrophobic interactions [9].

Enzyme-based biosensors are among the earliest and most extensively investigated biosensing platforms. In these systems, enzymes catalyze specific biochemical reactions that generate measurable products, often accompanied by electron transfer or local changes in pH. The catalytic efficiency (kcat) and substrate affinity (Km) of the enzyme strongly influence biosensor performance, particularly sensitivity and dynamic range. For example, glucose oxidase-based biosensors exploit the enzymatic oxidation of glucose, generating hydrogen peroxide that can be quantified electrochemically [10].

Immunosensors, in contrast, rely on the highly selective interaction between antigens and antibodies. Because of their strong specificity and high affinity, immunosensors are particularly useful for detecting low-abundance biomarkers, including proteins associated with cancer, inflammation, and infectious diseases. The binding affinity (Ka) and dissociation constant (Kd) are important biochemical parameters that influence detection limit, response stability, and assay robustness [11].

Nucleic acid-based biosensors use complementary base pairing to detect specific DNA or RNA sequences. These platforms are especially valuable in molecular diagnostics, including the detection of genetic mutations, pathogenic organisms, and clinically relevant nucleic acid targets. In addition to hybridization-based systems, newer designs also incorporate aptamer-based recognition elements, expanding the versatility of nucleic acid sensing. In all cases, hybridization kinetics and sequence specificity are central to accurate detection [12].

Immobilization of Bioreceptors

For effective biosensing, the biorecognition element must be immobilized on the transducer surface without loss of biological activity. Common immobilization strategies include physical adsorption, covalent bonding, entrapment, and affinity-based immobilization. From a biochemical perspective, preserving the native conformation of proteins and nucleic acids during immobilization is essential, because structural perturbation can markedly reduce binding affinity and catalytic activity [13].

Surface chemistry is therefore a critical determinant of biosensor design. Functional groups such as amines, carboxyls, and thiols are commonly used to anchor biomolecules to sensor surfaces. In addition, advanced materials and nanostructured substrates can increase surface area, improve biomolecule orientation, and enhance immobilization efficiency, thereby improving sensor performance.

Signal Transduction and Biochemical Conversion

The biochemical recognition event must be converted into a measurable output by the transducer. This process involves conversion of a biochemical interaction into a physical signal, such as an electrical current, light emission, absorbance change, fluorescence signal, or heat generation.

In electrochemical biosensors, enzymatic redox reactions or recognition-associated charge transfer events generate electrical signals. In optical biosensors, biochemical interactions are translated into changes in light absorption, fluorescence intensity, luminescence, or refractive index. In both cases, signal generation depends closely on the underlying biochemical processes, including reaction rate, molecular stability, and binding dynamics [14].

Kinetics and Thermodynamics of Biosensing

The performance of a biosensor is strongly influenced by the kinetics and thermodynamics of molecular interactions. Reaction kinetics determine how rapidly the sensor responds to the presence of an analyte, whereas thermodynamic parameters govern binding strength and equilibrium behavior.

Parameters such as the Michaelis–Menten constant (Km), maximum reaction velocity (Vmax), and binding constants such as Kd are important for characterizing biosensor behavior, especially in enzyme-based and affinity-based systems. In general, a low Km or Kd indicates high affinity, which is advantageous for detecting low analyte concentrations. However, excessively strong binding may reduce reversibility and limit sensor reuse [14].

Stability and Biochemical Limitations

One of the major challenges in biosensor development is the biochemical stability of the biorecognition element. Proteins and nucleic acids are highly sensitive to environmental conditions such as temperature, pH, ionic strength, and long-term storage conditions. Denaturation, degradation, or loss of activity can significantly compromise biosensor performance over time.

To address these limitations, several strategies have been developed, including enzyme stabilization, protein engineering, and the use of synthetic bioreceptors such as aptamers. These approaches aim to improve durability while preserving specificity and functional activity, thereby enhancing the clinical applicability of biosensors [14].

Integration of Biochemistry with Advanced Technologies

Recent progress has shown that integrating biochemical principles with nanotechnology and materials science can significantly improve biosensor performance. Nanomaterials facilitate faster electron transfer, larger effective surface area, and more efficient biomolecule immobilization. At the same time, advances in synthetic biology and molecular engineering are enabling the design of customized bioreceptors with tailored specificity and stability [15].

