ORIGINAL ARTICLE Open Access

ISSN 2278-1404
International Journal of Fundamental & Applied Sciences (IJFAS)

ELECTROCHEMICAL NANOSENSORS FOR EARLY DISEASE DIAGNOSIS: A CHEMISTRY-DRIVEN APPROACH TO AFFORDABLE HEALTHCARE

B.N. Chandrashekar[1*], Deepika[2], B.E. Kumara Swamy[2*]
[1]Department of Chemistry, Sri Adichunchanagiri First Grade College, Affiliated to Hassan University, Channarayapatna – 573116, Hassan, Karnataka, India
[2]Department of P G Studies and Research in Industrial Chemistry, Kuvempu University, Shankaraghatta 577451, Shivamogga, Karnataka, India
***Corresponding author email address**: chandrashekarbn1984@gmail.com; kumaraswamy21@yahoo.com

Paper Received: 02.07.2026 | Revised: 22.09.2026 | Accepted: 30.09.2026 | Published: 30.09.2026

DOI: https://doi.org/10.59415/ijfas.381

Abstract

The early diagnosis of diseases significantly enhances the chances of successful treatment and reduces healthcare costs. Electrochemical nanosensors, integrating advances in chemistry, nanotechnology, and materials science, have emerged as powerful tools in clinical diagnostics. These sensors combine high sensitivity, selectivity, rapid response, and portability, making them ideal for point-of-care testing (POCT). This chapter explores the fundamental principles, material designs, sensing mechanisms, and applications of electrochemical nanosensors for early disease diagnosis. Emphasis is placed on how chemistry facilitates the fabrication and optimization of nanosensors tailored for healthcare applications. Furthermore, this work addresses current challenges and future perspectives for translating lab-scale innovations to practical, affordable diagnostic tools aligned with global health goals.

Keywords: Nanosensors, Disease biomarkers, Redox reactions, Glucose sensor, Cancer detection, Green synthesis.

1. INTRODUCTION

Early disease detection is a cornerstone of modern healthcare. Accurate and timely diagnosis enables effective treatment, better prognoses, and significantly reduced medical expenses. In many cases, early-stage intervention can mean the difference between a manageable illness and a life-threatening condition. Diseases such as cancer, cardiovascular disorders, diabetes, and infectious diseases like COVID-19 often present asymptomatic or non-specific early symptoms, making conventional diagnostics insufficient for timely identification. Therefore, the development of novel, efficient, and accessible diagnostic technologies has become a top priority in global health initiatives. However, traditional diagnostic methods—including enzyme-linked immunosorbent assays (ELISA), polymerase chain reaction (PCR), and imaging technologies—often involve complex protocols, bulky instrumentation, expensive reagents, and require skilled personnel. These limitations hinder their deployment in decentralized or low-resource environments such as rural clinics or developing regions. Consequently, there is a growing demand for compact, low-cost, and user-friendly diagnostic platforms that provide rapid and reliable results without compromising sensitivity or specificity.

In this context, electrochemical nanosensors have emerged as transformative tools for affordable, sensitive, and rapid diagnostics, especially at the point-of-care (POC) level [1–3]. These sensors are capable of detecting disease biomarkers—such as proteins, nucleic acids, metabolites, and pathogens—at very low concentrations, often in real-

time, with minimal sample preparation. The working principle of these sensors involves the conversion of biochemical recognition events into quantifiable electrical signals. Their simplicity, coupled with potential for miniaturization and integration into portable devices, makes them ideal for widespread use, particularly in community-based or home healthcare settings.

