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Review Article

CONTEMPORARY BIOSENSOR SYSTEMS AND THEIR MULTIFACETED APPLICATIONS

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ABSTRACT

Biosensor technology has undergone transformative advancements in recent decades, enabling rapid, sensitive, and selective detection of a wide range of biological and chemical analytes. Contemporary biosensors integrate multidisciplinary innovations in materials science, nanotechnology, microfluidics, and molecular biology to achieve enhanced performance, scalability, and real-time monitoring capabilities. This review provides a comprehensive assessment of current biosensor systems, including enzyme-based, immunological, nucleic acid, microbial, fluorescent, and nanomaterial-assisted platforms. Their operational principles, fabrication strategies, and performance metrics are discussed in detail. The growing applications of biosensors in healthcare diagnostics, food quality monitoring, environmental surveillance, bioprocess control, and biodefense are critically evaluated. Recent breakthroughs in genetically encoded sensors, wearable biosensing technologies, and point-of-care testing devices highlight the expanding horizon of the field. The review concludes by outlining future directions and technological challenges that must be addressed to further enhance biosensor sensitivity, integration, and commercialization. Overall, contemporary biosensor systems demonstrate immense potential to revolutionize global health, industrial processing, and environmental sustainability.

Keywords: Biosensors, Enzyme-based biosensors, Immunosensors, DNA biosensors, Nanomaterial-based biosensors.

INTRODUCTION

Biosensors have emerged as indispensable analytical tools capable of detecting biological or chemical substances by converting a biochemical response into a measurable electrical, optical, thermal, or mechanical signal. Since the pioneering work of Clark and Lyons in the 1960s, biosensors have evolved considerably, driven by advancements in biomolecular engineering, nanotechnology, and microfabrication. Modern biosensor systems exhibit enhanced specificity, sensitivity, rapid response times, portability, and compatibility with digital data acquisition platforms, positioning them as crucial components in contemporary analytical science. A typical biosensor comprises three fundamental components: a biorecognition element (such as enzymes, antibodies, nucleic acids, microbial cells, or genetically engineered proteins), a transducer that converts the biorecognition event into a quantifiable signal, and a processing unit that interprets and displays the output. Depending on their biological material and transduction mechanisms, biosensors are broadly classified into enzyme-based biosensors, tissue-based sensors, immunosensors, DNA biosensors, thermal and piezoelectric sensors, optical sensors, and emerging nanomaterial-based platforms. The expanding applications of biosensors across diverse sectors underscore their technological significance. In healthcare, biosensors play a pivotal role in early disease diagnostics, continuous glucose monitoring, pathogen detection, cardiovascular biomarker monitoring, and personalized medicine. In the food industry, biosensors enhance quality

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assurance, authenticity verification, and contamination detection by offering rapid and cost-effective alternatives to traditional laboratory-based techniques. Environmental biosensing applications include monitoring toxic metals, pesticides, pollutants, eutrophication indicators, and water quality. Additionally, the fermentation and bioprocessing industries employ biosensors for real-time monitoring of metabolites, enzymes, and product formation to optimize industrial workflows. Recent technological progress has introduced nanoscale biosensors, genetically encoded fluorescent sensors, wearable devices, smartphone-integrated biosensing systems, and microfluidic lab-on-chip platforms, expanding the scope of biosensor capabilities. These innovations reflect the field's rapid evolution and its potential to revolutionize diagnostics, industrial processing, environmental monitoring, and public health surveillance Priyadharshini *et al*., 2025. This review aims to provide an in-depth exploration of contemporary biosensor systems, their structural principles, operational mechanisms, and multifaceted applications while highlighting future research directions and emerging challenges (Figure.1).

