



# Advancements in Electrochemical Sensors for Environmental and Biomedical Analysis

Janhavi Harish Indurkar<sup>1\*</sup>

<sup>1</sup>Gurunanak College of Pharmacy, Nagpur, Maharashtra, India

\*Corresponding Author E-mail: [janhaviindurkar478@gmail.com](mailto:janhaviindurkar478@gmail.com)

---

## Abstract:

The capability to change chemical information into measurable electrical signals with high sensitivity, quick response, and low cost has made electrochemical sensors a highly efficient and versatile analysis tool in environmental and biomedical analysis. In this review, the recent developments in the field of electrochemical sensors are assessed in detail, paying special attention to validation and use in animal research. Amperometric, conductometric and potentiometric sensors are discussed and important advancements made by incorporation of nanomaterials like graphene, carbon nanotubes and metal nanoparticles which are discussed in relation to enhanced electron transfer, selectivity and limits of detection. The review demonstrates the applicability of these sensors in the monitoring of a broad spectrum of analytes, such as heavy metals, glucose, neurotransmitters and pesticides, in dynamic in vivo and ex vivo conditions in animal models. In addition, the incorporation of biosensing components, wearable and implantable devices, microfluidic technologies, and artificial intelligence has increased their potential in terms of real-time, continuous, and multi-analyte detection. The review highlights the importance of designing new materials, enhancing biocompatibility, standardizing the methods, and developing state-of-the-art data analytics to improve the reliability, scalability, and practical use of electrochemical sensors. Taken collectively, these technologies have significant potential in further developing the fields of environmental monitoring, enhancing preclinical diagnostic capabilities, and even future translation of biomedical research.

**Keywords:** Electrochemical Sensors, Nanomaterials, Biosensors, Animal-Based Studies, Environmental Monitoring, Biomedical Analysis, Real-Time Detection, Wearable Sensors.

---

Received: Jan. 10, 2026

Revised: Feb. 19, 2026

Accepted: March. 28, 2026

Published: April 15, 2026

DOI: <https://doi.org/10.64062/IJPCAT.Vol2.Issue2.1>

<https://ijpcat.com/index.php/1/issue/archive>

*This is an Open Access article distributed under the terms of the Creative Commons Attribution (CC BY NC), which permits unrestricted use, distribution, and reproduction in any medium, as long as the original authors and source are cited. No permission is required from the authors or the publishers. (<https://creativecommons.org/licenses/by-nc/4.0/>)*

---

## 1. INTRODUCTION

Electrochemical sensors have formed an essential part of the modern environmental and biomedical research in the sense that they can convert chemical information into accurate electrical signals. They are sensitive, respond quickly, affordable and flexible, which makes

them applicable in the detection of a wide variety of analytes, such as pollutants, metabolites, and biomarkers. The recent advances in nanotechnology and material science, especially the application of graphene, carbon nanotubes, and metal nanoparticles have greatly improved the performance of sensors, increasing the efficiency of electron transfer, selectivity, and detection limits<sup>1</sup>. These sensors have been found to be remarkably able to monitor substances like heavy metals, glucose, neurotransmitters and pesticides in animal-based studies in real-time and continuously, thus giving more insight into the physiological processes and toxicological reactions.