A critical aspect that underpins the success of these sensors is the strategic use of nanomaterials, which significantly improve the analytical performance of electrochemical sensors. Nanostructured materials such as gold nanoparticles, carbon nanotubes, graphene, and metal oxides provide high surface area, excellent conductivity, and tunable surface chemistry, all of which contribute to enhanced sensitivity and selectivity. These materials also support the immobilization of biological recognition elements—such as antibodies, aptamers, and enzymes—on sensor surfaces, facilitating highly specific interactions with target analytes. Chemistry plays a pivotal and foundational role in the design**,** synthesis**,** and functionalization of nanomaterials, as well as in the selection of biocompatible interfaces and linkers that ensure optimal sensor performance. Surface chemistry techniques are used to tailor the sensor interface to enhance signal transduction while maintaining biorecognition accuracy. Moreover, green chemistry approaches are increasingly being explored to make the fabrication of these sensors more sustainable and environmentally friendly**.**

This interdisciplinary convergence of analytical chemistry, nanotechnology, materials science, and biomedical engineering fosters a new generation of diagnostic tools with immense potential to address current gaps in healthcare delivery. By enabling earlier and more accurate detection of diseases, electrochemical nanosensors contribute to preventive medicine, patient empowerment, and reduced burden on healthcare systems, especially in underserved areas. As research continues to evolve, these technologies are expected to play a central role in the future of personalized and precision medicine.

2. FUNDAMENTALS OF ELECTROCHEMICAL SENSING

Electrochemical sensing relies on redox (reduction–oxidation) reactions, where the analyte either donates or accepts electrons at the electrode interface. This process generates an electrical signal—typically current, potential, or impedance—that is directly related to the analyte concentration. These reactions occur at the electrode–electrolyte interface, a key zone for signal transduction.

A standard electrochemical sensor comprises three electrodes:

- **Working Electrode**: The primary surface where the analyte reacts. Its composition (e.g., carbon, gold, graphene) and surface modifications (such as nanomaterial coatings or bioreceptors like enzymes and antibodies) significantly influence the sensor's sensitivity and selectivity.
- **Reference Electrode**: Provides a stable potential to ensure accurate measurement of electrochemical changes. Common types include Ag/AgCl and calomel electrodes.
- **Counter Electrode**: Completes the circuit, allowing current flow without participating in the reaction, usually made from inert materials like platinum.

These components are typical in three-electrode systems, though simplified two-electrode setups are often used in portable devices like screen-printed electrodes (SPEs), especially for point-of-care testing [1–3].

Electrochemical techniques include amperometry (measuring current at a fixed potential), potentiometry (measuring potential under zero current), voltammetry (current response to varying potential), and electrochemical impedance spectroscopy (EIS)**,** which assesses resistance and capacitive properties of the interface—particularly useful for biosensing.

Sensor performance depends on the physicochemical characteristics of the electrode and the electrolyte medium, including pH and ionic strength. Incorporating nanomaterials such as metal nanoparticles, carbon nanotubes, or conductive polymers enhances surface area, electron transfer, and sensitivity, enabling detection of biomarkers at extremely low concentrations.

In summary, through thoughtful design and nanomaterial integration, electrochemical sensors enable rapid, sensitive,

and cost-effective clinical diagnostics, even in resource-limited settings.

2.1 Electrochemical Techniques

Electrochemical sensors utilize a variety of analytical techniques to transduce the interaction between the analyte and the sensor surface into measurable electrical signals. The selection of technique depends on the target biomarker, desired sensitivity, and operational environment.

- Amperometry involves measuring the current produced at a constant applied potential. It is particularly useful for detecting redox-active species such as glucose, hydrogen peroxide, or neurotransmitters. The magnitude of the current is directly proportional to the analyte concentration, making amperometry highly suitable for real-time monitoring in biosensors.
- Potentiometry measures the potential difference between a working and reference electrode under conditions of negligible current. It is commonly used in ion-selective electrodes (ISEs), such as pH sensors or potassium ion detectors, where it provides rapid, low-power sensing capabilities.
- Voltammetry records current as the potential is swept over a range. Techniques like cyclic voltammetry (CV) and differential pulse voltammetry (DPV) allow insight into redox processes, electrochemical kinetics, and sensor surface properties, which are valuable during sensor development.
- Electrochemical Impedance Spectroscopy (EIS) is a label-free technique that assesses the resistance and capacitive behavior at the electrode interface. It is highly sensitive to changes caused by biomolecular interactions, making it ideal for detecting antigen–antibody or aptamer–target binding events.

These techniques are used based on the sensor type and the disease biomarker being detected [4].

