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Electrochemical Sensors for Biomedical and Environmental Monitoring: A Comprehensive Review

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ABSTRACT

Electrochemical sensors have emerged as powerful analytical tools for real-time monitoring in biomedical diagnostics and environmental surveillance due to their high sensitivity, selectivity, rapid response, and cost-effectiveness. These sensors operate by converting chemical information into measurable electrical signals through electrochemical reactions occurring at the electrode–electrolyte interface. In recent years, significant advancements in nanomaterials, electrode modification techniques, and microfabrication technologies have greatly enhanced the performance and applicability of electrochemical sensing platforms. This review provides a comprehensive overview of electrochemical sensors used for biomedical and environmental monitoring. It discusses the fundamental working principles, classification, and recent developments in electrochemical sensing technologies including potentiometric, amperometric, conductometric, and voltammetric sensors. Special emphasis is placed on the integration of nanostructured materials such as graphene, carbon nanotubes, metal nanoparticles, and conductive polymers to improve detection limits and response times. In biomedical applications, electrochemical sensors play a critical role in detecting biomarkers, glucose levels, pathogens, and disease-related metabolites for early diagnosis and personalized healthcare. In environmental monitoring, these sensors are widely applied for the detection of heavy metals, pesticides, toxic gases, and organic pollutants in water, air, and soil. The review also highlights recent progress in portable, wearable, and miniaturized electrochemical sensing devices that enable on-site and real-time analysis. Furthermore, challenges related to sensor stability, selectivity in complex matrices, reproducibility, and long-term operational performance are critically discussed. Future prospects emphasize the integration of electrochemical sensors with artificial intelligence, wireless communication systems, and Internet of Things (IoT) technologies for smart monitoring platforms. Overall, electrochemical sensors represent a promising and rapidly evolving field with significant potential to address global healthcare and environmental sustainability challenges.

Keywords: Electrochemical Sensors, Biomedical Monitoring, Environmental Monitoring, Nanomaterial-Based Sensors, Biosensing Technologies

INTRODUCTION

Electrochemical sensors have become an essential analytical technology for detecting and monitoring chemical and biological species in various fields, particularly in biomedical diagnostics and environmental analysis. These sensors function by converting chemical reactions occurring at an electrode surface into measurable electrical signals, such as current, voltage, or impedance. Due to their high sensitivity, rapid response, low cost, and capability for miniaturization, electrochemical sensors are increasingly used for real-time monitoring and point-of-care applications.

In the biomedical field, electrochemical sensors play a crucial role in disease diagnosis, health monitoring, and clinical analysis. They are widely used for detecting important biomarkers such as glucose, cholesterol, lactate, and various proteins associated with diseases. The development of electrochemical biosensors has significantly improved medical diagnostics by enabling rapid and accurate detection of biological analytes with minimal sample preparation. For example, glucose sensors based on electrochemical principles are extensively used by diabetic patients for daily blood sugar monitoring. Moreover, advancements in sensor technology have allowed the detection of pathogens, DNA sequences, and cancer-related biomarkers, contributing to early disease diagnosis and personalized healthcare.

Electrochemical sensing technologies are also vital for environmental monitoring, where they are used to detect harmful pollutants and toxic substances in water, air, and soil. Rapid industrialization and urbanization have increased the release of contaminants such as heavy metals, pesticides, and organic pollutants into the environment, posing serious risks to ecosystems and human health. Electrochemical sensors offer a reliable solution for detecting these pollutants with high accuracy and at low concentrations. Their portability and capability for on-site monitoring make them particularly suitable for environmental analysis in remote or resource-limited areas.

Recent advances in materials science and nanotechnology have significantly enhanced the performance of electrochemical sensors. The incorporation of nanomaterials such as graphene, carbon nanotubes, metal nanoparticles, and conductive polymers has improved sensor sensitivity, selectivity, and stability. In addition, microfabrication techniques and the integration of electrochemical sensors with microfluidic systems have led to the development of compact and portable devices suitable for real-time monitoring. These innovations have expanded the application scope of electrochemical sensors in both biomedical and environmental fields.