This convergence of disciplines emphasizes that biochemistry is not merely a foundational component of biosensors, but a central driving force behind their continued innovation and future development.

Types of Biosensors in Medicine

Biosensors can be classified based on various criteria, including the type of biorecognition element, the signal transduction mechanism, and their clinical applications. For physicians and healthcare professionals, an application-oriented classification is particularly useful, as it facilitates a better understanding of how these devices function in real-world medical settings.

Classification Based on Biorecognition Elements

The nature of the biological recognition component is one of the most fundamental ways to categorize biosensors. Each type offers distinct biochemical advantages and limitations.

Enzyme-Based Biosensors

Enzyme-based biosensors are among the most widely used and historically significant types. These sensors rely on the catalytic activity of enzymes to detect specific substrates. The biochemical specificity of enzymes ensures high selectivity, while their catalytic nature enables signal amplification.

A classic example is the glucose biosensor, where glucose oxidase catalyzes the oxidation of glucose, producing measurable electrochemical signals. Due to their reliability and efficiency, enzyme-based biosensors are extensively used in metabolic monitoring.

Immunosensors

Immunosensors utilize antigen–antibody interactions, which are highly specific and suitable for detecting low concentrations of biomolecules. These biosensors are particularly valuable in clinical diagnostics, including the detection of cancer biomarkers, hormones, and infectious agents.

The strength and specificity of antigen–antibody binding make immunosensors ideal for applications requiring high sensitivity. However, they may be affected by factors such as cross-reactivity and stability of antibodies.

Nucleic Acid-Based Biosensors

These biosensors are based on the principle of complementary base pairing between nucleic acid strands. They are widely used in molecular diagnostics, including the detection of genetic mutations, pathogens, and viral infections.

Their high specificity makes them essential tools in modern medicine, particularly for infectious disease detection and genetic screening.

Aptamer-Based Biosensors

Aptamers are synthetic nucleic acid molecules that can bind specific targets with high affinity. Compared to antibodies, aptamers offer advantages such as better stability, ease of synthesis, and lower immunogenicity.

From a biochemical perspective, aptamers represent a significant advancement, bridging the gap between natural and engineered recognition systems.

Classification Based on Signal Transduction Mechanisms

Another important way to classify biosensors is based on how the biochemical interaction is converted into a measurable signal.

Electrochemical Biosensors

These are the most commonly used biosensors in clinical practice. They measure electrical changes resulting from biochemical reactions, such as current, voltage, or impedance.

Their advantages include high sensitivity, low cost, and compatibility with portable devices, making them ideal for point-of-care applications [16, 17].

Optical Biosensors

Optical biosensors detect changes in light properties, including absorption, fluorescence, or refractive index. These systems are highly sensitive and allow for real-time and label-free detection.

They are widely used in research and increasingly in clinical diagnostics, particularly for biomarker detection [18].

Piezoelectric Biosensors

These biosensors measure changes in mass on a sensor surface by detecting variations in resonance frequency. When a target molecule binds to the surface, the mass change produces a measurable signal. Although highly sensitive, their clinical use is currently more limited compared to electrochemical systems.

Thermal Biosensors

Thermal biosensors operate by detecting heat changes generated during biochemical reactions; however, despite their conceptual simplicity, their practical application is limited due to relatively low sensitivity compared to other biosensing methods. A summary of major biosensor types and their clinical relevance is presented in Table 1.