3. ROLE OF NANOMATERIALS IN ELECTROCHEMICAL SENSING

Nanomaterials enhance electrochemical sensor performance due to their high surface area, electronic properties, and biocompatibility. Commonly used nanomaterials include:

3.1 Carbon-Based Nanomaterials

Carbon nanomaterials have revolutionized the field of electrochemical sensing due to their exceptional electrical, mechanical, and chemical properties. Among them, graphene—a two-dimensional sheet of sp^2-hybridized carbon atoms—and carbon nanotubes (CNTs)—cylindrical nanostructures—are widely utilized to enhance the performance of electrochemical sensors. Their high surface-to-volume ratio facilitates the immobilization of biorecognition elements, while their superior electrical conductivity ensures efficient electron transfer between the analyte and electrode surface [5,6].

Graphene oxide (GO), a functional derivative of graphene rich in oxygen-containing groups (e.g., hydroxyl, carboxyl, and epoxy), provides reactive sites for covalent bonding with enzymes, antibodies, and aptamers. This makes GO highly suitable for developing biosensors that require stable and oriented immobilization of biomolecules for improved sensitivity and selectivity.

3.2 Metal and Metal Oxide Nanoparticles

Metal nanoparticles such as gold (Au), silver (Ag), and platinum (Pt) exhibit excellent electrical conductivity, chemical stability, and biocompatibility. These properties make them ideal for signal amplification and enhancing electron transfer at the electrode interface [7]. Additionally, metal oxide nanoparticles—including zinc oxide (ZnO), titanium dioxide (TiO_2), and magnetite (Fe_3O_4)—are valued for their catalytic properties and their ability to interact selectively with biomolecules, contributing to signal enhancement and improved detection limits [8].

3.3 Quantum Dots and Polymer Nanocomposites

Quantum dots (QDs) are semiconductor nanocrystals that offer both optical and electrochemical transduction

capabilities. Their tunable size and photoluminescence make them attractive for dual-mode biosensors that combine fluorescence with electrochemical readouts [9]. Conducting polymers, such as polyaniline (PANI) **and** polypyrrole (PPy)**,** serve as electron-conducting matrices and provide mechanical support for immobilizing biological elements, further enhancing signal transduction in sensor platforms [10].

4. FABRICATION STRATEGIES AND SURFACE CHEMISTRY

4.1 Electrode Modification

Functionalizing electrode surfaces with nanomaterials improves analyte capture. Drop-casting, electrodeposition, and layer-by-layer assembly are common techniques [11].

4.2 Biorecognition Elements

- Antibodies: High specificity for protein biomarkers.
- Aptamers: Synthetic oligonucleotides with strong affinity.
- Enzymes: Catalyze analyte transformation for signal generation.
- Molecularly Imprinted Polymers (MIPs): Artificial receptors mimicking natural binding sites [12].

4.3 Linker Chemistry

To ensure stable and functional attachment of biorecognition elements onto sensor surfaces, various chemical linkers are employed. Commonly used strategies include EDC/NHS coupling (stable amide bonds between carboxyl (–COOH) and amine ($–NH_2$) groups), which activates carboxyl groups for amide bond formation with amines, enabling covalent immobilization of proteins or aptamers. Thiol–gold interactions are another widely used approach, particularly for anchoring thiol-modified biomolecules onto gold nanoparticle-modified electrodes. Additionally, click chemistry offers a highly selective and efficient method for conjugating molecules under mild conditions, making it suitable for preserving the activity of delicate biological entities [13].

5. ELECTROCHEMICAL NANOSENSORS FOR DISEASE DIAGNOSIS

5.1 Diabetes

Electrochemical glucose sensors represent one of the earliest and most impactful successes in biosensor technology. These devices are essential for continuous glucose monitoring in diabetic patients. Enzymatic sensors, typically employing glucose oxidase (GOx), work by catalyzing glucose to produce hydrogen peroxide, which is electrochemically detected. More recently, non-enzymatic sensors using metal nanoparticles like platinum, gold, or nickel have gained attention due to their improved stability and resistance to temperature and pH variations. These sensors offer rapid, accurate, and minimally invasive glucose detection, supporting better disease management [14,15].