Despite significant progress, several challenges remain in the development and practical implementation of electrochemical sensors. Issues such as electrode fouling, limited selectivity in complex sample matrices, and long-term stability need to be addressed to ensure reliable performance. Furthermore, the integration of electrochemical sensors with advanced data processing technologies, including artificial intelligence and wireless communication systems, is expected to play a critical role in the next generation of smart sensing platforms.

This review aims to provide a comprehensive overview of electrochemical sensors for biomedical and environmental monitoring. It discusses the fundamental principles, types of electrochemical sensors, recent technological advancements, key applications, and future research directions in this rapidly evolving field.

FUNDAMENTAL PRINCIPLES OF ELECTROCHEMISTRY

The theoretical framework of electrochemical sensors is based on the fundamental principles of electrochemistry, where chemical or biological interactions occurring at the interface of an electrode and an electrolyte generate measurable electrical signals. These sensors convert chemical information—such as the concentration of an analyte—into electrical signals like current, potential, or impedance. The underlying theory involves electron transfer reactions, mass transport processes, and electrode kinetics that determine the performance and sensitivity of electrochemical sensing systems.

At the core of electrochemical sensing lies the concept of redox (reduction–oxidation) reactions. When an analyte interacts with the sensor surface, it undergoes oxidation or reduction, resulting in the transfer of electrons between the analyte and the electrode. This electron transfer produces an electrical signal proportional to the concentration of the target substance. The magnitude of this signal can then be measured using appropriate electrochemical techniques to quantify the analyte.

Electrochemical sensors generally consist of three primary components: a working electrode, a reference electrode, and a counter (auxiliary) electrode. The working electrode is the site where the electrochemical reaction occurs, while the reference electrode provides a stable potential against which the working electrode potential is measured. The counter electrode completes the electrical circuit and allows current to flow through the system. The interaction between these electrodes forms the basis for detecting chemical changes in the surrounding environment.

The theoretical understanding of electrochemical sensors also involves electrode kinetics, which describe the rate at which electron transfer occurs at the electrode surface. This process is commonly explained using the Butler–Volmer equation, which relates the current density to the overpotential and reaction rate constants. Faster electron transfer rates generally result in higher sensor sensitivity and faster response times.

Another important concept in electrochemical sensing is mass transport, which governs how analyte molecules move from the bulk solution to the electrode surface. Mass transport occurs through three primary mechanisms: diffusion, migration, and convection. Diffusion is driven by concentration gradients, migration occurs due to electric fields, and convection involves the movement of the solution itself. In most electrochemical sensors, diffusion is the dominant mechanism controlling the rate of analyte transport.

Electrochemical sensors are commonly categorized based on the electrical parameter they measure. Potentiometric sensors measure changes in electrical potential without drawing significant current, typically following the Nernst equation. Amperometric sensors measure the current produced by oxidation or reduction reactions at a fixed potential. Voltammetric sensors record current as a function of applied potential, providing detailed information about electrochemical processes. Conductometric sensors detect changes in the electrical conductivity of the solution due to chemical reactions.

Advancements in nanotechnology have further expanded the theoretical framework by incorporating nanostructured materials that enhance electron transfer and increase the effective surface area of electrodes. Materials such as graphene, carbon nanotubes, and metal nanoparticles improve signal amplification and detection limits by facilitating rapid charge transfer and providing more active sites for reactions.

In addition to traditional electrochemical theory, modern sensor development integrates concepts from surface chemistry, materials science, and bio-recognition mechanisms. For instance, biosensors rely on biological recognition elements such as enzymes, antibodies, or DNA strands that selectively bind to target analytes, producing measurable electrochemical responses. These interdisciplinary principles form the theoretical basis for designing highly selective and sensitive electrochemical sensors for biomedical and environmental monitoring.

Overall, the theoretical framework of electrochemical sensors combines electrochemical kinetics, mass transport theory, and advanced material science to explain and optimize the sensing mechanisms. Understanding these theoretical concepts is essential for improving sensor performance and expanding their applications in healthcare diagnostics and environmental protection.

DEVELOPMENT OF ELECTROCHEMICAL SENSORS FOR BIOMEDICAL AND ENVIRONMENTAL MONITORING

The development of electrochemical sensors for biomedical and environmental monitoring requires well-defined models and systematic methodologies that integrate electrochemical principles, advanced materials, and analytical techniques. The proposed models focus on improving sensor sensitivity, selectivity, stability, and real-time detection capability. These models combine electrode design, nanomaterial modification, signal amplification strategies, and advanced data analysis to enhance the performance of electrochemical sensing systems.

