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Applications of Electrochemical Biosensors across Medical, Environmental and Food Safety Fields

Baoyi Jiao[1, *]

[1] Department of Biochemical Engineering, University Collage London, London, WC1H 0AW, England

*Corresponding author: zcbebji@ucl.ac.uk

Abstract:

Traditional laboratory tests remain accurate, but they are slow, costly, and difficult to use outside controlled settings. Electrochemical sensors (including different sensor types and materials) have become indispensable tools nowadays. They offer major advantages, including high sensitivity, strong selectivity, fast response, low cost, simple miniaturization and reliable real-time online monitoring. Recent research have shown the application in three main fields: medical diagnostics, environmental monitoring, and food safety, such as glucose monitoring in diabetes, heavy metal detection in water, and bacterial identification in food, confirming the value of real-time monitoring. They reduce the dependence on complex laboratory equipment. Relevant working mechanisms include signal conversion and biological recognition. As materials and designs improve, they move from experimental trials into daily practice. Meanwhile, limitations still exist. Sensors face problems such as signal interference and short lifespan. Further exploration is needed in the future, in the hope that it can be better applied in clinical practice.

Keywords: Electrochemical biosensors, Medical diagnostics, Environmental monitoring, Food safety, Biological recognition.

1. Introduction

Biosensors are tools that combine a biological element with a physical detector. They are designed to identify specific substances quickly and accurately. When a target molecule is present, the sensor gives a readable output. This process helps people detect things quickly and easily.

Electrochemical biosensors are one of the most common types. They are small, fast, and easy to use. They turn chemical reactions into electrical signals [1]. Many researchers use them because they work well in real-world samples, such as blood, water, or food. They do not need large machines or complex lab work.

These sensors are used in various fields, particularly medicine, environmental science, and food safety. They not only help with detecting diseases but are

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also useful for finding pollution. What's more, they assist with looking for harmful bacteria, viruses or chemicals. Compared to older methods like PCR or chromatography, biosensors save time and cost less.

Most current studies on electrochemical biosensors primarily focus on a single application domain. Therefor, this paper will show how they work in the three application areas: medical diagnosis, environmental monitoring, and food safety, conduct a detailed analysis of specific application cases, explore the challenges currently faced by technological development, and look forward to its future development trends, with the aim of providing references for research and application in related fields.

2. Medicine

Electrochemical biosensors are fast, sensitive and easy to use. Many devices are small and work outside of traditional labs. These features make them ideal for point-of-care medical testing.

2.1 Glucose Biosensor

One of the most well-known examples is the glucose biosensor. It helps diabetes patients check their blood sugar at home. This sensor uses glucose oxidase to react with glucose in the blood, which produces hydrogen peroxide. These sensors measures the electrical signal from this reaction. This signal indicates the amount of glucose present. Continuous glucose monitors (CGMs) are used by millions worldwide. As of the early 2020s, over 9 million people globally use CGMs for daily diabetes care [2]. These sensors deliver real time glucose readings every few minutes. Users can track glucose trends without the need for frequent finger-prick tests. Patients experience fewer painful fingersticks and better daily management of diet, exercise, and medication.Clinically, CGMs allow doctors to detect glucose fluctuations early. This enables timely intervention and prevention of diabetes complications. Studies show that continuous detection supports adjustments in insulin dosing and lifestyle choices. These changes contribute to an improved patient quality of life and reduce the risks of severe events, such as hypoglycemia and hyperglycemia.

2.2 Cancer Detection

In recent years, researchers have developed sensors for other medical uses. Cancer detection is one important area. Traditional detection methods rely on the phenotypic characteristics of tumors to achieve detection. Imaging detection techniques such as X-ray examination, magnetic resonance imaging, endoscopic examination and tissue biopsy required tumors to grow to a certain size before they can be detected. Consequently, these techniques cannot achieve precise early diagnosis of cancer, which has certain limitations. Some electrochemical biosensors can detect markers such as carcinoembryonic antigen, rostate-specific antigen and alpha-fetoprotein. These are linked to cancers like colon, prostate, and liver cancer [3]. The sensor uses antibodies that bind to the marker. When binding occurs, a small electrical current is generated, indicating the presence and level of the cancer marker.

2.3 Detection of Viruses and Bacteria

Electrochemical biosensors also help in detecting viruses and bacteria. During the COVID 19 pandemic, SARS CoV 2 proteins and viral RNA is detected by these biosensors. These devices offered rapid, accurate and affordable alternatives to PCR. They enabled testing outside traditional laboratories. They enabled testing outside traditional laboratories. As Chaibun et al. reported the detection of viral spike (S) and nucleocapsid (N) proteins as low as 1 copy/μL [4].