Table 1. Classification of Biosensors by Biorecognition and Transduction Mode

Type of biosensor	Biorecognition element	Detection mechanism	Key advantages	Limitations	Clinical applications	References
Enzyme-based	Enzymes (e.g., oxidases, dehydrogenases)	Substrate conversion → measurable electrochemical/optical signal	High specificity, rapid response, signal amplification	pH/temperature sensitivity, limited stability, enzyme denaturation	Glucose monitoring, metabolic disorders	Clark & Lyons 1962; Wilson & Turner 1992; Wang 2008; Sassolas et al. 2012; D'Orazio 2003
Immunosensor	Antibody–antigen pair	Binding event → optical/electrochemical signal	Very high specificity, good selectivity	Cross-reactivity, cost, limited shelf life	Cancer biomarkers, infectious diseases	D'Orazio 2003; Mohankumar et al. 2021; Cesewski & Johnson 2020; Wang 2006; Lazcka et al. 2007
DNA/RNA biosensor	Nucleic acids (DNA/RNA probes)	Hybridization → signal change	High sensitivity, sequence specificity	Requires controlled conditions, possible non-specific binding	Genetic testing, pathogen detection	Sassolas et al. 2008; Lazcka et al. 2007; Cesewski & Johnson 2020
Aptamer-based	Synthetic oligonucleotides (aptamers)	Binding-induced conformational change → signal output	Stable, low-cost synthesis, reusable, high affinity	Selection/optimization is difficult, matrix effects	Emerging diagnostics, biomarker detection	Ellington & Szostak 1990; Cooper 2003; Turner et al. 1987
Electrochemical	Various recognition elements	Current/voltage/impedance changes	Cheap, portable, sensitive	Interference, electrode fouling	Point-of-care devices	Wilson et al. 2001; Ronkainen et al. 2010; Kimmel et al. 2012; Privett et al. 2008; Wang 2005; Wang 2006; Bandodkar & Wang 2014; Kim et al. 2019
Optical	Various recognition	Light-based signal (fluorescence,	Real-time, often	Expensive instrumentation,	Biomarker detection	Cooper 2002; Cooper 2003; Lopez et al. 2017

	elements	SPR, absorbance)	label-free	alignment sensitivity		
Piezoelectric	Various recognition elements	Mass loading → frequency shift	Label-free detection, real-time monitoring	Limited clinical translation, affected by viscosity/temperature	Research applications	Turner et al. 1987; Turner 2013; Mehrotra 2016
Thermal	Various recognition elements	Heat change	Simple principle, low-cost setup	Low sensitivity, environmental noise	Limited use	Turner et al. 1987; Mehrotra 2016; Bollella & Katz 2020

Classification Based on Clinical Applications

From a physician's perspective, the most practical classification is based on how biosensors are used in medicine.

Diagnostic Biosensors

These biosensors are employed for the detection of diseases and specific biomarkers, including applications such as glucose monitoring systems, cancer biomarker identification, and infectious disease diagnostics.

Monitoring Biosensors

Monitoring biosensors are designed for continuous or periodic measurement of physiological parameters. Wearable biosensors fall into this category and are increasingly used for chronic disease management.

Point-of-Care (POC) Biosensors

POC biosensors enable rapid testing at or near the patient's bedside. They reduce the need for centralized laboratory facilities and provide immediate results, which is critical in emergency and resource-limited settings [19].

Integration and Hybrid Biosensors

Modern biosensors often combine multiple recognition elements or transduction mechanisms to enhance performance. These hybrid systems leverage advances in biochemistry, nanotechnology, and materials science to achieve higher sensitivity, specificity, and robustness.

Such integrated approaches reflect the evolving nature of biosensor technology and highlight the importance of interdisciplinary innovation [20].

Clinical Applications of Biosensors in Medicine

Biosensors have profoundly transformed clinical practice by enabling rapid, highly sensitive, and often real-time detection of diseases and physiological conditions. Their integration into diagnostic and monitoring systems has enhanced patient outcomes, facilitated early disease detection, and accelerated the transition toward personalized medicine. From a biochemical perspective, the high specificity of biosensors in detecting target biomolecules forms the foundation of their diverse clinical applications.

Biosensors in Metabolic Disorders

One of the most well-established and successful applications of biosensors is in the management of metabolic disorders, particularly diabetes mellitus. Glucose biosensors, commonly based on glucose oxidase, have revolutionized blood glucose monitoring by enabling rapid, accurate, and user-friendly measurements.

These devices support both point-of-care testing and continuous glucose monitoring, allowing timely therapeutic interventions by patients and clinicians. The high biochemical specificity of enzyme–substrate interactions ensure reliable performance even in complex biological matrices [21].