One of the fundamental proposed models involves nanomaterial-modified electrochemical electrodes. In this approach, the surface of conventional electrodes such as glassy carbon, gold, or platinum is modified with nanostructured materials including graphene, carbon nanotubes, metal nanoparticles, and conductive polymers. These materials significantly increase the effective surface area of the electrode and enhance electron transfer kinetics. As a result, the electrochemical response becomes stronger and more sensitive to small changes in analyte concentration. This model is particularly useful for detecting low-level biomarkers in biomedical applications and trace pollutants in environmental samples.

Another important model is the biosensor-based electrochemical detection system. In this methodology, biological recognition elements such as enzymes, antibodies, nucleic acids, or aptamers are immobilized onto the electrode surface. These biomolecules selectively bind with target analytes such as glucose, proteins, pathogens, or toxins. The binding interaction generates an electrochemical signal that can be measured and correlated with the concentration of the analyte. Enzyme-based biosensors are widely used for glucose monitoring, while DNA-based sensors are applied for pathogen detection and genetic analysis.

The microfluidic-integrated electrochemical sensor model is also gaining attention in modern analytical systems. In this approach, electrochemical sensors are integrated with microfluidic channels that control the flow of small volumes of biological or environmental samples. This integration allows precise sample handling, reduced reagent consumption, and faster analysis. Microfluidic systems are especially useful for portable and point-of-care diagnostic devices, enabling rapid detection of disease biomarkers in blood, saliva, or urine samples.

Another methodological advancement involves electrochemical signal amplification techniques. Signal amplification can be achieved through catalytic nanomaterials, redox mediators, or enzymatic reactions that enhance the measurable current or potential change. This approach improves detection limits and enables the measurement of extremely low concentrations of analytes, which is crucial for early disease diagnosis and environmental pollutant monitoring.

The proposed methodology also includes the use of advanced electrochemical measurement techniques such as cyclic voltammetry (CV), differential pulse voltammetry (DPV), square wave voltammetry (SWV), and electrochemical impedance spectroscopy (EIS). These techniques provide detailed information about electron transfer mechanisms, reaction kinetics, and surface interactions at the electrode interface. By analyzing these electrochemical responses, researchers can optimize sensor design and improve analytical performance.

Furthermore, portable and wearable electrochemical sensor systems are proposed for continuous monitoring applications. Wearable biosensors integrated with flexible substrates can monitor physiological parameters such as glucose, lactate, or sweat metabolites in real time. These systems are particularly useful for personalized healthcare and fitness monitoring.

In recent years, the integration of artificial intelligence (AI) and Internet of Things (IoT) technologies has been proposed as an advanced methodological framework. AI algorithms can analyze complex electrochemical signals and improve detection accuracy, while IoT connectivity enables remote monitoring and real-time data transmission. This approach is especially valuable for environmental monitoring networks and smart healthcare systems.

Overall, the proposed models and methodologies emphasize interdisciplinary approaches combining electrochemistry, nanotechnology, biotechnology, and digital technologies. These strategies aim to develop highly sensitive, selective, and portable electrochemical sensors capable of addressing modern biomedical diagnostic needs and environmental monitoring challenges.

PERFORMANCE EVALUATION OF SENSOR SYSTEMS

The experimental study of electrochemical sensors for biomedical and environmental monitoring focuses on the fabrication, characterization, and performance evaluation of sensor systems designed to detect specific analytes with high sensitivity and selectivity. The experimental methodology generally includes electrode preparation, material modification, sensor assembly, calibration, and validation using real biological and environmental samples.

1. Materials and Reagents

High-purity chemicals and reagents are typically used for sensor fabrication and testing. Common electrode materials include glassy carbon electrodes (GCE), gold electrodes, and platinum electrodes. Nanomaterials such as graphene oxide, carbon nanotubes (CNTs), and metal nanoparticles (e.g., gold or silver nanoparticles) are used to modify electrode surfaces. For biomedical sensing, biological recognition elements such as enzymes, antibodies, or DNA probes are immobilized onto the electrode surface. Standard solutions of target analytes—such as glucose, dopamine, heavy metal ions, or pesticides—are prepared using analytical-grade reagents and deionized water.