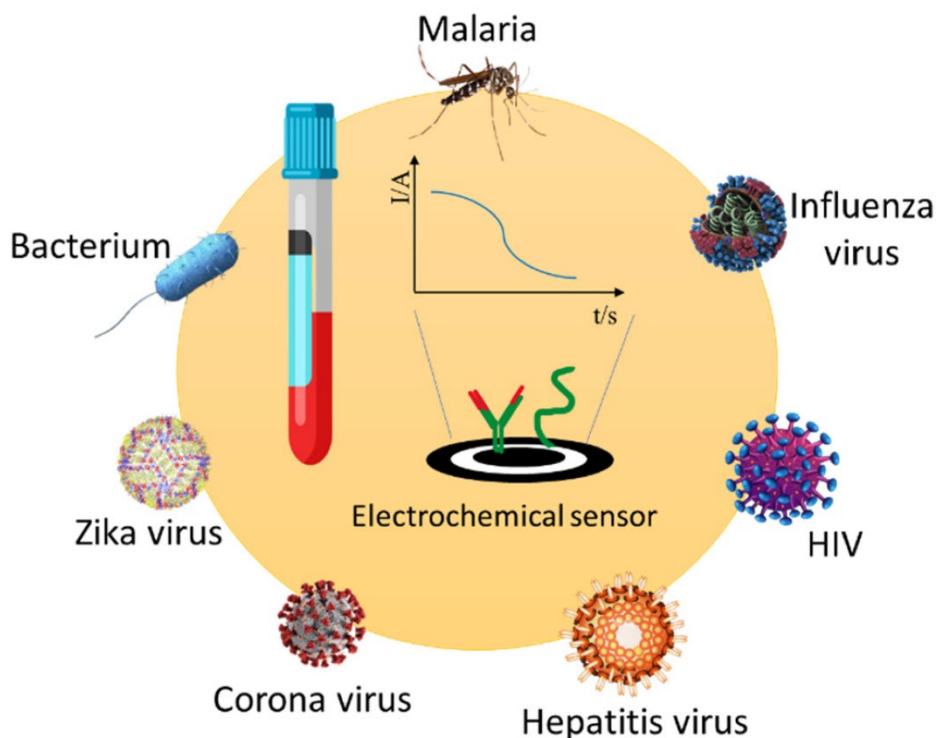


Figure 1: Electrochemical Sensors<sup>2</sup>

The increased importance of electrochemical sensing technologies has been further enhanced by the increasing need to monitor the environment with high accuracy and detect diseases at an early stage. These sensors are important as they are used to detect environmental contaminants and determine their biological effect, and also to monitor physiological parameters continuously in preclinical biomedical studies. The creation of sophisticated systems, such as biosensors, wearable devices, and implantable sensors, has increased their usability and enhanced efficiencies of experiments with minimal invasiveness in animal models<sup>3</sup>. Moreover, electrochemical sensors are being turned into extremely advanced and dependable instruments with the incorporation of emerging technologies, including artificial intelligence, microfluidics, and multi-analyte detection platforms. Consequently, they have a great potential in the enhancement of environmental safety, better diagnostics, and in the promotion of future innovations in the field of translational research.

### 1.1 Background and Context

Electrochemical sensors have proved to be very effective analytical tools which can be used to transform chemical information into electrical signals which can be measured. These sensors are very sensitive, fast in response and cheap and easy to work with that is why they find

extensive usage in the environmental monitoring and biomedical research<sup>4</sup>. The recent developments in nanotechnology, material science, and biosensor design have dramatically enhanced their performance, but most especially their selectivity, detection limits, and real-time analysis. Electrochemical sensors have been widely used in both *in vivo* and *ex vivo* studies to monitor a variety of analytes such as heavy metals, glucose, neurotransmitters, and pesticides, which can be important in understanding physiological and toxicological mechanisms in animals.

## 1.2 Objectives of the Review

The primary objective of this review is to:

- To examine the design, working principles and performance of various types of electrochemical sensors (potentiometric, Amperometric, and conductometric) in the study on animals.
- To assess how nanomaterials and biosensing components can be used to improve sensitivity, selectivity, and real-time detection of electrochemical sensors.
- To investigate the performance of electrochemical sensors in the detection of environmental pollutants and physiological biomarkers such as using animal models.
- To critically evaluate methodologies, strengths, and limitations that come with the use of electrochemical sensors in preclinical research.
- To determine the future research directions, technological advances, and new trends in enhancing the reliability, stability and scalability of electrochemical sensors.

## 1.3 Importance of the Topic

The increasing issues surrounding the environmental pollution and the requirement of early and proper detection of disease have escalated the demands of highly sensitive technologies. Electrochemical sensors are important in dealing with these issues because they allow quick, sensitive and real time detection of chemical and biological analytes<sup>5</sup>. Animal-based studies are particularly important as they provide preclinical validation of sensor performance under realistic biological conditions. The ongoing evolution of such sensors such as wearable and implantable sensors has great potential to enhance the safety of the environment, biomedical diagnostic and futuristic translational research.

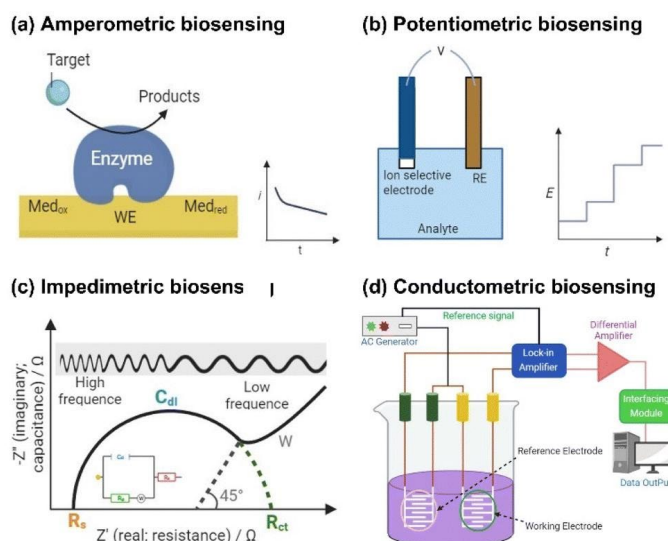
## 2. OVERVIEW AND ANIMAL-BASED EVALUATION OF ELECTROCHEMICAL SENSORS

Electrochemical detectors (potentiometric, Amperometric, and conductometric) can be improved with nanomaterials (e.g. graphene and metal nanoparticles) to provide sensitive and real-time detection of environmental and biological analytes in animal research. Animal tests indicate their applicability in the detection of heavy metals, glucose, neurotransmitters, and pesticides, but there are still issues such as biofouling, stabilization, and standardization<sup>6</sup>.