Overview: contemporary scope and significance: Biosensors today combine biology, materials science and electronics to deliver rapid, often real-time biochemical detection for healthcare, environment and industry; recent comprehensive reviews show a strong surge in interest from 2020-2025 driven by pandemic diagnostics, wearable health monitoring and food-safety needs (Muspira *ET AL*., 2025, Bhalla *et al*., 2016). Electrochemical biosensors: the workhorse for POC and food testing: Electrochemical approaches remain dominant for point-of-care and on-site assays because of low cost, miniaturizability and high sensitivity; recent reviews highlight extensive nanomaterial-enabled signal amplification (gold nanoparticles, graphene) and multifunctional electrodes reported across 2020–2024 (Bjerketorp *et al*., 2006, Borisov & Wolfbeis 2008). Optical biosensors: label-free and high-sensitivity detection: Optical platforms including SPR, fluorescence and resonant sensors continue to expand, offering label-free, real-time detection with advances in photonic architectures and nanostructured surfaces reported heavily in 2023-2024 (Devasena *et al*., 2025, Dincer *et al*., 2019). Paper-based and lateral-flow devices: democratizing diagnostics: Paper-based and lateral-flow biosensors have matured as low-cost POC tools; reviews from 2022–2025 document improved sensitivity (enzyme/aptamer integration), smartphone readout compatibility, and use in low-resource settings for infectious disease and miRNA diagnostics (Justino *et al*., 2017, Kim *et al* 2019).

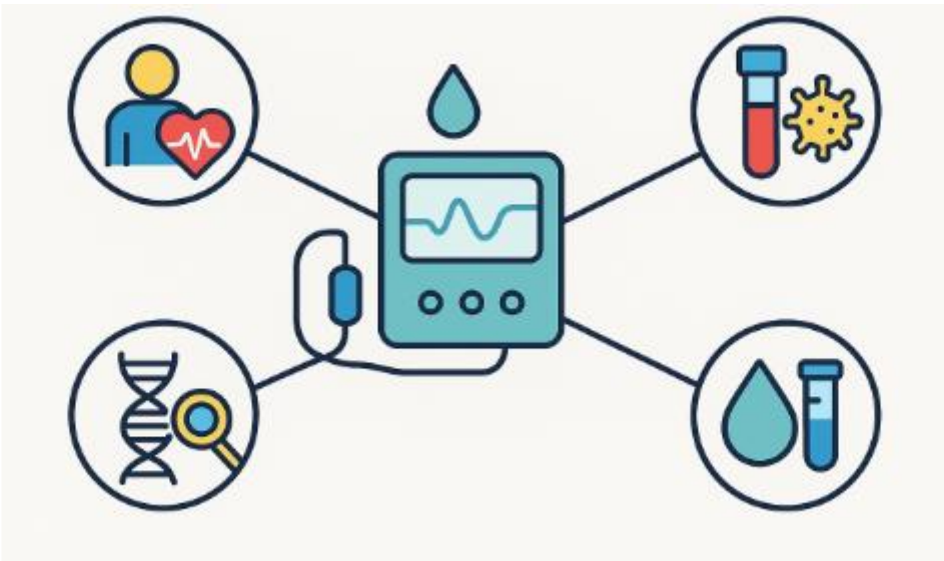

Figure 1. Contemporary biosensor systems and their multifaceted applications.

Wearable biosensors and continuous health monitoring: Wearable biosensing progressed rapidly between 2020-2024, with textile integration, skin-adhesive electrochemical patches and continuous metabolite monitoring being emphasized; major reviews (2023–2024) report improvements in comfort, on-board processing and sustained measurements for personalized care (Koch & Düring 2019, Lim Ahmed 2021). Nanomaterials and 2D-materials: performance boosters: Two-dimensional nanomaterials (graphene, MXenes) and engineered nanoparticles have been repeatedly identified in 2020-2024 literature as critical for boosting sensitivity, lowering limits of detection, and enabling flexible/stretchable sensor substrates for both electrochemical and optical transducers (Nafisa Farheen *et al*., 2025). Microfluidics, lab-on-chip integration and multiplexing: Microfluidic integration enables automated sample handling, reduced reagent consumption and multiplexed assays; reviews from 2021–2024 indicate lab-on-chip biosensors have progressed from prototypes to integrated POC platforms for infectious disease and biomarker panels. Continued work focuses on manufacturability and sample prep integration (Annual Reviews / Wachholz review; 2024). Data integration: IoT, AI and digital biosensing ecosystems: Contemporary work

