A Study of Novel Electrochemical Sensors and Their Applications: Food Analysis and Biomedical Object Detection

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Abstract. Electrochemical biosensors have developed into a sophisticated and versatile technology, which are driven by advances in biology, chemistry, physics, and medicine. These sensors have undergone significant enhancements with the integration of novel materials like carbon nanotubes and metal nanoparticles, which have greatly improved their sensitivity, selectivity, and overall performance. As a result, electrochemical biosensors have become indispensable tools in a wide range of applications, including agriculture, food safety, environmental monitoring, and medical diagnostics. The ability to detect various biological and chemical substances with high accuracy has made these sensors crucial in both industrial and clinical settings. However, despite their advantages, they still face challenges related to complex fabrication processes, material compatibility, and the need for specialized equipment, which can increase costs. The ongoing research and technological advancements are continually addressing these limitations, leading to more accessible and effective biosensors. This paper provides a comprehensive overview of the evolution of electrochemical biosensors. It also outlines various electrode modification techniques. Meanwhile, it explores their critical applications in food analysis and biomedicine detection. This technology would play a vital role in early disease detection, food safety, and personalized health monitoring.

Keywords: Electrochemical sensors; food analysis; biomedical object detection.

1. Introduction

Electrochemical biosensors originated in 1962. Clark et al. reported the use of enzyme electrodes combined with glucose oxidase to detect glucose. So far, it has gradually developed into biosensing technology, which integrates biology, physics, chemistry and medicine. With the progress of science and technology, many new materials have also been integrated into chemical sensors, such as carbon nanomaterials [1].

Electrochemical sensors have a wide range of applications. These electrochemical sensors can be used in agriculture, food industries and environmental monitoring [2]. Electrochemical sensors play an important role in food analysis. Electrochemical sensors often have high sensitivity for detecting chemical substances in complex matrices. Therefore, there has been an increasing number of researches on electrochemical sensors in food analysis in recent years. In addition, electrochemical sensors have also attracted the attention of researchers in biomedical detection. There are many types of electrochemical sensors. Among them, biosensors based on electrochemical principles exhibit excellent performance [3]. These sensors are crucial in biomedicine [4]. In the biomedical field, many biomolecules and trace chemicals need to be detected for diagnosis. An analytical device called a biosensor is used to find different chemical and biological compounds. A sensitive element and a signal processing element make up the two primary parts of biosensors [5]. The development of electrochemical sensors for biomedical analysis is very rapid in recent years. Therefore, it is necessary to study the electrochemical sensors. Meanwhile, it is needed to explore their applications in food analysis and biomedical object detection.

2. Modification Methods

As electrochemical applications become more widespread, the materials used for electrodes continue to evolve to optimize the performance of electrochemical sensors. Sensitivity enhancement of electrochemical sensors using novel functional materials are an important means of modifying electrochemical sensors.

It has been demonstrated that using electrodes enhanced with carbon nanotubes can improve electrochemical performance. Carbon nanotubes are frequently added to electrodes using drop-coating, electrodeposition, vacuum-assisted filtering, and self-assembly techniques. The electrode is deposited by using a voltage after being submerged in an electrolyte using the electrodeposition method. To enhance the performance of the thin film modified electrode, annealing or washing are needed. To enhance the performance of the thin film modified electrode, ink is disseminated onto the electrode by the drop coating method, which is then dried by heat treatment. The process of depositing solid particles or solvents on a filter membrane while it is under vacuum is known as vacuum-assisted filtration. By washing the residue off the filter membrane, thin films are produced. The process of self-assembly entails layering a self-assembled solution over an even and flat electrode in order to generate thin films. During this process, the self-assembled molecules interact with one another to form a smooth, organized pattern. Nevertheless, these techniques typically involve intricate procedures, inadequate material compatibility, significant equipment needs, and exorbitant expenses [6].