### 2.1 Overview of Electrochemical Sensor Technologies

Electrochemical sensors are common analytical instruments that transform chemical data and translate this data into electrical signals that can be measured<sup>7</sup>. They are appreciated due to

their high sensitivity, fast response, low-cost and capability to detect a broad spectrum of analyte in the environment, biomedical and industrial fields. Such sensors usually have:



**Figure 2:** Classification of Electrochemical Sensors Based on Measurement Techniques<sup>8</sup>

- Potentiometric sensors:** The sensors are used to measure the potential difference between a working electrode and a reference electrode in near zero current conditions. The concentration of a particular ion in the sample is directly related to the measured potential, according to the Nernst equation. They are typically employed in pH meters and ion-selective electrodes to detect the ions, sodium, potassium and chloride. They have the benefits of being simple, consuming low power, and selective to target ions<sup>9</sup>.
- Amperometric sensors:** These sensors are used to measure the electric current produced due to oxidation or reduction (redox) reactions taking place at the electrode surface when a fixed potential is imposed. The size of the current is proportional to the concentration of the analyte. Amperometric sensors are widely used in applications such as glucose monitoring, detection of dissolved oxygen, and environmental pollutant analysis due to their high sensitivity and fast response time.
- Conductometric sensors:** These sensors are used to detect variations in electrical conductivity of a solution due to chemical reactions or the presence of charged species. The changes in ionic concentration result in a change in conductivity that is measurable and therefore these sensors can be used to detect gases, water quality and biochemical reactions. They are user-friendly and do not need a reference electrode making them cheap and easy to use<sup>10</sup>.

Electrochemical sensors have been greatly improved by nanomaterials like graphene, carbon nanotubes and metal nanoparticles (e.g., gold and silver nanoparticles). These materials offer high surface-to-volume ratio, high electrical conductivity, and high catalytic activity that enhances the rate of electron transfer, as well as the number of active sensing sites. Consequently, sensors that use nanomaterials are more sensitive, selective, have lower detection limits and are more stable and are thus suitable in advanced sensing processes<sup>11</sup>.

## 2.2 Key Research Studies

Recent animal studies demonstrate significant advancements:

- **Heavy Metal Detection:** Gold nanoparticle-modified electrochemical sensors have been widely tested on rodent models to detect heavy metals that are toxic to the body such as lead and mercury in biological tissues. Such nanostructured sensors are extremely sensitive and have very low detection limits as a result of improvement in electron transfer and active surface area. They have been demonstrated to be able to detect trace metals in organs like liver, kidney and brain in vivo, which allows early diagnosis of metal toxicity and allows real time toxicology evaluations<sup>12</sup>.
- **Glucose Monitoring:** Implantable electrochemical glucose sensors that have been tested on diabetic rat models have shown that they can measure the blood glucose levels, real-time and continuously with high precision. The sensors are important in comparison to the traditional intermittent measurement systems because they have better accuracy, are quicker to respond and have a lesser level of interference with the signal. Moreover, new developments in biocompatible surfaces and the stabilization of enzymes (e.g., glucose oxidase immobilization) have enhanced the sensor durability and robustness, which is why they would also be useful in long-term diabetes management.
- **Neurotransmitter Detection:** In mouse models, carbon-based microelectrodes, especially those that integrate novel nanomaterials, have been utilized to record neurotransmitters like dopamine in high temporal and spatial resolution. Such sensors allow real-time recording of the rapid changes in the neurotransmitters level in certain areas of the brain. These studies have helped to understand better neurological disorders, such as Parkinson disease and depression, because they have been shown to change the dynamics of neurotransmitters and synaptic activity in various physiological and pathological conditions<sup>13</sup>.
- **Pesticide Detection:** Electrochemical biosensors that have been tested on aquatic animal models, particularly fish have been found to have high potential of detection of organophosphate pesticides in water bodies. The detection of toxic compounds is usually based on inhibition of enzymes by the sensors like acetylcholinesterase inhibition. Their capacity to offer quick, sensitive and on-site detection of pesticide exposure has been proved in experimental studies and has been a key element in environmental monitoring and protection of aquatic ecosystems. Moreover, these biosensors are also used to determine bioaccumulation and toxicity in living organisms, aid ecological risk assessment, and food safety investigations.

### 2.3 Methodologies Used

Common methodologies in animal-based studies include:

- **In vivo implantation of sensors for real-time monitoring:** This technique is based on the direct implantation of electrochemical sensors into living animal models in order to constantly measure physiological and biochemical parameters. These systems allow real-time monitoring of such analytes as glucose, neurotransmitters or toxic

components in dynamic biological settings. Miniaturization and biocompatible materials have enhanced sensor stability, minimal immune reactivity and long-term monitoring with minimal tissue injury<sup>14</sup>.