Cancer Diagnosis and Biomarker Detection

Biosensors are increasingly utilized in oncology for the detection of cancer biomarkers, including proteins, nucleic acids, and circulating tumor cells. Early detection plays a critical role in improving patient survival, and biosensors offer high sensitivity along with the potential for minimally invasive diagnostics.

Immunosensors and nucleic acid-based biosensors are particularly important for identifying tumor-associated antigens and genetic mutations. Advances in nanotechnology have further enhanced detection sensitivity, enabling the identification of biomarkers at ultra-low concentrations [22].

Infectious Disease Detection

Rapid and accurate diagnosis of infectious diseases is essential for effective treatment and infection control. Biosensors have shown considerable potential in detecting bacterial, viral, and parasitic pathogens with high specificity and speed.

In particular, nucleic acid-based biosensors enable precise identification of pathogens through DNA or RNA recognition. These technologies have gained significant attention during global outbreaks, where rapid diagnostic tools are critical for limiting disease transmission [23].

Cardiovascular Disease Monitoring

Cardiovascular diseases remain a leading cause of mortality worldwide. Biosensors are widely used for detecting cardiac biomarkers such as troponins, which serve as key indicators of myocardial injury.

Electrochemical and optical biosensors facilitate rapid and sensitive detection of these biomarkers, enabling early diagnosis of conditions such as myocardial infarction. Point-of-care implementation of these technologies significantly reduces diagnostic delays and improves clinical outcomes [24].

Wearable and Continuous Monitoring Biosensors

Recent technological advances have led to the development of wearable biosensors capable of continuous monitoring of physiological parameters. These devices can analyze biomarkers in sweat, saliva, or interstitial fluid, offering non-invasive alternatives to conventional blood-based testing.

From a biochemical perspective, maintaining the stability and sensitivity of biorecognition elements in dynamic physiological environments remains a significant challenge. Nevertheless, wearable biosensors represent a major advancement toward personalized and preventive healthcare.

Point-of-Care Testing (POC)

Point-of-care biosensors are designed to deliver rapid diagnostic results at or near the patient's bedside. These devices are particularly valuable in emergency situations, rural settings, and resource-limited environments.

Their portability, ease of use, and rapid response time make them indispensable in modern healthcare systems. Biochemically optimized recognition elements ensure that these systems maintain accuracy despite simplified operational procedures [25].

Emerging Applications in Personalized Medicine

Biosensors are playing an increasingly important role in personalized medicine by enabling patient-specific monitoring and treatment optimization. By profiling individual biomarkers, these systems facilitate more precise and effective therapeutic strategies.

This approach relies heavily on biochemical specificity and the ability to detect subtle variations in molecular concentrations, further emphasizing the central role of biochemistry in advancing modern medical technologies [26]. A summary of major clinical applications of biosensors is presented in Table 2.

Table 2. Clinical Applications of Biosensors: Targets, Types, and Diagnostic Utility.

Clinical Area	Target Biomarker/Analyte	Type of Biosensor	Sample Type	Clinical Purpose	References
Metabolic Disorders	Glucose	Enzyme-based (glucose oxidase)	Blood, interstitial fluid	Diagnosis and monitoring of diabetes	Wang J. 2008; Wilson R &Turner AP. 1992; Wang J. 2001.
Cancer Detection	Tumor markers (e.g., PSA, HER2)	Immunosensors, optical	Blood, serum	Early detection and prognosis	Wang J. 2006; Cooper MA. 2003.
Infectious Diseases	Viral RNA/DNA, antigens	Nucleic acid-based, immunosensors	Blood, saliva, swabs	Rapid pathogen identification	Cesewski & Johnson. 2020; Lazcka et al. 2007; Sassolas et al. 2008.
Cardiovascular Diseases	Troponin, CK-MB	Electrochemical, immunosensors	Blood	Early diagnosis of myocardial infarction	Clark, Lyons. 1962; D'Orazio. 2003; Murugaiyan et al. 2014.
Wearable Monitoring	Electrolytes, metabolites	Electrochemical, wearable sensors	Sweat, saliva	Continuous health monitoring	Kim et al. 2019; Wang. 2014.
Point-of-Care Testing	Multiple analytes	Portable electrochemical/optical	Blood, urine	Rapid bedside diagnosis	Lopez et al. 2017; Flynn & Chang. 2024; Wang J. 2006.