Sensors are also being designed to detect diseases such as HIV, influenza, and hepatitis. For example, hepatitis B surface antigen is detected using a gold electrode and an antibody. The test is simple and takes only a short time. It helps doctors diagnose early and begin treatment sooner.

Electrochemical biosensors can detect harmful bacteria such as E. coli, Salmonella, and Listeria monocytogenes. The sensor utilizes a biological component, such as an antibody, aptamer, or DNA probe, that specifically binds to the target bacteria. When the bacteria attach to this part, a reaction happens on the sensor's surface. This reaction changes the electrical signal such as the current, voltage or resistance. The sensor detects this change to indicate whether the bacteria are present and how much is present. For example, aptamer-modified carbon nanotube electrodes can detect Salmonella enteritidis at about 55 CFU/mL and Salmonella typhimurium at concentrations of approximately 67 CFU/mL [5]. Aptamer-based sensors achieve even higher sensitivity to detect Escherichia coli O157:H7, which is as low as 4 CFU/mL in standard buffer systems [6].

2.4 Mental Health and the Brain

Another exciting application is mental health and brain research. Electrochemical biosensors can measure neurotransmitters such as dopamine and serotonin. These chemicals affect mood, memory, and movement. Imbalances can cause diseases like Parkinson's and depression. Parkinson's disease is a brain disorder that cause shaking, slow movements, and stiff muscles. Depression is a mental health condition that changes how a person feels and thinks. It can lead to constant sadness, loss of interest, and trouble with daily activities. Traditional lab tests are slow and costly. Biosensors can detect these molecules in real-time, even in tiny amounts. This helps doctors better understand brain disorders.

2.5 Optimize Experimental Equipment

These sensors were used in research labs and pilot deployments. Validated point-of-care platforms provide rapid testing. In S.N. Vaz et al.'s study with 40 saliva specimens, the results matched standard qRT-PCR methods with 100% agreement and the GeneXpert Xpress assay processed saliva samples in about 45 minutes [7]. These tests also showed complete concordance with reference PCR assays. These sensors brought clear benefits,such as shortening detection time from hours to minutes. For example, one sensor identified viral proteins in a saliva sample in under 100 ms with high specificity. They cut reliance on scarce reagents and expensive instruments. They offered low-cost, miniaturized alternatives for mass and remote testing and also allowed testing in settings such as clinics, airports, and field sites where PCR was not feasible.

Wearable electrochemical sensors are now being developed. Some can stick to the skin like a patch. They collect data from sweat, tears, or interstitial fluid. These sensors can monitor glucose, lactate, cortisol, and more. Athletes can use them during exercise. Patients with chronic illnesses can track their bodies in real-time. Although these devices offer many benefits, some challenges remain. Biosensors may become less stable over time. In real biological samples, other molecules may interfere with the signal. The sensors are carefully calibrated to give accurate results. Currently, new technologies such as nanomaterials, smart signal processing and improved electronics make sensors more reliable.

3. Environmental Applications

Electrochemical biosensors have become important tools in environmental monitoring. These devices are often simple to operate and do not need large instruments or complex lab setups. Because of this, they are well-suited for on-site detection in rivers, soil, and even in the air.

3.1 Detection of Heavy Metals

Traditional lab tests, such as ICP-MS or AAS are accurate. But they often cost hundreds or even thousands of dollars per test. They can also take hours or days because of complex sample preparation. Electrochemical biosensors provide a cheaper and faster alternative. Some paper-based or portable designs cost only a few dollars per test. They can detect heavy metals in just a few minutes.

One major application is the detection of heavy metals which are toxic to both humans and ecosystems. Studies demonstrate that these sensors achieve very low detection limits. Bismuth-based electrodes have detected Pb at about 0.105 ng/mL and Cd at about 0.054 ng/mL using anodic stripping voltammetry [8]. Even low concentrations can cause serious health problems. Excess heavy metals can accumulate in the body, harming the nervous system, liver and kidneys. They also pollute soil and water, disrupting the balance of ecosystems. When the metal ion binds to the sensor, it creates an electrical signal. This signal can be measured to determine the type and concentration of the pollutant.

3.2 Pesticide Detection

Pesticides are widely used in agriculture. Pesticides first enter the soil and water where they cause pollution. This pollution harms plants, animals and other living organisms. Over time, pesticide residues accumulate in the food chain and disrupt the entire ecosystem. Some biosensors use the enzyme acetylcholinesterase (AChE). This enzyme reacts with organophosphate and carbamate pesticides [9]. These pesticides block the enzyme's activity. When this happens, the sensor shows a lower signal. The drop in signal matches the amount of pesticide present. AChE-based biosensors demonstrate strong sensitivity toward pesticide inhibitors. Sun et al. used a hollow gold nanosphere sensor to achieve a detection limit of 0.06 μg/L for chlorpyrifos, while the detection limit for carbofuran was approximately 0.08 μg/L [10]. These sensors work quickly, protecting both water quality and human health.