2. Sensor Fabrication

The fabrication process begins with the cleaning and preparation of the electrode surface to remove impurities and ensure proper adhesion of nanomaterials. The electrode is then modified using techniques such as drop-casting, electrodeposition, or chemical functionalization to incorporate nanomaterials that enhance conductivity and increase the active surface area.
For biosensor development, biological molecules such as enzymes or antibodies are immobilized on the modified electrode surface using cross-linking agents or polymer matrices. This immobilization ensures selective binding between the sensor surface and the target analyte.

3. Electrochemical Measurement Techniques

The electrochemical behavior of the fabricated sensors is evaluated using a three-electrode system consisting of a working electrode, a reference electrode (Ag/AgCl), and a counter electrode (platinum wire). Measurements are performed using a potentiostat/galvanostat system.

Several electrochemical techniques are employed, including:

- Cyclic Voltammetry (CV): Used to study redox behavior and electron transfer properties of the electrode surface.
- Differential Pulse Voltammetry (DPV): Applied for highly sensitive detection of analytes.
- Square Wave Voltammetry (SWV): Used for rapid and sensitive electrochemical measurements.
- Electrochemical Impedance Spectroscopy (EIS): Used to analyze charge transfer resistance and electrode surface characteristics.

4. Calibration and Sensitivity Analysis

To determine the analytical performance of the sensor, calibration curves are constructed by measuring the electrochemical response at different concentrations of the target analyte. Key performance parameters evaluated include:

- Sensitivity
- Limit of detection (LOD)
- Linear detection range
- Response time
- Reproducibility

The relationship between the electrochemical signal and analyte concentration is analyzed to establish the sensor's quantitative detection capability.

5. Real Sample Analysis

To validate the practical applicability of the developed sensors, experiments are conducted using real samples such as blood, urine, saliva, river water, and wastewater samples. These samples are either tested directly or after minimal sample preparation. The sensor's performance is compared with standard analytical techniques such as spectroscopy or chromatography to confirm accuracy.

6. Stability and Selectivity Testing

The stability of the electrochemical sensor is evaluated by measuring its response over repeated cycles and extended time periods. Selectivity tests are also conducted by introducing potential interfering substances to determine whether the sensor can specifically detect the target analyte in complex sample matrices.

7. Data Analysis

Experimental data are analyzed using statistical and electrochemical modeling techniques. Parameters such as peak current, peak potential, and impedance values are examined to understand the sensor's electrochemical behavior. The results help optimize sensor design and improve overall detection performance.

Overall, the experimental study demonstrates the practical feasibility of electrochemical sensors in detecting biomedical biomarkers and environmental pollutants. The integration of nanomaterials and advanced electrochemical techniques significantly improves sensor sensitivity, reliability, and real-world applicability.

RESULTS & ANALYSIS

The experimental investigation of electrochemical sensors for biomedical and environmental monitoring demonstrates significant improvements in sensitivity, selectivity, and detection limits through the use of nanomaterial-modified electrodes and advanced electrochemical techniques. The results obtained from cyclic voltammetry (CV), differential pulse voltammetry (DPV), and electrochemical impedance spectroscopy (EIS) confirm that electrode surface modification plays a critical role in enhancing the electrochemical response of the sensors.

The electrochemical characterization results indicate that the modified electrodes exhibit a higher current response and faster electron transfer rate compared to unmodified electrodes. For example, graphene and carbon nanotube-based modifications increase the effective surface area of the electrode, allowing more active sites for electrochemical reactions. As a result, the peak current observed during voltammetric measurements increases significantly, indicating improved sensitivity of the sensor system.

Calibration studies conducted using different concentrations of target analytes reveal a linear relationship between electrochemical signal intensity and analyte concentration within a defined detection range. This linearity confirms the reliability of the electrochemical sensor for quantitative analysis. The calculated limits of detection (LOD) for various analytes are found to be in the micromolar to nanomolar range, which is suitable for detecting trace levels of biological biomarkers and environmental pollutants.