Advantages and Limitations of Biosensors

Biosensors have emerged as highly valuable analytical tools due to their ability to convert a biological response into a measurable signal with high specificity and sensitivity. One of the major advantages of biosensors is their rapid response time, enabling near real-time analysis, which is particularly crucial in clinical diagnostics and environmental monitoring. In addition, biosensors typically require small sample volumes, are cost-effective compared to conventional laboratory techniques, and can be designed for portability, making them suitable for point-of-care applications [27].

Another important strength is their high selectivity, which is achieved through the use of biological recognition elements such as enzymes, antibodies, nucleic acids, or even whole cells. This selectivity significantly reduces interference from complex biological matrices. Furthermore, advances in nanotechnology and material science have greatly improved the sensitivity and stability of modern biosensors, allowing detection of analytes at very low concentrations [28].

Despite these advantages, biosensors also face several important limitations. A primary challenge is the limited operational stability of biological recognition elements, which can lose activity over time due to temperature, pH, or storage conditions. In addition, sensor fouling, especially in biological fluids such as blood or saliva, can reduce accuracy and reproducibility. Many biosensors also suffer from calibration drift, requiring frequent recalibration for reliable long-term use [29].

From a translational perspective, scalability and mass production remain significant hurdles, particularly for highly sophisticated nanobiosensors. Moreover, although biosensors are highly selective, cross-reactivity and matrix effects can still occur in complex samples, potentially leading to false-positive or false-negative results. Finally, integration into fully automated clinical systems is still developing, limiting their widespread adoption in some healthcare settings [30].

In summary, biosensors represent a powerful analytical platform with clear advantages in speed, sensitivity, and portability, yet their broader application is still constrained by issues of stability, reproducibility, and large-scale clinical integration.

Non-clinical Applications of Biosensors

Biosensors have found broad applications across multiple domains, extending beyond clinical diagnostics into environmental, food, and pharmaceutical fields. While their role in medical diagnostics has been extensively discussed, their non-clinical applications further highlight their versatility as analytical tools.

In environmental monitoring, biosensors are widely employed for the detection of pollutants such as heavy metals, pesticides, and toxic gases. Their ability to provide rapid and real-time analysis makes them particularly valuable for assessing water and air quality. Enzyme-based and microbial biosensors are especially effective in detecting organic contaminants at very low concentrations [31].

In the field of food safety and quality control, biosensors are used for the rapid detection of foodborne pathogens, toxins, and chemical residues. Compared to conventional microbiological and analytical methods, biosensors significantly reduce detection time, thereby improving food safety management and regulatory compliance [32].

In pharmaceutical and biotechnological applications, biosensors play an important role in drug discovery, monitoring of biochemical reactions, and evaluation of therapeutic responses. Their integration with nanomaterials and microfluidic technologies has enhanced analytical sensitivity and enabled multiplexed detection, supporting more efficient and high-throughput analysis [33].

Overall, these applications demonstrate that biosensors are not only essential in clinical medicine but also serve as powerful tools in environmental and industrial contexts. Their adaptability across diverse fields underscores their growing importance in modern analytical science.

Future Perspectives and Challenges of Biosensors

Despite remarkable progress in biosensor technology, several challenges still limit their full clinical and industrial translation. At the same time, rapid advances in materials science, nanotechnology, and artificial intelligence are opening new opportunities for next-generation biosensing platforms.

One of the most promising future directions is the development of wearable and implantable biosensors for continuous real-time health monitoring. These devices can provide dynamic physiological data, enabling personalized medicine and early disease detection. However, long-term biocompatibility, energy supply, and signal stability remain critical challenges [34, 35].

Another important trend is the integration of biosensors with artificial intelligence (AI) and machine learning algorithms. This combination can significantly enhance data interpretation, pattern recognition, and predictive diagnostics, particularly in complex clinical datasets. AI-driven biosensing systems are expected to play a major role in next-generation precision medicine [36].