5.2 Cancer

Early detection of cancer significantly improves treatment outcomes. Electrochemical biosensors have been engineered to detect specific tumor biomarkers, including carcinoembryonic antigen (CEA)**,** prostate-specific antigen (PSA)**,** and microRNAs (miRNAs)**.** The integration of nanomaterials**,** such as gold nanoparticles or carbon nanostructures, into electrode surfaces increases the effective surface area and improves electron transfer, thereby enhancing sensor sensitivity. These innovations allow for ultra-sensitive detection**,** often in the picomolar or femtomolar range, crucial for early cancer diagnostics [16,17].

5.3 Cardiovascular Diseases

Electrochemical detection of cardiac biomarkers such as troponin I**,** myoglobin, and C-reactive protein (CRP) plays a vital role in diagnosing acute myocardial infarction and related conditions. Sensors incorporating gold nanoparticles

(AuNPs) and graphene-based composites facilitate fast, real-time analysis with high precision. Such devices are increasingly adapted for emergency care and portable diagnostics, enabling immediate clinical decisions [18].

5.4 Infectious Diseases

The growing need for rapid and accurate diagnosis of infectious diseases like COVID-19**,** dengue**,** and malaria has accelerated the development of aptamer-based electrochemical sensors**.** These sensors are capable of detecting viral proteins, antibodies, or nucleic acids with high specificity and speed. Their low-cost**,** portable**,** and label-free formats make them particularly suited for point-of-care (POC) testing in remote or resource-limited settings. Advances in nanomaterial integration further enhance their analytical performance [19–21].

6. POINT-OF-CARE DEVICE INTEGRATION

6.1 Microfluidics and Lab-on-a-Chip

The integration of microfluidics with electrochemical nanosensors allows for automated, multiplexed detection of multiple disease biomarkers using very small sample volumes (e.g., a drop of blood or saliva). These lab-on-a-chip systems offer rapid analysis, reduced reagent consumption, and high throughput, making them ideal for point-of-care diagnostics in low-resource settings [22].

6.2 Smartphone-Interfaced Sensors

Advancements in Bluetooth-enabled potentiostats and smartphone-based apps now permit real-time data acquisition, visualization, and wireless communication. These portable platforms make diagnostics more accessible, supporting remote healthcare, self-monitoring, and timely clinical decision-making in both urban and rural environments [23].

7. GREEN CHEMISTRY IN SENSOR FABRICATION

Green chemistry principles are increasingly applied to the development of electrochemical nanosensors to reduce environmental impact. Sustainable synthesis methods include the use of plant extracts as natural reducing agents for converting metal salts into nanoparticles, offering a non-toxic and renewable alternative to chemical reducers. Biodegradable polymers such as chitosan and cellulose are employed as eco-friendly matrix materials for sensor platforms. Additionally, traditional toxic organic solvents are being replaced with safer alternatives like water or ethanol, ensuring greener production without compromising sensor performance. These practices support safer, more sustainable diagnostics and align with global environmental goals [24].

8. CHALLENGES AND FUTURE PERSPECTIVES

Despite their immense potential, electrochemical nanosensors face several challenges that limit their large-scale deployment in clinical diagnostics. A major concern is reproducibility, as sensor performance can vary due to inconsistencies in nanomaterial synthesis or electrode modification. To overcome this, standardized fabrication protocols and automated sensor manufacturing are being explored.

Stability is another critical issue, especially for biosensors operating in complex biological environments. Enzymatic and aptamer-based sensors may degrade over time, reducing shelf life. Robust packaging and surface passivation techniques, such as polymer coatings, can improve operational stability.

The simultaneous detection of multiple biomarkers, is essential for accurate disease profiling. The integration of microarray platforms and microfluidic networks offers promising solutions for parallel analysis within a single sensor chip.