- **Ex vivo tissue analysis using electrochemical techniques:** In this technique, tissues or biological samples are removed out of animal models and examined in the laboratories out of the organism in controlled conditions. Measures of analyte concentrations and biochemical changes are measured by electrochemical methods like voltammetry and impedance spectroscopy. This technique is very accurate and gives detailed mechanistic information and enables researchers to confirm in vivo results and examine localized effects in particular organs or tissues.
- **Surface modification of electrodes with nanomaterials for improved performance:** Sensors based on electrodes are usually optimized using novel nanomaterials like graphene, carbon nanotubes, and metal nanoparticles. These alterations enhance the electrode surface area, enhance the electrical conductivity and accelerate the electron transfer kinetics. Consequently, the sensors are more sensitive, selective and less sensitive, and thus are more applicable in the detection of trace-level analytes in complex biological samples.
- **Calibration and validation using controlled dosing in animal models:** Calibration is the determination of a correlation between sensor response and analyte concentration, done through the administration of known doses of a substance to animal models. Validation measures the accuracy, precision and reproducibility of the sensor under physiological conditions. Controlled dosing experiments are useful in determining sensor performance at various concentration ranges, in establishing detection limits, and in establishing reliability in the real biological system. These measures will be critical in converting experimental sensors into useful diagnostic and monitoring instruments<sup>15</sup>.

## 2.4 Critical Evaluation

Electrochemical sensor technologies tested on the basis of animal studies provide both a positive and negative picture of the characteristics to reveal the strength and limitations of these technologies in both terms of technological potential and implementation issues<sup>16</sup>.

### Strengths

Electrochemical sensors are highly sensitive and can detect the analytes very fast thus enabling the detection of the analytes at very low levels. This renders them extremely appropriate in the diagnosis of disease at an early stage and also in monitoring the environment. Among the many benefits that come with it is the ability to monitor physiological and biochemical activities in the living organisms in real-time and in vivo without necessarily requiring repeated sampling. Also, these sensors frequently do not need much sample preparation, shortening the time spent on the analyses and making the work of the experiment easier<sup>17</sup>. Their versatility also adds to their utility as they can be used in a wide variety of biological systems- to measure metabolites, neurotransmitters and toxins, and in the environment, to measure water quality and detect pollutants.

### Weaknesses

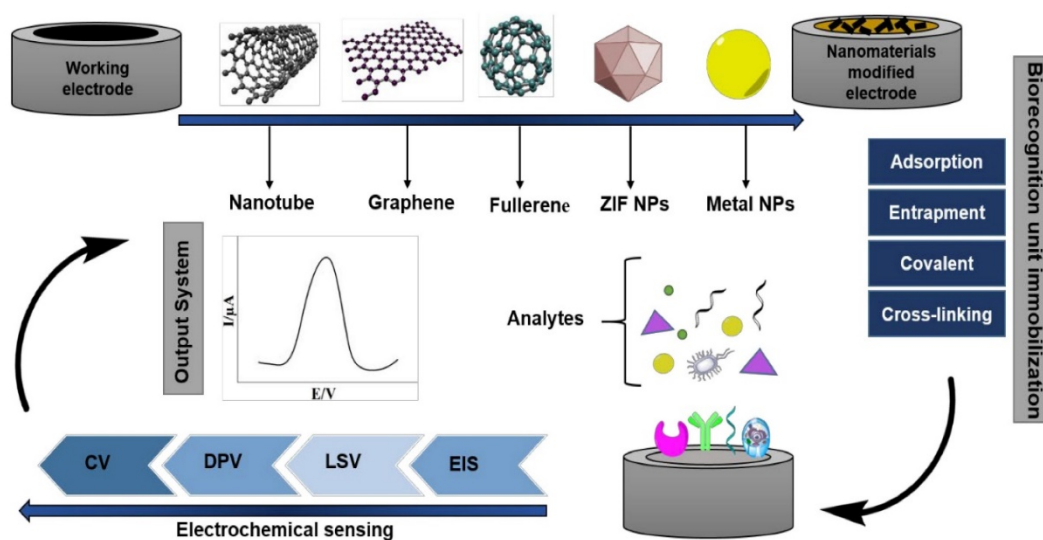
Although these benefits are realized, there are a few limitations. Biofouling, the build-up of proteins and other biological substances onto the sensor surface can have a major effect on sensor performance over time by decreasing sensitivity and accuracy. In addition, electrochemical sensors are usually not very stable over time in harsh biological conditions because of deterioration of electrode material or functional integrity of functional coatings. Animal response variability is also a challenge because the biological differences among subjects may influence the reproducibility and consistency of the results<sup>18</sup>. Lastly, scale and standardization also pose significant challenges, especially when moving an experimental model of an animal to clinical or commercial practice. Variations in sensor fabrication, calibration procedures, and biological states may impede the design of universally applicable and dependable sensor systems.

### 3. ADVANCED ELECTROCHEMICAL SENSOR APPLICATIONS IN ANIMAL-BASED STUDIES

Nanomaterial enhanced electrochemical sensors and the biosensors have high sensitivity, selectivity and real-time detection of biomarkers, toxins and metabolites in animal's models because of the enhanced conductivity and biological recognition elements. Their uses in environmental monitoring and wearable/implantable devices are also noted in animal-based studies, although their reliability in the long term and their practical scalability is yet to be improved<sup>19</sup>.

#### 3.1 Nanomaterial-Enhanced Electrochemical Sensors

The use of nanomaterials like graphene and metal nanoparticles (e.g., gold and silver nanoparticles) has transformed the design of electrochemical sensors because they can greatly improve the speed of the electron transfer and increase the surface area, which is effective. Their peculiar physicochemical characteristics, including high conductivity, catalytic activity, and high surface-to-volume ratio, enable quicker signal production and better sensitivity<sup>20</sup>. The sensors engineered with these nanomaterials have been shown to be better in the detection of biomarkers, toxins and trace analytes at very low concentrations in animal studies. These improvements result in reduced detection limits, increased signal stability and selectivity, and are very useful in biomedical diagnostics and in toxicology monitoring.