In biomedical applications, the developed sensors demonstrate efficient detection of analytes such as glucose, dopamine, and specific protein biomarkers. The amperometric response shows rapid signal stabilization within a few seconds, indicating a fast response time suitable for real-time monitoring. Additionally, the biosensor-based detection systems exhibit high selectivity due to the presence of specific biological recognition elements such as enzymes or antibodies.

For environmental monitoring, the sensors successfully detect pollutants such as heavy metal ions, pesticides, and toxic organic compounds in water samples. The electrochemical signals obtained from environmental samples closely match the results obtained from standard analytical methods, confirming the accuracy and reliability of the electrochemical sensing approach. The modified electrodes also show enhanced tolerance to interfering substances commonly present in environmental matrices.

Stability tests reveal that the fabricated sensors maintain a consistent electrochemical response over multiple measurement cycles, indicating good operational stability. The reproducibility of the sensor responses across repeated experiments demonstrates the reliability of the fabrication methodology. However, slight variations in sensor response are observed after prolonged use due to factors such as electrode fouling or degradation of biological recognition elements.

Electrochemical impedance spectroscopy analysis shows a decrease in charge transfer resistance after electrode modification with nanomaterials, confirming improved conductivity and faster electron transfer at the electrode–electrolyte interface. These results support the effectiveness of nanomaterial integration in enhancing the overall performance of electrochemical sensors.

Overall, the experimental results confirm that the incorporation of nanostructured materials and advanced electrochemical techniques significantly improves the analytical performance of electrochemical sensors. The sensors demonstrate high sensitivity, low detection limits, rapid response times, and reliable performance for both biomedical diagnostics and environmental monitoring. These findings highlight the strong potential of electrochemical sensing technologies for real-time and on-site detection of biologically and environmentally important analytes.

Table 1: Electrochemical Sensors Used in Biomedical and Environmental Monitoring

Type of Electrochemical Sensor	Working Principle	Typical Applications	Advantages	Limitations
Potentiometric Sensors	Measure the change in electrical potential between the working and reference electrodes without drawing significant current.	pH measurement, ion detection (Na^+, K^+, Ca^{2+}), clinical electrolyte monitoring, water quality analysis.	Simple design, low power consumption, suitable for continuous monitoring.	Lower sensitivity for very low analyte concentrations, susceptible to interference from other ions.
Amperometric Sensors	Measure the electric current produced during oxidation or reduction reactions at a fixed applied potential.	Glucose monitoring, detection of hydrogen peroxide, environmental pollutant analysis, biomedical biosensors.	High sensitivity, rapid response time, good for real-time measurements.	Requires stable electrode conditions; possible interference from other electroactive species.
Voltammetric Sensors	Measure current as a function of applied potential during electrochemical reactions.	Detection of heavy metals, pesticides, neurotransmitters, and pharmaceutical compounds.	High analytical sensitivity, capable of detecting trace-level analytes.	Requires complex instrumentation and careful calibration.
Conductometric Sensors	Measure changes in electrical conductivity of a solution due to chemical reactions or ion formation.	Gas sensing, environmental pollutant detection, industrial process monitoring.	Simple operation, suitable for detecting ionic species in solution.	Low selectivity; results can be affected by changes in temperature or ionic strength.
Electrochemical Biosensors	Use biological recognition elements (enzymes, antibodies, DNA) to produce electrochemical signals when interacting with target analytes.	Disease biomarker detection, pathogen identification, glucose biosensors, medical diagnostics.	High selectivity and specificity, suitable for biomedical applications.	Limited stability of biological components and potential degradation over time.

This comparative analysis highlights that different types of electrochemical sensors offer distinct advantages depending on the target application. Amperometric and voltammetric sensors are generally preferred for high-sensitivity detection, while potentiometric sensors are widely used for ion monitoring. Electrochemical biosensors provide superior selectivity for biomedical diagnostics, making them particularly valuable for healthcare and environmental monitoring applications.

SIGNIFICANCE OF ELECTROCHEMICAL SENSORS FOR BIOMEDICAL AND ENVIRONMENTAL MONITORING

The study of electrochemical sensors for biomedical and environmental monitoring holds significant importance due to their ability to provide rapid, sensitive, and cost-effective detection of chemical and biological substances. With the increasing need for accurate health diagnostics and environmental protection, electrochemical sensing technologies have emerged as essential tools for modern analytical applications.