3.3 Detection of organic pollutants

Electrochemical biosensors are also useful for detecting organic pollutants,which include phenols, dyes, hormones, and endocrine-disrupting compounds, especially the pollutants at very low concentrations. These substances originate from industries, farms, and household waste, and may harm aquatic ecosystems and impact human reproductive health. Bisphenol A(BPA) is an exogenous estrogen that is harmful to humans and wildlife [11]. Some designs detect the BPA at 0.071 ng/mL [11]. Others measure phenol at 0.09 μM and synthetic dyes, such as methylene blue at 0.02 μM [12,13]. Hormones such as 17β-estradiol have been detected at 0.000023 ng/mL in samples using split-type immunoassays (UV–vis mode) [14]. These sensors are valuable for early warning systems and real-time monitoring of pollution. And then fast action is allowed to protect

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water quality and public health.

In addition,multi-analyte electrochemical biosensors have gained attention. These sensors can detect multiple pollutants simultaneously. For example, a single chip can measure lead, mercury and cadmium together [15]. This saves time and reduces the number of tests needed. It also allows for rapid decision-making during pollution events or emergencies.

Although electrochemical biosensors still face challenges, natural samples such as river water or wastewater are complex. They may contain many substances that interfere with the sensor. Long-term stability and sensor fouling are also concerns. Researchers are working to develop improved sensor coatings and anti-interference materials to address these issues.

Portable and wearable environmental sensors are also being explored, such as drones or smart buoys [16]. Others can be worn by workers or residents near industrial zones. These devices collect real-time data and send it to a central system. This technology can be utilized for environmental risk assessment and in support of government regulations.

4. Food

Researchers designed them to detect pathogens, toxins, pesticides, antibiotics and allergens. The World Health Organization reports approximately 600 million foodborne illnesses and 420,000 deaths occur each year. Traditional lab tests, such as chromatography or ELISA, are accurate but slow and costly. Electrochemical biosensors are widely used in food safety applications. It provides fast, sensitive, and portable detection.

4.1 Detection of Contaminants

Electrochemical biosensors can work with minimal sample preparation and detect contaminants at very low limits. For instance, aptamer-based sensors can detect aflatoxin B1 at a limit of 2pg/mL [17]. Another example is the detection of shellfish toxins, such as saxitoxin, with a detection limit of 0.92 nM, using nanotetrahedron-assisted aptasensors [18]. harmful bacteria Salmonella is detected by a carbon nanotube–based immunosensor at under 1000 cfu/mL in complex broth samples [19]. Multiplexed biosensors allow simultaneous detection of multiple contaminants. For example, metal organic nanohybrids enabled the detection of Staphylococcus aureus and E.coil in food samples within minutes [20].

4.2 Measure Chemical Residues

Electrochemical sensors can measure chemical residues. They detect pesticides using enzyme-based methods. For organophosphate pesticides, the process works by acetylcholinesterase inhibition. This inhibition changes the electrochemical signal. The change allows the sensor to estimate the pesticide level in food. Chloramphenicol(CAP) residue in milk is detected by CAP immunosensors at 0.0047 ng/mL under the most suitable conditions [21]. Allergens can cause allergic reactions and serious health problems. An electrochemical dual immunosensor can detect the allergenic proteins Ara h 1 at 5.2 ng/mL and Ara h 6 at concentrations of 0.017 ng/mL [22].

Despite progress, there still remain challenges. Biosensor stability in complex food matrices can degrade over time. Some reagents have limited shelf life.

5. Conclusion

Electrochemical biosensors hold strong potential in medicine, the environment and food safety. They respond quickly, show high sensitivity, and are easy to carry. These features make them a valuable supplement to traditional methods, enabling real-time detection. Despite clear progress, many challenges remain in practice. First, stability and selectivity in complex samples are still major concerns. Blood, wastewater, and food often contain impurities. These impurities interfere with signals and reduce accuracy. For this reason, better biological recognition molecules are needed. Second, new nanomaterials such as carbon nanotubes and metal–organic frameworks improve performance. However, their long-term stability and safety remain uncertain. In addition, most sensors detect only one target. This limits their use when multiple indicators must be monitored at the same time. Future research should focus on multi-target, integrated and intelligent platforms. Miniaturization and portability are also important, since they support rapid on-site testing. Finally, paper-based and low-cost portable sensors have entered trials. However, large-scale production and standardized use remain limited. Ensuring sensitivity and reliability while moving toward commercialization will be a key challenge.

However, there is no doubt that with the continuous integration and innovation of interdisciplinary fields, electrochemical sensors will surely play an increasingly important role in safeguarding human health, protecting the ecological environment and maintaining food safety, providing solid technical support for building a safer and healthier world.

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