**Figure 3:** Nanomaterial-Enhanced Electrochemical Sensor Interface<sup>21</sup>

### 3.2 Electrochemical Biosensors

Electrochemical biosensors are combinations of biological recognition components (e.g. enzymes, antibodies or nucleic acids) and electrochemical transducers that are used to obtain a highly specific detector of the target analyte<sup>22</sup>. These biosensors have been utilized effectively in detecting in animal models:

- **Glucose:** Sensors based on enzymes (e.g., glucose oxidase) can be used to continuously monitor the blood glucose level of diabetic animal models at very high accuracy.
- **Lactate:** Lactate biosensors monitor the metabolic activity and tissue oxygenation, especially in the research associated with exercise physiology and critical care.
- **Neurotransmitters:** Neurotransmitter biosensors that can identify neurotransmitters like dopamine and serotonin give real-time information about the functioning of the brain and neurological diseases.

Their selectivity leads to their high specificity because the biological recognition element can selectively bind with the analyte, lowering interference with other substances. This renders electrochemical biosensors very convenient in accurate biomedical diagnostics, disease monitoring, and personalized medicine practices<sup>23</sup>.

### 3.3 Environmental Monitoring Using Animal Models

Animal experiments are important to help in the validation of the electrochemical sensors that have been developed to monitor the environment by giving realistic biological conditions. For example:

- **Detection of heavy metals in rodents:** Accumulation of toxic metals such as lead and mercury in tissues can be monitored using sensors to help measure levels of exposure and toxic effects.
- **Monitoring pesticide toxicity in aquatic species:** Biosensors that can sense enzyme inhibition or biochemical variations are used when fish and other aquatic organism are used to measure the impact of pesticide contamination<sup>24</sup>.
- **Assessing air pollutant exposure through physiological changes in animals:** Electrochemical sensors have the potential to detect biomarkers of oxidative stress or respiratory capacity in animals in polluted air, which can shed light on hazards of the environment to human health.

Such studies are useful to determine the reliability, sensitivity and applicability of sensors in real world and environmental safety and regulation.

### 3.4 Wearable and Implantable Sensors

In electrochemical sensing, recent growth in technology has resulted in flexibility, wearable, and implantable types of sensors that have been widely tested in animal models. These devices are made of stretchable and biocompatible material, and they can be easily incorporated with biological tissues. They offer a number of benefits, such as:

- **Real-time physiological data:** The dynamic evaluation of health state is possible with constant control of such parameters as glucose, pH and neurotransmitter levels.
- **Reduced invasiveness:** These sensors reduce the number of times invasive procedures have to be repeated, which enhances the efficiency of the experiment compared to conventional methods of sampling.
- **Improved animal welfare during experiments:** The minimally invasive or non-invasive devices lead to a decrease in stress and discomfort in animal models, which is in accordance with ethical research practices<sup>25</sup>.

These state-of-the-art sensor systems are an important move towards translational applications, such as wearable health sensors and implantable diagnostic sensors to be used on animals.

#### 4. EMERGING TRENDS AND TECHNOLOGICAL INNOVATIONS IN ELECTROCHEMICAL SENSORS

The convergence of electrochemical sensors with nanotechnology and smart materials, such as graphene derivatives, metal-organic frameworks (MOFs), and conductive polymers, has been a force that has acted to drive the latest developments in the field of electrochemical sensors. The materials are capable of greatly improving electron transfer efficiency, surface reactivity, and signal stability, resulting in higher sensitivity and selectivity to trace-level biomarkers and environmental toxins<sup>26</sup>. Animal experiments have shown that this type of nanostructured sensors can work in the complex biological systems, and in vivo monitoring can be done accurately. Also, the introduction of miniaturized and microfluidic systems has enabled the analysis of small samples (using very small sample volumes) with high accuracy, which is especially useful when small animal models such as mice and zebrafish are used, and the invasiveness of the analysis is minimal, and experimental control is necessary.

The other notable innovation is the emergence of wireless and real time monitoring technologies, which make it possible to constantly collect data without having to handle the animals again and again. Such systems enhance the validity of physiological measurements because they record dynamic biological changes in natural conditions<sup>27</sup>. In addition, artificial intelligence (AI) and modern data analytics have enabled the analysis of complex electrochemical signals to a great extent. In animal research, AI-enhancing platforms have enhanced the ability to detect small biochemical changes, which are useful in identifying toxic exposure early and disease progression.

Moreover, the creation of multi-analyte electrochemical sensors is another significant step towards the enhancement of the efficiency of the experiment<sup>28</sup>. The sensors can be used to measure several physiological parameters at once, including glucose, lactate and neurotransmitters, in a single system, minimizing variance and improving the accuracy of data. Together, these advances in technology are turning electrochemical sensing into a more accurate, efficient, and scalable instrument in animal-based research in the environment and biomedical contexts<sup>29</sup>.