Metal nanoparticles have demonstrated entirely distinct properties from their native nanoparticles with the rapid advancement of nanotechnology research, making them highly versatile for applications in various industries. AuNPs exhibit superior electrical conductivity, high surface-area-to-volume ratios, low electrical resistance, and great stability. They are perfect for linking biometric systems to signal transduction because of these characteristics. They also act as important reagents in the development and application of bio-detection systems. Because of their special qualities, AuNPs are very well-liked. They are very useful due to their biocompatibility, sensitivity, and simplicity of surface functionalization with different ligands. In conclusion, since their invention in 1962, electrochemical biosensors have developed into a strong and adaptable instrument. They have changed dramatically because of developments in disciplines including biology, chemistry, physics, and medicine. The utilization of novel materials, such metal nanoparticles and carbon nanotubes, has improved the overall performance, selectivity, and sensitivity of electrochemical biosensors.

Electrochemical biosensors have several benefits, including high sensitivity, quick response times, and the capacity to shrink for point-of-care testing. They also have some drawbacks. These drawbacks include complex fabrication processes, material compatibility issues, and the need for specialized equipment, which can increase costs. Nonetheless, the ongoing research and technological advancements continue to address these limitations, making electrochemical biosensors increasingly accessible and effective. These advancements also enhance their ability for the selective binding of molecules and ions, further improving their functionality [7].

3. Applications

Electrochemical sensors are often used in food analysis. Traditional techniques include colorimetric testing, meteorological chromatography, high performance liquid chromatography (HPLC), and Raman spectroscopy. The most recent generation of ratio metric electrochemical sensors offer improved precision, sensitivity, and dependability. Ratio metric sensors accept two electrochemical signals and use their ratio as the output. While conventional sensors rely on a single signal output. Their performance is improved by this way as opposed to conventional ones. This offers a built-in error correction function that traditional single-signal sensors do not offer. The study of food detection benefits greatly from this trait [8].

To achieve rapid detection of biomarkers, a series of rapid quantitative techniques have been developed in the clinic, including radioimmunoassay, electrophoretic immunoassay, fluorescence immunoassay and enzyme-linked immunosorbent assay. However, the detection of these techniques is time-consuming, cumbersome, with low sensitivity, and susceptible to the interference of complex components in serum. Biosensors, an emerging technology at the intersection of information and biotechnology, hold significant potential for the early detection of human diseases. They also play a crucial role in subsequent medical monitoring, diagnosis, and treatment [5]. For example, Hossein Kamali et al. reported a DNAzyme-assisted aptasensor for early detection of cancer biomarkers. It improved the ability of biosensors to achieve precise targeting by incorporating nanomaterials and nanoparticles [9].

Milk serves as an important food that provides the body with a wide range of nutrients. It is characterized by its nutrient-rich nature, with proteins, fats, carbohydrates, vitamins and minerals, all of which play an important role in maintaining human health. However, there are also safety hazards. Pesticide residues in cattle feed, antibiotic and anti-parasite veterinary drug residues can affect the quality of milk, which in turn can adversely affect human health. Long-term consumption of milk containing such residues may increase the resistance to antibiotics, which may complicate the treatment of infectious diseases. Detection of residues in milk is essential, and biosensors play an important role in this regard. For example, enzyme sensors can accurately measure the amount of lactose in milk, helping people with lactose intolerance to make appropriate product choices. Antibody sensors are used to identify antibiotic residues in milk, thus ensuring milk quality and safety. In addition, biosensors can effectively detect bacterial contamination in milk, including Lactobacillus and E. coli [2].

Electrochemical sensors are also used in biomedical object detection. With the development of personalized medicine, people are preferring more personalized and targeted tests to cumbersome health screening processes. Traditional methods of blood collection, despite being standard, are being replaced by emerging technologies due to their discomfort and risks. Interstitial fluid (ISF) is considered as a highly promising biofluid alternative to blood due to its compositional similarity to blood and ease of continuous monitoring. However, there are still technical challenges in obtaining ISF. Microneedle (MN) technology demonstrates superiority as a non-invasive method and is attracting widespread attention. In particular, micro-sensors based on electrochemical sensing show great potential in the field of personalized health monitoring due to their high sensitivity, selectivity and portability, driving the development of a new generation of wearable health testing devices [10].