(2022-2024) increasingly links biosensors to IoT ecosystems and AI analytics for remote monitoring, anomaly detection and predictive health; papers highlight secure wireless telemetry, edge processing and cloud analytics as enablers of large-scale deployment (Priyadharshini *et al*., 2025). Environmental, agricultural and food safety applications: Beyond healthcare, recent reviews (2023–2025) document expanding biosensor use in environmental monitoring (water quality, air pathogens), agricultural surveillance, and food safety (mycotoxins, pathogens), where portable electrochemical and optical sensors address the need for rapid, on-site assays (Ramya *et al*., 2025, Vigneshwari *et al*., 2025, Rubala Nancy *et al*., 2025, Senthilkumar *et al*., 2025, Thankgasubha *et al*., 2025, Sindhuja *et al*., 2025, Steniffer Jebaruby Stanly *et al*., 2025). Regulatory, manufacturing and commercialization challenges: Multiple 2023–2025 analyses note that despite technical advances, translation to market faces regulatory, reproducibility, and scale-up hurdles; regulatory pathways for wearable and in-vitro diagnostic biosensors require standardized validation and user-safety evidence (Ramya *et al*., 2025, Vigneshwari *et al*., 2025, Rubala Nancy *et al*., 2025, Senthilkumar *et al*., 2025, Thankgasubha *et al*., 2025, Sindhuja *et al*., 2025, Steniffer Jebaruby Stanly *et al*., 2025).

MATERIALS AND METHODS

This review adopts a structured literature survey approach to analyze contemporary biosensor systems, their design principles, and their diversified applications across healthcare, environmental monitoring, food technology, bioprocess engineering, and biodefense. A systematic search was conducted across major scientific databases including Primary keywords used included biosensors, enzyme-based biosensors, immunosensors, DNA biosensors, nanobiosensors, fluorescent biosensors, wearable biosensors, food safety biosensing, medical diagnostics biosensors, environmental biosensors, and point-of-care devices. Boolean combinations such as "biosensor AND nanotechnology," "immunosensor AND point-of-care," and "fluorescent biosensor AND disease diagnosis" were applied to ensure precision. Inclusion criteria consisted of peer-reviewed journal articles, review papers, conference proceedings, and relevant patents focusing on biosensor innovation, fabrication techniques, performance evaluation, and real-world applications Revathi *et al*., 2025. Exclusion criteria filtered out non-English publications, duplicated reports, and studies lacking experimental or practical relevance Bjerketorp *et al*., 2006. All selected documents were critically analyzed to extract information on sensor types, materials, transduction mechanisms, target analytes, sensitivity and selectivity parameters, fabrication strategies, and domain-specific applications Priyadharshini *et al*., 2025, Revathi *et al*., 2025. Additional foundational information was incorporated from the user-provided document, which includes detailed descriptions of biosensor categories and their applications Borisov & Wolfbeis 2008.

RESULTS AND DISCUSSION

Evolution of Biosensor Technology: The collected literature indicates rapid growth in biosensor technology driven by advancements in nanomaterials, microfabrication, biochemistry, microfluidics, and AI-enabled analytics**.** Traditional biosensors enzyme-based, tissue-based, and immunosensors have matured into advanced hybrid systems capable of high sensitivity, portability, and real-time monitoring Devasena *et al*., 2025. The integration of nanostructures**,** particularly graphene, quantum dots, metal nanoparticles, and carbon nanotubes, has significantly enhanced transduction efficiency and lowered detection limits, enabling early disease diagnosis and ultra-trace chemical detection Senthilkumar *et al*., 2025. Enzyme-based biosensors remain dominant in medical and industrial applications due to their catalytic specificity. Their sensitivity has been greatly improved through immobilization strategies and nanostructured electrode materials. The literature review shows enhanced stability in glucose, lactate, and glutamate sensors widely used in clinical diagnostics and fermentation control. However, limitations include enzyme denaturation**,** short shelf life, and interference from environmental factors, highlighting the need for robust immobilization matrices Immunosensors exhibit exceptional specificity for pathogen, toxin, and protein biomarker detection. Recent developments include label-free electrochemical immunosensors for rapid COVID-19 screening, cancer marker detection, and cardiovascular disease diagnostics. Nanomaterial-assisted immunosensors demonstrate ultra-low detection limits but face challenges in mass production, antibody stability, and cost. Nucleic-acid biosensors have become essential for pathogen detection, genetic mutation analysis, and forensic applications**.** Advancements in CRISPR-based biosensing platforms and isothermal amplification techniques have improved detection specificity for viral RNA, environmental microbes, and genetically modified organisms. Their integration with microfluidic chips has further enhanced point-of-care usability Dincer *et al*., 2019.