**Table 1:** Summary of Key Studies on Electrochemical Sensor Advancements<sup>30</sup>

Author(s) & Year	Study Focus	Methodology/Technology	Key Findings

<b>Mahato &amp; Wang (2021)<sup>31</sup></b>	Evolution of electrochemical sensors toward wearable devices	Flexible electronics, biocompatible materials, skin-integrated sensors	Enabled real-time, continuous monitoring with high sensitivity and rapid response; suitable for point-of-care applications
<b>Perumal et al. (2021)<sup>32</sup></b>	SERS-based sensors for biomedical and agri-food applications	Nanostructured substrates, signal amplification techniques	High sensitivity and specificity; capable of detecting trace-level analytes in complex matrices
<b>Oiye et al. (2019)<sup>33</sup></b>	Electrochemical sensors using Schiff bases and metal complexes	Transition metal complexes, catalytic sensing mechanisms	Enhanced selectivity and sensitivity; effective detection of forensic, pharmaceutical, and environmental analytes
<b>Godja &amp; Munteanu (2024)<sup>34</sup></b>	Hybrid nanomaterials in sensor technology	Combination of nanomaterials (hybrid systems)	Improved conductivity, surface reactivity, and multifunctional sensing capabilities
<b>Kalkal et al. (2021)<sup>35</sup></b>	Graphene quantum dot-based sensors	Optical and electrochemical sensing using graphene quantum dots	High sensitivity, उच्च conductivity, tunable photoluminescence; effective for biological and environmental detection

## 5. DISCUSSION

Nanomaterial-enhanced electrochemical sensors are sensitive and real-time and can be widely used in animal-based environmental and biomedical research. Nevertheless, issues like biofouling, stability, and non-standardization still exist, which puts a strain on sophisticated materials, enhanced procedures, and the implementation of AI and smart technologies in the future<sup>36</sup>.

### 5.1 Interpretation and Analysis of Findings

The studies reviewed show that the use of nanomaterials and biosensing elements has greatly improved the electrochemical sensors to bring a new level of sensitivity, selectivity, and real time detection. Experiments using animals establish that these sensors are useful in the dynamic physiological context to monitor a broad spectrum of analytes, such as heavy metals, glucose, neurotransmitters, and pesticides<sup>37</sup>. Their capability of offering continuous and precise data has been enhanced by the in vivo and implantable systems and this has made them very useful tools in the preclinical research.

### 5.2 Implications and Significance

Electrochemical sensing technologies have significant environmental and biomedical implications due to the kind of progress that has been achieved in this field. These sensors can

be used in ecological studies to evaluate ecological risks through the use of animal models and are also useful in environmental applications where pollutants are detected quickly. They are useful in biomedical studies to aid early diagnosis of diseases, constant check of physiological functions and better comprehension of complicated biological occurrences. The wearable and implantable sensors are also developed that are contributing to improved efficiency of the experiment and animal welfare by minimizing invasive procedures. Moreover, the combination of artificial intelligence and multi-analyte sensing systems increases their data analysis potential based on detailed and accurate data collection<sup>38</sup>.

### **5.3 Research Gaps and Limitations**

Although these have benefits, there are a number of constraints. The problem of biofouling is also very significant because over time, the biofouling on sensor surfaces may lead to a decreased performance. Reliability is also impacted by limited long-term stability in complex biological environments<sup>39</sup>. The differences in the reaction of animals may also cause the variation in the results and the absence of standardized protocols may make the results of the studies incomparable. Moreover, the challenge of scaling sensor production and guarantees the reproducibility of the results is a challenge to application and commercialization.

### **5.4 Future Research Directions**

Future studies are needed to come up with more sophisticated anti-fouling measures and enhance the biocompatibility and longevity of sensor materials that can be used in vivo. Experimental protocols and validation methods should be standardized to provide consistency and reliability of results across studies. The combination of wireless technologies, microfluidic systems, and AI-based data analysis needs to be further developed to increase functionality and data interpretation. Also, the creation of biodegradable and sustainable sensor materials, and enhanced multi-analyte sensors will be instrumental in developing electrochemical sensors to practical work in the environment and in biomedical applications<sup>40</sup>.

## **6. CONCLUSION**

Electrochemical sensors are new instruments of analysis in the environment and biomedical fields with some of its strengths such as high sensitivity, selectivity, fast response and real-time monitoring. The review highlights the importance of the integration of nanomaterials like graphene, carbon nanotubes and metal nanoparticles and biological recognition components in improving the functionality of such sensors in animal models. Such integration makes it possible to detect various analytes (including heavy metals, glucose, neurotransmitters, and pesticides) with high accuracy in dynamic in vivo and ex vivo conditions. Moreover, wearable and implantable sensors have come to light, as well as the development of microfluidics, wireless technology, and artificial intelligence, which has expanded their fields of use, making them more efficient and minimally invasive, and enabling the detection of multiple analytes. There are however challenges such as biofouling, low long-term stability, variability in biological responses and lack of standardization which are setbacks to mass usage and commercialization. It is essential to overcome these problems with the help of advanced materials, enhanced biocompatibility, standardized practices, and refined data analysis to continue development in the future. Overall, electrochemical sensors hold colossal opportunities in the field of environmental monitoring, preclinical diagnostics, and next

generation translational technologies development, particularly once proven through comprehensive animal-based research models.