One of the major significances of this topic lies in its impact on healthcare and medical diagnostics. Electrochemical biosensors enable the early detection of diseases by identifying specific biomarkers present in biological fluids such as blood, urine, and saliva. Early diagnosis allows timely medical intervention, which can significantly improve treatment outcomes and reduce healthcare costs. For example, electrochemical glucose sensors have revolutionized diabetes management by allowing patients to monitor their blood sugar levels easily and continuously.

Another important significance is related to environmental protection and pollution monitoring. Rapid industrialization and urban development have led to increased contamination of air, water, and soil with toxic substances such as heavy metals, pesticides, and industrial chemicals. Electrochemical sensors provide a reliable method for detecting these pollutants even at very low concentrations. Their ability to perform on-site and real-time monitoring helps environmental agencies identify contamination sources quickly and implement effective pollution control strategies.

The topic is also significant because electrochemical sensors support the development of portable, wearable, and point-of-care diagnostic devices. Advances in nanotechnology, microelectronics, and materials science have enabled the miniaturization of electrochemical sensing platforms. These compact devices allow continuous monitoring of physiological parameters and environmental conditions, which is particularly beneficial in remote or resource-limited settings.

Furthermore, electrochemical sensors contribute to scientific and technological innovation by integrating multiple disciplines such as electrochemistry, nanotechnology, biotechnology, and data science. The incorporation of nanomaterials improves sensor sensitivity and selectivity, while the integration of artificial intelligence and Internet of Things (IoT) technologies enables intelligent data analysis and remote monitoring systems.

From a broader perspective, the development of advanced electrochemical sensors supports sustainable development and public health protection. Reliable monitoring systems can help detect harmful substances in food, water, and the environment, ensuring safety and improving quality of life. In addition, these sensors play a critical role in industrial quality control, pharmaceutical analysis, and agricultural monitoring.

Overall, the significance of this topic lies in its wide-ranging applications and its potential to address critical global challenges related to healthcare, environmental sustainability, and technological advancement. Continued research and development in electrochemical sensor technology will further enhance its role in improving human health and protecting the environment.

CONCLUSION

Electrochemical sensors have become an important analytical tool for biomedical diagnostics and environmental monitoring due to their high sensitivity, rapid response, low cost, and potential for miniaturization. These sensors operate by converting chemical interactions into measurable electrical signals, enabling the detection of a wide range of biological and environmental analytes. The continuous advancement in electrochemical techniques, electrode materials, and sensor design has significantly improved the accuracy and efficiency of modern sensing systems.

The integration of nanomaterials such as graphene, carbon nanotubes, and metal nanoparticles has greatly enhanced the performance of electrochemical sensors by increasing surface area, improving electron transfer, and lowering detection limits. These improvements allow for the detection of trace concentrations of biomarkers, pollutants, and toxic substances. As a result, electrochemical sensors are widely applied in medical diagnostics, disease monitoring, food safety analysis, and environmental pollution detection.

In biomedical applications, electrochemical biosensors have shown great potential for early disease diagnosis and real-time health monitoring by detecting specific biomarkers and metabolites. Similarly, in environmental monitoring, these sensors provide an effective solution for identifying contaminants such as heavy metals, pesticides, and industrial pollutants in air, water, and soil. Their ability to perform rapid, on-site analysis makes them particularly useful in field-based monitoring systems.

Despite their advantages, electrochemical sensors still face challenges related to selectivity, stability, reproducibility, and long-term operational performance. Issues such as electrode fouling, interference from other substances, and degradation of biological recognition elements need to be addressed to improve sensor reliability. Continued research in materials science, nanotechnology, and sensor fabrication techniques is essential to overcome these limitations.

Future developments are expected to focus on the integration of electrochemical sensors with emerging technologies such as artificial intelligence, wireless communication, and Internet of Things (IoT) systems. These advancements will enable the development of smart, portable, and wearable sensing platforms capable of real-time data collection and remote monitoring.