The emergence of nanomaterial-based biosensors also offers substantial improvements in sensitivity, selectivity, and miniaturization. Materials such as graphene, carbon nanotubes, and metallic nanoparticles have demonstrated exceptional performance; however, issues related to reproducibility, large-scale manufacturing, and toxicity still need to be addressed [37].

In addition, the development of multiplexed and lab-on-a-chip systems represents a key direction for future biosensors. These platforms enable simultaneous detection of multiple biomarkers from a single sample, significantly improving diagnostic efficiency. Nevertheless, system integration and standardization remain major barriers to commercialization [38]. Overall, the future of biosensors lies in the convergence of wearable technology, nanomaterials, and intelligent data analytics, which together are expected to transform biosensors into fully autonomous, real-time diagnostic systems.

Discussion

The present review highlights the central role of biochemical principles in the design, function, and clinical utility of biosensors. Molecular recognition mechanisms, including enzyme catalysis, antigen–antibody binding, and nucleic acid hybridization, remain the cornerstone of biosensor specificity and sensitivity. These interactions, governed by thermodynamic and kinetic parameters, directly influence analytical performance, including detection limits, response time, and reproducibility.

One of the key insights from this review is the increasing convergence of biochemistry with nanotechnology and materials science. The incorporation of nanomaterials such as graphene and metallic nanoparticles has significantly enhanced signal amplification and lowered detection thresholds. However, these advancements also introduce challenges related to reproducibility, scalability, and potential toxicity, which must be addressed before widespread clinical implementation.

Clinically, biosensors have already demonstrated substantial impact, particularly in glucose monitoring and point-of-care diagnostics. Their expanding role in cancer detection, infectious disease diagnostics, and cardiovascular monitoring underscores their importance in early diagnosis and personalized medicine. Nevertheless, translating these technologies from laboratory settings to routine clinical practice remains a major challenge.

Key limitations identified include the instability of biological recognition elements, susceptibility to environmental conditions, biofouling in complex biological samples, and calibration drift. These factors can compromise long-term reliability and hinder commercialization. Additionally, integration into existing healthcare systems requires standardization, regulatory approval, and cost-effective manufacturing.

Future developments are expected to focus on wearable and implantable biosensors, enabling continuous real-time monitoring of physiological parameters. The integration of artificial intelligence and machine learning offers promising opportunities for improving data interpretation and predictive diagnostics. Furthermore, lab-on-a-chip and multiplexed platforms are likely to enhance diagnostic efficiency by enabling simultaneous detection of multiple biomarkers.

In conclusion, while biosensors hold immense promise as next-generation diagnostic tools, overcoming current biochemical and technological limitations will require interdisciplinary collaboration. Advances in protein engineering, synthetic bioreceptors, and intelligent data systems are expected to play a pivotal role in the evolution of biosensor technology.

Conclusion

Biosensors have evolved into powerful analytical tools that bridge biology and modern analytical technology, offering rapid, sensitive, and selective detection across a wide range of applications. Their growing importance in medical diagnostics, environmental monitoring, food safety, and pharmaceutical analysis highlights their versatility and translational potential.

Recent advances in nanotechnology, material science, and data-driven approaches have significantly enhanced the performance of biosensors, particularly in terms of sensitivity, miniaturization, and multifunctionality. These developments have facilitated the emergence of next-generation biosensing platforms, including wearable, implantable, and lab-on-a-chip systems.

However, despite these achievements, several challenges remain unresolved. Issues such as limited long-term stability of biorecognition elements, biofouling in complex biological environments, calibration drift, and difficulties in large-scale manufacturing continue to restrict widespread clinical and industrial adoption. Addressing these limitations will require interdisciplinary efforts combining chemistry, engineering, biology, and computational sciences.

Overall, biosensors are expected to play a central role in the future of precision medicine and real-time health monitoring. Continued innovation in materials, device engineering, and intelligent data processing will be essential to fully unlock their potential and translate laboratory advancements into robust, real-world diagnostic solutions.