## REFERENCES

1. Hassan, R. Y. (2022). Advances in electrochemical nano-biosensors for biomedical and environmental applications: from current work to future perspectives. *Sensors*, 22(19), 7539.
2. Liu, Y., Liu, X., Wang, X., & Jiang, H. (2025). AI-empowered electrochemical sensors for biomedical applications: technological advances and future challenges. *Biosensors*, 15(8), 487.
3. Mishra, Y. K., Kaushik, A., & Singh, A. (2024). Introduction to advanced materials for sensing and biomedical applications. *Materials Advances*, 5(16), 6346-6350.
4. Tovar-Lopez, F. J. (2023). Recent progress in micro-and nanotechnology-enabled sensors for biomedical and environmental challenges. *Sensors*, 23(12), 5406.
5. Hernández-Rodríguez, J. F., Rojas, D., & Escarpa, A. (2020). Electrochemical sensing directions for next-generation healthcare: trends, challenges, and frontiers. *Analytical Chemistry*, 93(1), 167-183.
6. Pan, Y., Zhang, J., Guo, X., Li, Y., Li, L., & Pan, L. (2024). Recent advances in conductive polymers-based electrochemical sensors for biomedical and environmental applications. *Polymers*, 16(11), 1597.
7. Liu, R., Zhao, M., Zhang, X., Zhang, C., Ren, B., & Ma, J. (2025). Advances and challenges in molecularly imprinted electrochemical sensors for application in environmental, biomedicine, and food safety. *Critical Reviews in Analytical Chemistry*, 1-19.
8. Hassan, M. H., Khan, R., & Andreescu, S. (2022). Advances in electrochemical detection methods for measuring contaminants of emerging concerns. *Electrochemical Science Advances*, 2(6), e2100184.
9. Barhoum, A., & Altintas, Z. (Eds.). (2022). *Advanced Sensor Technology: Biomedical, Environmental, and Construction Applications*. Elsevier.
10. Rasheed, T., Hassan, A. A., Kausar, F., Sher, F., Bilal, M., & Iqbal, H. M. (2020). Carbon nanotubes assisted analytical detection–Sensing/delivery cues for environmental and biomedical monitoring. *TrAC Trends in Analytical Chemistry*, 132, 116066.
11. Buledi, J. A., Shah, Z. U. H., Mallah, A., & Solangi, A. R. (2022). Current perspective and developments in electrochemical sensors modified with nanomaterials for environmental and pharmaceutical analysis. *Current Analytical Chemistry*, 18(1), 102-115.
12. Sharma, E., Singh, A., Singh, K., Ganti, S. S., Das Gupta, G., & Verma, S. K. (2025). Advancements in electrochemical sensors for detection of environmental pollutants: a review. *Electrocatalysis*, 16(5), 773-798.
13. Khanmohammadi, A., Jalili Ghazizadeh, A., Hashemi, P., Afkhami, A., Arduini, F., & Bagheri, H. (2020). An overview to electrochemical biosensors and sensors for the detection of environmental contaminants. *Journal of the Iranian Chemical Society*, 17(10), 2429-2447.