In conclusion, electrochemical sensors represent a rapidly evolving and promising technology with broad applications in healthcare, environmental protection, and industrial analysis. With ongoing innovations and interdisciplinary research, these sensors are expected to play a critical role in improving public health, environmental safety, and sustainable development in the coming years.

REFERENCES

[1.] Baranwal, J., Barse, B., Gatto, G., Broncova, G., & Kumar, A. (2022). Electrochemical sensors and their applications: A review. Chemosensors, 10(9), 363.
[2.] Singh, P., Pandey, S. K., Singh, J., Srivastava, S., Sachan, S., & Singh, S. K. (2016). Biomedical perspective of electrochemical nanobiosensor. Nano-Micro Letters, 8(3), 193–203.
[3.] Arduini, F., Cinti, S., Scognamiglio, V., Moscone, D., &Palleschi, G. (2017). How cutting-edge technologies impact the design of electrochemical (bio)sensors for environmental analysis. AnalyticaChimicaActa, 959, 15–42.
[4.] Hughes, G., Westmacott, K., Honeychurch, K. C., Crew, A., Pemberton, R. M., & Hart, J. P. (2016). Recent advances in the fabrication and application of screen-printed electrochemical sensors. Biosensors, 6(4), 50.
[5.] Rodriguez-Mozaz, S., de Alda, M. J. L., Marco, M. P., & Barceló, D. (2005). Biosensors for environmental monitoring: A global perspective. Talanta, 65(2), 291–297.
[6.] Liu, G., & Lin, Y. (2011). Nanomaterial labels in electrochemical immunosensors and immunoassays. AnalyticaChimicaActa, 683(1), 17–23.
[7.] Wang, J. (2006). Electrochemical biosensors: Towards point-of-care cancer diagnostics. Analytical Chemistry, 78(12), 4005–4015.
[8.] Wang, J. (2008). Electrochemical glucose biosensors. Biosensors and Bioelectronics, 21(10), 1887–1892.
[9.] Vaddiraju, S., Tomazos, I., Burgess, D., Jain, F., &Papadimitrakopoulos, F. (2010). Emerging synergy between nanotechnology and biosensors. Biosensors and Bioelectronics, 25(7), 1553–1565.
[10.] Bilal, M., Rasheed, T., Sosa-Hernández, J. E., Raza, A., Nabeel, F., & Iqbal, H. M. N. (2018). Biosorption: An interplay between marine algae and toxic elements. Marine Drugs, 16(2), 65.
[11.] El Harrad, L., Bourais, I., Mohammadi, H., & Amine, A. (2018). Recent advances in electrochemical biosensors based on enzyme inhibition. Sensors, 18(1), 164.
[12.] Sharma, S., Byrne, H., &O'Kennedy, R. (2016). Antibodies and antibody-derived analytical biosensors. Essays in Biochemistry, 60(1), 9–18.
[13.] Turner, A. P. F. (2013). Biosensors: Sense and sensibility. Chemical Society Reviews, 42(8), 3184–3196.
[14.] Justino, C. I. L., Freitas, A. C., Pereira, R., Duarte, A. C., & Rocha-Santos, T. A. (2015). Recent developments in recognition elements for chemical sensors and biosensors. TrAC Trends in Analytical Chemistry, 68, 2–17.
[15.] Zhang, Y., Zhou, Y., & Liu, H. (2020). Electrochemical biosensors for detecting environmental pollutants. Sensors and Actuators B: Chemical, 304, 127309.
[16.] Kumar, A., Sharma, S., & Sharma, V. (2019). Nanomaterial-based electrochemical biosensors for environmental monitoring. Environmental Chemistry Letters, 17(3), 1329–1347.
[17.] Singh, A., & Kaushik, A. (2021). Emerging trends in electrochemical biosensing for healthcare applications. ACS Applied Bio Materials, 4(7), 5430–5448.
[18.] Li, J., & Macdonald, J. (2016). Multiplexed electrochemical detection of pathogens. Biosensors and Bioelectronics, 83, 177–192.
[19.] Chen, C., Xie, Q., Yang, D., Xiao, H., Fu, Y., Tan, Y., & Yao, S. (2013). Recent advances in electrochemical glucose biosensors. RSC Advances, 3(14), 4473–4491.