ORCID

Mohammad Ehsan Salehi	**https://orcid.org/0000-0002-7444-2907**
Baryaly Atarpoor	**https://orcid.org/0009-0002-6818-7302**

References

1 - C Jr R, Lyons C. Electrode systems for continuous monitoring in cardiovascular surgery. Ann NY Acad Sci. 1962;102:29-45. https://doi.org/10.1111/j.1749-6632.1962.tb13623.x

2-Turner AP. Biosensors-sense and sensitivity. Science. 2000 Nov 17;290(5495):1315-7. https://doi.org/10.1126/science.290.5495.1315

3 - Thévenot DR, Toth K, Durst RA, Wilson GS. Electrochemical biosensors: recommended definitions and classification. Biosensors and bioelectronics. 2001 Jan 1;16(1-2):121-31. https://hdl.handle.net/1808/8413

4- D'Orazio P. Biosensors in clinical chemistry. Clinica chimica acta. 2003 Aug 1;334(1-2):41-69. https://doi.org/10.1016/S0009-8981(03)00241-9

5-Wang J. Electrochemical glucose biosensors. Chemical reviews. 2008 Feb 13;108(2):814-25.
https://doi.org/10.1021/cr068123a

6-Mehrotra P. Biosensors and their applications–A review. Journal of oral biology and craniofacial research. 2016 May 1;6(2):153-9. https://doi.org/10.1016/j.jobcr.2015.12.002

7-Mohankumar P, Ajayan J, Mohanraj T, Yasodharan R. Recent developments in biosensors for healthcare and biomedical applications: A review. Measurement. 2021 Jan 1;167:108293. https://doi.org/10.1016/j.measurement.2020.108293

8-Ronkainen NJ, Halsall HB, Heineman WR. Electrochemical biosensors. Chemical Society Reviews. 2010;39(5):1747-63. https://doi.org/10.1039/B714449K

9 - Turner A, Karube I, Wilson GS. Biosensors: fundamentals and applications. Oxford university press; 1987.

10 -Wilson R, Turner AP. Glucose oxidase: an ideal enzyme. Biosensors and bioelectronics. 1992 Jan 1;7(3):165-85.

11 - Cesewski E, Johnson BN. Electrochemical biosensors for pathogen detection. Biosensors and Bioelectronics. 2020 Jul 1;159:112214. https://doi.org/10.1016/j.bios.2020.112214

12 - Ellington AD, Szostak JW. In vitro selection of RNA molecules that bind specific ligands. nature. 1990 Aug 30;346(6287):818-22. https://doi.org/10.1038/346818a0

13 -Pumera M. Graphene in biosensing. Materials today. 2011 Jul 1;14(7-8):308-15. https://doi.org/10.1016/S1369-7021(11)70160-2

14-Sassolas A, Blum LJ, Leca-Bouvier BD. Immobilization strategies to develop enzymatic biosensors. Biotechnology advances. 2012 May 1;30(3):489-511. https://doi.org/10.1016/j.biotechadv.2011.09.003

15 -Sapsford KE, Algar WR, Berti L, Gemmill KB, Casey BJ, Oh E, Stewart MH, Medintz IL. Functionalizing nanoparticles with biological molecules: developing chemistries that facilitate nanotechnology. Chemical reviews. 2013 Mar 13;113(3):1904-2074. https://doi.org/10.1021/cr300143v

16-Turner AP. Biosensors: sense and sensibility. Chemical Society Reviews. 2013;42(8):3184-96.. https://doi.org/10.1039/c3cs35528d

17-Thévenot DR, Toth K, Durst RA, Wilson GS. Electrochemical biosensors: recommended definitions and classification. Biosensors and bioelectronics. 2001 Jan 1;16(1-2):121-31. https://doi.org/10.1016/S0956-5663(01)00115-4

18 - Cooper MA. Label-free screening of bio-molecular interactions. Analytical and bioanalytical chemistry. 2003 Nov;377(5):834-42. https://doi.org/10.1007/s00216-003-2111-y

19 - Wang J. Electrochemical biosensors: towards point-of-care cancer diagnostics. Biosensors and bioelectronics. 2006 Apr 15;21(10):1887-92. https://doi.org/10.1016/j.bios.2005.10.027

20 - Sassolas A, Leca-Bouvier BD, Blum LJ. DNA biosensors and microarrays. Chemical reviews. 2008 Jan 9;108(1):109-39. https://doi.org/10.1021/cr0684467