14. Baranwal, J., Barse, B., Gatto, G., Broncova, G., & Kumar, A. (2022). Electrochemical sensors and their applications: A review. *Chemosensors*, 10(9), 363.
15. Nashruddin, S. N. A. B. M., Salleh, F. H. M., Yunus, R. M., & Zaman, H. B. (2024). Artificial intelligence– powered electrochemical sensor: Recent advances, challenges, and prospects. *Heliyon*, 10(18).
16. Ramachandran, R., Chen, T. W., Chen, S. M., Baskar, T., Kannan, R., Elumalai, P., ... & Dinakaran, K. (2019). A review of the advanced developments of electrochemical sensors for the detection of toxic and bioactive molecules. *Inorganic Chemistry Frontiers*, 6(12), 3418-3439.
17. Ivanišević, I. (2023). The role of silver nanoparticles in electrochemical sensors for aquatic environmental analysis. *Sensors*, 23(7), 3692.
18. Ghoneim, M. T., Nguyen, A., Dereje, N., Huang, J., Moore, G. C., Murzynowski, P. J., & Dagdeviren, C. (2019). Recent progress in electrochemical pH-sensing materials and configurations for biomedical applications. *Chemical reviews*, 119(8), 5248-5297.
19. Hui, Y., Huang, Z., Alahi, M. E. E., Nag, A., Feng, S., & Mukhopadhyay, S. C. (2022). Recent advancements in electrochemical biosensors for monitoring the water quality. *Biosensors*, 12(7), 551.
20. Fritea, L., Banica, F., Costea, T. O., Moldovan, L., Dobjanschi, L., Muresan, M., & Cavalu, S. (2021). Metal nanoparticles and carbon-based nanomaterials for improved performances of electrochemical (Bio) sensors with biomedical applications. *Materials*, 14(21), 6319.
21. Liu, X., Huang, L., & Qian, K. (2021). Nanomaterial-based electrochemical sensors: mechanism, preparation, and application in biomedicine. *Advanced NanoBiomed Research*, 1(6), 2000104.
22. Ozcelikay, G., Karadurmus, L., Kaya, S. I., Bakirhan, N. K., & Ozkan, S. A. (2020). A review: New trends in electrode systems for sensitive drug and biomolecule analysis. *Critical reviews in analytical chemistry*, 50(3), 212-225.
23. Uniyal, S., & Sharma, R. K. (2018). Technological advancement in electrochemical biosensor based detection of Organophosphate pesticide chlorpyrifos in the environment: A review of status and prospects. *Biosensors and bioelectronics*, 116, 37-50.
24. Sumitha, M. S., & Xavier, T. S. (2023). Recent advances in electrochemical biosensors– A brief review. *Hybrid Advances*, 2, 100023.
25. Tajik, S., Beitollahi, H., Nejad, F. G., Dourandish, Z., Khalilzadeh, M. A., Jang, H. W., ... & Shokouhimehr, M. (2021). Recent developments in polymer nanocomposite-based electrochemical sensors for detecting environmental pollutants. *Industrial & engineering chemistry research*, 60(3), 1112-1136.
26. Duan, H., Peng, S., He, S., Tang, S. Y., Goda, K., Wang, C. H., & Li, M. (2025). Wearable electrochemical biosensors for advanced healthcare monitoring. *Advanced Science*, 12(2), 2411433.
27. Laghlimi, C., Moutcine, A., Chtaini, A., Isaad, J., Soufi, A., Ziat, Y., ... & Belkhanchi, H. (2023). Recent advances in electrochemical sensors and biosensors for monitoring drugs and metabolites in pharmaceutical and biological samples. *ADMET and DMPK*, 11(2), 151-173.

28. Suhito, I. R., Koo, K. M., & Kim, T. H. (2020). Recent advances in electrochemical sensors for the detection of biomolecules and whole cells. *Biomedicines*, 9(1), 15.
29. Ferrari, A. G. M., Carrington, P., Rowley-Neale, S. J., & Banks, C. E. (2020). Recent advances in portable heavy metal electrochemical sensing platforms. *Environmental Science: Water Research & Technology*, 6(10), 2676-2690.
30. Li, Z., Mohamed, M. A., Vinu Mohan, A. M., Zhu, Z., Sharma, V., Mishra, G. K., & Mishra, R. K. (2019). Application of electrochemical aptasensors toward clinical diagnostics, food, and environmental monitoring. *Sensors*, 19(24), 5435.
31. Mahato, K., & Wang, J. (2021). Electrochemical sensors: From the bench to the skin. *Sensors and Actuators B: Chemical*, 344, 130178.
32. Perumal, J., Wang, Y., Attia, A. B. E., Dinish, U. S., & Olivo, M. (2021). Towards a point-of-care SERS sensor for biomedical and agri-food analysis applications: A review of recent advancements. *Nanoscale*, 13(2), 553-580.
33. Oiyé, É. N., Ribeiro, M. F. M., Katayama, J. M. T., Tadini, M. C., Balbino, M. A., Eleotério, I. C., ... & de Oliveira, M. F. (2019). Electrochemical sensors containing Schiff bases and their transition metal complexes to detect analytes of forensic, pharmaceutical and environmental interest. A review. *Critical Reviews in Analytical Chemistry*, 49(6), 488-509.
34. Godja, N. C., & Munteanu, F. D. (2024). Hybrid nanomaterials: a brief overview of versatile solutions for sensor technology in healthcare and environmental applications. *Biosensors*, 14(2), 67.
35. Kalkal, A., Kadian, S., Pradhan, R., Manik, G., & Packirisamy, G. (2021). Recent advances in graphene quantum dot-based optical and electrochemical (bio) analytical sensors. *Materials Advances*, 2(17), 5513-5541.
36. Zare-Shehneh, N., Mollarasouli, F., & Ghaedi, M. (2023). Recent advances in carbon nanostructure-based electrochemical biosensors for environmental monitoring. *Critical Reviews in Analytical Chemistry*, 53(3), 520-536.
37. Curulli, A. (2020). Nanomaterials in electrochemical sensing area: Applications and challenges in food analysis. *Molecules*, 25(23), 5759.
38. Wang, Y., Yang, B., Hua, Z., Zhang, J., Guo, P., Hao, D., ... & Huang, J. (2022). Recent advancements in flexible and wearable sensors for biomedical and healthcare applications. *Journal of Physics D: Applied Physics*, 55(13), 134001.
39. Simoska, O., Gaffney, E. M., Minter, S. D., Franzetti, A., Cristiani, P., Grattieri, M., & Santoro, C. (2021). Recent trends and advances in microbial electrochemical sensing technologies: An overview. *Current Opinion in Electrochemistry*, 30, 100762.
40. Singh, R., Gupta, R., Bansal, D., Bhateria, R., & Sharma, M. (2024). A review on recent trends and future developments in electrochemical sensing. *ACS omega*, 9(7), 7336-7356.