The application of glucose oxidase (GOx)-based enzyme biosensors has been the subject of numerous attempts. In the 1960s, Clark and Updike described the first enzyme electrodes and enzyme sensors. They have been utilized and researched extensively because of their great selectivity and high sensitivity. Enzyme glucose sensors can be broadly categorized into three categories. When glucose is present, the amperometric techniques used by the first class of glucose sensors convert O2 to H2O2 by immobilizing catalase. The oxygen dependence and high operating potentials of these sensors are just two of their many shortcomings. An additional category of glucose sensors has been created to address the issue of oxygen scarcity at low oxygen concentrations and elevated applied potentials. The foundation of these sensors is GOx immobilization on a redox medium. Electronic redox mediators include ferrous cyanides, conductive organic salts, quinones, and organic or organometallic redox molecules. However, the nature of GOx continues to influence the electrochemical characteristics of glucose sensors, and the process of making glucose sensors gets more intricate. Direct electron transfer between the electrode surface and the immobilized enzyme active site is the basis of the third class of sensors. Comparing the third generation of glucose sensors to the first and second types, their detection qualities are the worst. Their linear range is narrower than the other sensors. Overall, the nature of GOx continues to have an impact on enzyme sensors. It is commonly known that at pH values of 2 or above, GOx becomes unstable. Furthermore, temperatures which are higher than 40°C and humidity can significantly lower enzyme activity. Conversely, non-enzymatic sensors possess transition metal centers, are electrocatalytically active, and rely on the direct oxidation of glucose on the electrode surface [11].

Since the middle of the 20th century, there has been an increase in interest in the electrochemical study of proteins. Many electrochemists have concentrated their attention on metalloproteins, a small class of proteins with metal centers and reversible redox activity, since the early 1970s. Researchers are now very interested in the fact that most proteins lacking metal centers can display electrochemical activity based on the structure of their amino acids. Mercury electrodes were the source of the first electrochemical reactions of unlabelled proteins because polarography is a well-established technique. With the aid of Hg-S bond creation, disulfide bond degradation, and catalytic hydrogen release in cobalt-containing solutions, peptides and proteins containing cysteine/cystine (Cys) displayed distinct electrochemical signals at the mercury electrode. With mercury electrodes, hydrogen precipitation catalysis was also performed for proteins containing or not having sulfur-containing amino acids at high negative potentials and without the presence of transition metal ions. Pre-sodium catalysis generated distinct signals when coupled with chronopotentiometric dissolution tests, which made it possible to identify a number of significant proteins. The ability of protein residues containing tyrosine (Tyr) and tryptophan (Trp) to be electrooxidized at carbon electrodes was shown by Reynaud et al. and Brabec et al. in the early 1980s. Tyr residues are electrooxidized by transferring two electrons and two protons. This electrode process is comparable to the oxidation of basic para-substituted phenols. It is reported that good oxidation peaks for Tyr and Trp were achieved by using voltammetry in conjunction with intricate baseline corrections [12].

4. Conclusion

The integration of innovative materials, such as carbon nanotubes and metal nanoparticles, has greatly enhanced the sensitivity, selectivity, and overall performance of electrochemical biosensors. These improvements have made them indispensable in numerous applications. These applications range from agriculture and food safety to environmental monitoring and medical diagnostics.

Despite their many advantages, such as high sensitivity, rapid response times, and the ability to miniaturize for point-of-care testing, electrochemical biosensors also face challenges. These include complex fabrication processes, material compatibility issues, and the need for specialized equipment, which can increase costs. Nonetheless, ongoing research and technological advancements are continually addressing these limitations. As a result, electrochemical biosensors are becoming increasingly accessible and effective.

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