Genetically encoded FRET biosensors and fluorescent probes have enabled live-cell imaging, drug discovery, and molecular pathway analysis Vigneshwari *et al*., 2025. As highlighted in the user's uploaded review, fluorescent biosensors have revolutionized intracellular signalling studies and cancer monitoring. Nanomaterials consistently appear as the most influential factor driving biosensor innovation Koch & Düring 2019, Lim Ahmed 2021. Their high surface area, strong optical/electrical properties, and tunable chemistry have improved sensor sensitivity and miniaturization. Metal-organic frameworks, quantum dots, and plasmonic nanoparticles are enabling new sensing modalities such as single-molecule detection and wearable nanosensors**.** However, reproducibility, batch variability, and toxicity concerns remain major obstacles to commercialization. The literature strongly supports the use of biosensors for food safety assessment, pesticide detection, fermentation control, and quality monitoring. The uploaded document notes numerous applications—

from detecting *E. coli* in vegetables to monitoring beer ageing and sugar quality demonstrating practical industrial relevance Ramya *et al*., 2025, Vigneshwari *et al*., 2025, Rubala Nancy *et al*., 2025, Senthilkumar *et al*., 2025, Thankgasubha *et al*., 2025, Sindhuja *et al*., 2025, Steniffer Jebaruby Stanly *et al*., 2025. Environmental biosensors are increasingly used to measure heavy metals, pesticides, water toxins, and indicators of eutrophication. DNA-based and immunosensor platforms show promise for detecting biowarfare agents with high specificity. Field applications require rugged designs, multi-analyte capability, and low maintenance areas where research is ongoing. Wearable biosensors for glucose, sweat biomarkers, cardiac monitoring, and stress detection are experiencing rapid adoption. Integration with IoT devices, smartphone interfaces, and cloud-based analytics is enabling personalized medicine and remote healthcare. AI-powered signal processing is increasingly used for noise reduction, pattern recognition, and predictive analytics, marking an important future direction.

CONCLUSION

This review highlights the significant advancements in biosensor technologies and their extensive applications across diverse sectors. Contemporary biosensors have evolved into powerful analytical tools influenced by nanotechnology, microfluidics, biomolecular engineering, and computational technologies. Enzyme-based, immunological, nucleic-acid, fluorescent, nanomaterial-enabled, and wearable biosensors each offer unique advantages, addressing critical needs in healthcare diagnostics, food safety, environmental monitoring, industrial fermentation, and biodefense. While biosensors demonstrate exceptional potential, persistent challenges include sensor stability, reproducibility, biocompatibility, regulatory approval, real-sample interference, and large-scale manufacturing. Overcoming these limitations will require multidisciplinary innovation and strong collaboration between researchers, clinicians, and industry. Overall, biosensors represent a transformative technology capable of shaping future healthcare systems, enhancing food security, protecting the environment, and fostering technological progress across both scientific and industrial domains. Future research should focus on the following areas: Nanomaterial Standardization and Safety: Develop standardized fabrication protocols to address batch variability and toxicity issues associated with nanomaterial-based biosensors. Ensuring reproducible nanostructures will be critical for clinical translation and regulatory approval. Fully Integrated Point-of-Care Systems: Next-generation biosensors will require seamless integration with sample preparation units, microfluidics, and user-friendly interfaces. This will facilitate decentralized diagnostics in low-resource environments and support personalized medicine initiatives. AI-Driven Biosensing Platforms: Machine learning algorithms can drastically improve pattern recognition, multi-analyte interpretation, and early prediction of disease markers. AI-enabled biosensors should be explored for smart health monitoring and real-time environmental surveillance**.** Long-term Wearable and Implantable Sensors: Future designs should emphasize biocompatible materials, self-powered systems (energy harvesting), and stable long-term monitoring for continuous physiological tracking. Future designs should emphasize biocompatible materials, self-powered systems (energy harvesting), and stable long-term monitoring for continuous physiological tracking. Multi-Analyte and Multiplexed Biosensing: Developing sensors capable of detecting multiple biomarkers simultaneously will improve diagnostic accuracy in medical and environmental applications. Commercialization, Cost Reduction, And Regulatory Frameworks: Advanced biosensors must transition from laboratory prototypes to commercially viable products. This requires addressing cost, robustness, and guidelines for manufacturing consistency, especially in medical applications.

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CONFLICT OF INTERESTS

The authors declare no conflict of interest

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Not applicable

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AI TOOL DECLARATION

The authors declares that no AI and related tools are used to write the scientific content of this manuscript.

DATA AVAILABILITY

Data will be available on request

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