Cost remains a barrier for widespread adoption, particularly in resource-limited settings. Innovations in using paper-based electrodes, flexible plastic substrates, and scalable printing techniques are helping to reduce manufacturing expenses without compromising performance. Looking ahead, future developments should prioritize wearable

nanosensors, self-powered diagnostic platforms, and seamless integration with telemedicine systems. These advancements will expand the utility of electrochemical nanosensors, enabling real-time, decentralized, and affordable healthcare solutions on a global scale.

9. CONCLUSION

Electrochemical nanosensors represent a transformative leap in the field of medical diagnostics. Leveraging the synergistic advancements in chemistry, nanotechnology, and materials science, these sensors offer unmatched benefits: high sensitivity, specificity, low-cost fabrication, and the potential for real-time and decentralized testing. Their compact design and ability to function with minimal sample volumes make them particularly well-suited for point-of-care (POC) diagnostics and use in resource-limited environments, where traditional laboratory infrastructure may be unavailable.

The incorporation of nanomaterials such as graphene, carbon nanotubes, metal nanoparticles, and quantum dots has enhanced their analytical performance, enabling detection of ultra-low concentrations of disease biomarkers associated with diabetes.

10. STATEMENTS AND DECLARATIONS

AI Statement: NIL

Ethical Standards: All the ethical Research standards were followed while writing this Research Article.

Conflict of Interest: The authors state that they do not have any conflict of interest.

Human or animal involvement in the article: Nil

Data Availability: NA

References

1. I.-H. Cho, D. H. Kim and S. Park, “Electrochemical biosensors: perspective on functional nanomaterials for on-site analysis,” *Biomaterials Research*, 2020, 24, 6. DOI: 10.1186/s40824-019-0181-y.
2. K. P. Channabasavana Hundi Puttaningaiah, “Innovative Carbonaceous Materials and Metal/Metal Oxide Nanoparticles for Electrochemical Biosensor Applications,” *Nanomaterials*, 2024, 14, 1890. DOI: 10.3390/nano14231890.
3. S. Gupta, C. N. Murthy and C. Ratna Prabha, “Recent advances in carbon nanotube based electrochemical biosensors,” *International Journal of Biological Macromolecules*, 2018, 108, 687–703. DOI: 10.1016/j.ijbiomac.2017.12.038.
4. K. Theyagarajan and Y.-J. Kim, “Recent Developments in the Design and Fabrication of Electrochemical Biosensors Using Functional Materials and Molecules,” *Biosensors*, 2023, 13, 424. DOI: 10.3390/bios13040424.
5. S. Taniselass, M. K. M. Arshad and S. C. B. Gopinath, “Graphene-based electrochemical biosensors for monitoring noncommunicable disease biomarkers,” *Biosensors and Bioelectronics*, 2019, 130, 276–292. DOI: 10.1016/j.bios.2019.01.047.
6. S. Gupta, C. N. Murthy and C. Ratna Prabha, “Recent advances in carbon nanotube based electrochemical biosensors,” *International Journal of Biological Macromolecules*, 2018, 108, 687–703. DOI: 10.1016/j.ijbiomac.2017.12.038.
7. K. P. Channabasavana Hundi Puttaningaiah, “Innovative Carbonaceous Materials and Metal/Metal Oxide Nanoparticles for Electrochemical Biosensor Applications,” *Nanomaterials*, 2024, 14, 1890. DOI: 10.3390/nano14231890.
8. G. Keles, E. S. Ataman, S. B. Taskin, İ. Polatoglu and S. Kurbanoglu, “Nanostructured Metal Oxide-Based Electrochemical Biosensors in Medical Diagnosis,” *Biosensors*, 2024, 14, 238. DOI: 10.3390/bios14050238.
9. M. A. Farzin and H. Abdoos, “A critical review on quantum dots: From synthesis toward applications in electrochemical biosensors for determination of disease-related biomolecules,” *Talanta*, 2021, 224, 121828. DOI: 10.1016/j.talanta.2020.121828.
10. J. H. T. Luong, T. Narayan, S. Solanki and B. D. Malhotra, “Recent Advances of Conducting Polymers and Their Composites for Electrochemical Biosensing Applications,” *Journal of Functional Biomaterials*, 2020,