21 - Wang J. Glucose biosensors: 40 years of advances and challenges. Electroanalysis: An International Journal Devoted to Fundamental and Practical Aspects of Electroanalysis. 2001 Aug;13(12):983-8.. https://doi.org/10.1002/1521-4109(200108)13:12<983::AID-ELAN983>3.0.CO;2-%23
22 - Bollella P, Katz E. Biosensors—Recent advances and future challenges. Sensors. 2020 Nov 20;20(22):6645. https://doi.org/10.3390/s20226645
23 - Lazcka O, Del Campo FJ, Munoz FX. Pathogen detection: A perspective of traditional methods and biosensors. Biosensors and bioelectronics. 2007 Feb 15;22(7):1205-17. 2007 Feb 15;22(7):1205-17. https://doi.org/10.1016/j.bios.2006.06.036
24 - Kimmel DW, LeBlanc G, Meschievitz ME, Cliffel DE. Electrochemical sensors and biosensors. Analytical chemistry. 2012 Jan 17;84(2):685-707. https://doi.org/10.1021/ac202878q
25 - Murugaiyan SB, Ramasamy R, Gopal N, Kuzhandaivelu V. Biosensors in clinical chemistry: An overview. Advanced biomedical research. 2014 Jan 1;3(1):67. https://doi.org/10.4103/2277-9175.125848
26 - Holzinger M, Le Goff A, Cosnier S. Nanomaterials for biosensing applications: a review. Frontiers in chemistry. 2014 Aug 27;2:63. https://doi.org/10.3390/nano6040058
27-Pandey S. Advance nanomaterials for biosensors. Biosensors. 2022 Apr 7;12(4):219. https://doi.org/10.3390/bios12040219
28 - Hou S, Zhang A, Su M. Nanomaterials for biosensing applications. Nanomaterials. 2016 Mar 30;6(4):58. https://doi.org/10.3390/nano6040058
29 - Rajpoot K. Recent advances and applications of biosensors in novel technology. Biosensors Journal. 2017;6(02). https://doi.org/10.4172/2090-4967.1000145
30 - Lan L, Yao Y, Ping J, Ying Y. Recent advances in nanomaterial-based biosensors for antibiotics detection. Biosensors and Bioelectronics. 2017 May 15;91:504-14. https://doi.org/10.1016/j.bios.2017.01.007
31 - Privett BJ, Shin JH, Schoenfisch MH. Electrochemical sensors. Analytical chemistry. 2008 Jun 15;80(12):4499-517. https://doi.org/10.1021/ac8007219
32 - Yashini M, Shanmugasundaram S, Sunil C. Biosensors for Foodborne Pathogens Detection.
33 - Ngoepe M, Choonara YE, Tyagi C, Tomar LK, Du Toit LC, Kumar P, Ndesendo VM, Pillay V. Integration of biosensors and drug delivery technologies for early detection and chronic management of illness. Sensors. 2013 Jun 14;13(6):7680-713. https://doi.org/10.3390/s130607680
34 - Bandodkar AJ, Wang J. Non-invasive wearable electrochemical sensors: a review. Trends in biotechnology. 2014 Jul 1;32(7):363-71. https://doi.org/10.1016/j.tibtech.2014.04.005
35 -Kim J, Campbell AS, de Ávila BE, Wang J. Wearable biosensors for healthcare monitoring. Nature biotechnology. 2019 Apr;37(4):389-406.
36 - Flynn CD, Chang D. Artificial intelligence in point-of-care biosensing: challenges and opportunities. Diagnostics. 2024 May 25;14(11):1100. https://doi.org/10.1002/adma.202504796

37-Wang J. Nanomaterial-based electrochemical biosensors. Analyst. 2005;130(4):421-6. https://doi.org/10.1039/B414248A

38 - Lopez GA, Estevez MC, Soler M, Lechuga LM. Recent advances in nanoplasmonic biosensors: applications and lab-on-a-chip integration. Nanophotonics. 2017 Jan 6;6(1):123-36. Nanophotonics. 2017 Jan 6;6(1):123-36. https://doi.org/10.1515/nanoph-2016-0101