11, 71. DOI: 10.3390/jfb11040071.
11. K. Theyagarajan and Y.-J. Kim, "Recent Developments in the Design and Fabrication of Electrochemical Biosensors Using Functional Materials and Molecules," *Biosensors*, 2023, 13, 424. DOI: 10.3390/bios13040424.
12. R. Gui, H. Jin, H. Guo and Z. Wang, "Recent advances and future prospects in molecularly imprinted polymers-based electrochemical biosensors," *Biosensors and Bioelectronics*, 2018, 100, 56–70. DOI: 10.1016/j.bios.2017.08.058.
13. I. I. Suni, "Substrate Materials for Biomolecular Immobilization within Electrochemical Biosensors," *Biosensors*, 2021, 11, 239. DOI: 10.3390/bios11070239.
14. P. Si, Y. Huang, T. Wang and J. Ma, "Nanomaterials for electrochemical non-enzymatic glucose biosensors," *RSC Advances*, 2013, 3, 3487–3502. DOI: 10.1039/C2RA22360K.
15. D.-W. Hwang, S. Lee, M. Seo and T. D. Chung, "Recent advances in electrochemical non-enzymatic glucose sensors – A review," *Analytica Chimica Acta*, 2018, 1033, 1–34. DOI: 10.1016/j.aca.2018.05.051.
16. H. Mohamed Fahmy, E. Samy Abu Serea, M. Casiano et al., "Recent Progress in Graphene- and Related Carbon-Nanomaterial-based Electrochemical Biosensors for Early Disease Detection," *ACS Biomaterials Science & Engineering*, 2022, 8, 1081–1102. DOI: 10.1021/acsbiomaterials.1c00710.
17. B. Wang, U. Akiba and J.-I. Anzai, "Recent Progress in Nanomaterial-Based Electrochemical Biosensors for Cancer Biomarkers: A Review," *Molecules*, 2017, 22, 1048. DOI: 10.3390/molecules22071048.
18. M. Pedrero, S. Campuzano and J. M. Pingarrón, "Electrochemical Biosensors for the Determination of Cardiovascular Markers: a Review," *Electroanalysis*, 2014, 26, 1132–1153. DOI: 10.1002/elan.201300597.
19. E. Cesewski and B. N. Johnson, "Electrochemical biosensors for pathogen detection," *Biosensors and Bioelectronics*, 2020, 159, 112214. DOI: 10.1016/j.bios.2020.112214.
20. K. Y. Goud, K. Koteshwara Reddy, A. Khorshed, V. Sunil Kumar, R. K. Mishra, M. Oraby, A. H. Ibrahim, H. Kim and K. V. Gobi, "Electrochemical diagnostics of infectious viral diseases: Trends and challenges," *Biosensors and Bioelectronics*, 2021, 180, 113112. DOI: 10.1016/j.bios.2021.113112.
21. S. S. Mahshid, S. E. Flynn and S. Mahshid, "The potential application of electrochemical biosensors in the COVID-19 pandemic: A perspective on the rapid diagnostics of SARS-CoV-2," *Biosensors and Bioelectronics*, 2021, 176, 112905. DOI: 10.1016/j.bios.2020.112905.
22. L. M. Schmidt-Speicher and K. Länge, "Microfluidic integration for electrochemical biosensor applications," *Current Opinion in Electrochemistry*, 2021, 29, 100755. DOI: 10.1016/j.coelec.2021.100755.
23. A. Sun, T. Wambach, A. G. Venkatesh and D. A. Hall, "A Low-Cost Smartphone-Based Electrochemical Biosensor for Point-of-Care Diagnostics," *IEEE Biomedical Circuits and Systems Conference (BioCAS)*, 2014, 312–315. DOI: 10.1109/BioCAS.2014.6981725.
24. A. C. Mendes Hacke, D. Lima and S. Kuss, "Green synthesis of electroactive nanomaterials by using plant-derived natural products," *Journal of Electroanalytical Chemistry*, 2022, 922, 116786. DOI: 10.1016/j.jelechem.2022.116786