Application of Nanomaterials in Electrochemical Sensors

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Abstract. Electrochemical sensors are widely used in various fields, and traditional sensors face problems such as poor selectivity, low stability and limited sensitivity, and nanomaterials are expected to improve their performance. In this study, the application of nanomaterials in electrochemical sensors is discussed in depth using an enzyme-free electrochemical biosensor as an example. The results of this paper show that nanomaterials can significantly improve the sensitivity, selectivity and stability of sensors. The high specific surface area and good electronic conductivity endow it with a high sensitivity coefficient. The chemical modification effect can enhance its selectivity for target substances and the physical protection function makes it have better stability, and can accelerate the response speed to promote the transmission process of measured substances and intermediate products such as electrons. However, the existence of problems such as complex preparation methods, high cost and possible toxicity to the human body also restricts the development of nanocomposite membrane sensors. The significance of this study is to elucidate the advantages and disadvantages of nanomaterials in electrochemical sensors and provide guidance for future research. Future development should center on new material development and technology integration to reduce costs and overcome existing problems, promoting the progress of electrochemical sensors.

Keywords: Nanomaterials; Electrochemical sensor; Application; Development.

1. Introduction

Electrochemical sensors are devices that convert information such as chemical concentration into electrical signals for detection, and are widely used in many fields such as environmental monitoring, biomedical, food safety testing, and industrial production supervision [1]. At present, many water quality testing devices are equipped with electrochemical sensors, which can be used to measure various indicators such as heavy metal ions such as mercury and lead, pH value, and dissolved oxygen to judge the degree of water pollution and water quality. The medical blood glucose meter is an electrochemical sensor. When in use, it can quickly and accurately determine the glucose content in the blood, thereby facilitating diabetics to monitor their own blood samples. The food hygiene department sometimes uses such sensors to detect pesticide residues to ensure food safety and health and safeguard the legitimate rights and interests of consumers. This type of sensor will also be applied in industrial production, for example, chemical plants can use it to monitor the reaction environment, etc. Therefore, electrochemical sensors are of great importance to the development of human society, and improving their lifespan and performance is particularly important. Conventional electrochemical sensors face many problems in practical applications [1]. Firstly, their selectivity is poor. In complex sample environments, the coexistence of multiple chemical substances often reacts with substances other than the target substance and interferes with the detection results. For example, when detecting heavy metal ions in water, other metal ions can easily interfere with the signal [2]. The stability of general electrochemical sensors is also insufficient, and the electrode material is easy to age, and the performance will be degraded due to corrosion, oxidation or adsorption of impurities after long-term use [2]. At the same time, changes in environmental factors such as temperature, humidity, and air pressure will also affect their performance, resulting in fluctuations in results [3]. Moreover, their sensitivity is limited, and there is a high detection limit when detecting low concentrations of target substances [4]. The weak electrical signals generated by trace substances are difficult to amplify and prone to noise interference [4,5].

In terms of lifespan, some sensors that use electrolytes suffer from electrolyte loss and require regular replacement. Even under normal circumstances, performance will gradually decline after long-term use, requiring regular calibration and maintenance, which increases usage costs and operational complexity [6]. However, numerous studies have shown that applying nanomaterials to electrochemical sensors can effectively improve their performance and address the aforementioned drawbacks. Research has shown that the application of nanomaterials greatly enhances electron transfer, improves the sensitivity of electrochemical sensors, and enhances the catalytic efficiency of fuel cells [4-6]. This study takes enzyme free electrochemical biosensors as an example and summarizes the specific application methods, advantages and disadvantages of nanomaterials in sensors by comparing them with traditional enzyme based electrochemical biosensors. On this basis, consider the future development trend of nanomaterials applied to electrochemical sensors.

2. Nanomaterials in Electrochemical Sensors

The application of nanomaterials in enzyme free electrochemical biosensors has made significant improvements compared to previous enzyme based electrochemical biosensors. Compared with traditional enzyme-based biosensors, enzyme free electrochemical biosensors have some unique advantages and high stability due to the use of nanomaterials. Due to the absence of enzyme variation and deactivation issues in enzyme free electrochemical biosensors, they exhibit better stability under different environmental conditions (such as temperature, pH, etc.) and can maintain long-term detection performance [2]. Meanwhile, using nanomaterials instead of enzymes also reduces the production cost of sensors. Not only does it reduce the preparation cost of the sensor by not requiring expensive enzymes, but it also extends its lifespan. This gives it certain advantages in the large-scale application and commercial production of enzyme free electrochemical biosensors. In addition, the application of nanomaterials accelerates the electron transfer process, enabling sensors to quickly respond to targets and typically complete detection in a short period of time, improving detection efficiency. The unique advantage of enzyme free electrochemical biosensors is due to the use of nanomaterials. This case proves that the application of nanomaterials in electrochemical sensors can improve sensor sensitivity, selectivity, stability, and reaction speed. Enzyme-based sensors use enzymes as biometric identification elements to convert biochemical reactions into detectable electrical and optical signals, etc., so as to realize sensors for qualitative or quantitative analysis of specific substances. However, the enzyme-free electrochemical biosensor is a sensor based on electrochemical principles that can detect and analyze biomolecules or other related substances without the use of enzymes as biometric identification elements. It replaces easily denatured and inactive enzymes with other materials and solves the problems of low sensor life and high cost caused by the use of enzymes. The special material that can replace the enzyme and achieve the function of the enzyme catalyzing a specific biochemical reaction is the nanomaterial-modified layer [7-10].

This nanomaterial-modified layer is used to modify the electrode of the sensor. The fabricator will modify the nanomaterial to the electrode surface by physical adsorption, chemical covalent bonding, electrochemical deposition and other methods to form a nanomaterial-modified layer [3,5,7]. The modified electrode is placed into a sample solution containing the target analyte. When the target analyte approaches the nanomaterial modified layer on the electrode surface, due to its excellent electron transfer performance, electrocatalytic activity, or specific recognition ability, the nanomaterial modified layer will interact with the target analyte. For example, nanomaterials with electrocatalytic activity will catalyze the oxidation-reduction reaction of the target, causing changes in the electrical properties of the electrode surface. Electrochemical detection instruments connected to the electrodes will detect these changes in electrical properties and convert them into readable electrical signals. By analyzing and processing these electrical signals, researchers can detect and analyze objects.

The nanomaterials used in the nanomaterial modification layer on the electrode of the enzyme-free electrochemical biosensor are not fixed, which is one of its advantages [4,6]. By replacing different nanomaterials, specific recognition of different substances can be achieved. For example, in the enzyme-free electrochemical immunosensor for detecting tumor markers, the nanomaterial modified with tumor marker-specific antibodies on the surface is used as the modification layer, and these antibodies can specifically capture tumor markers. When there is a target tumor marker in the sample, it will bind to the antibody on the surface of the nanomaterial, causing the electrical properties of the electrode surface to change, to achieve highly sensitive and highly selective detection of tumor markers. It is this advantage that allows enzyme-free electrochemical biosensors to be applied to various fields such as biomedical diagnostics, environmental testing, food safety testing, and even industrial production process monitoring.

The unique advantages of enzyme-free electrochemical biosensors are due to the use of nanomaterials. This case proves that the application of nanomaterials in electrochemical sensors can enhance sensor sensitivity, improve sensor selectivity, enhance stability and accelerate reaction speed.

The most typical physical property of nanomaterials is that they have a very high specific surface area. The specific surface area refers to the surface area of a unit mass or unit volume of a substance, while the specific surface area of nanomaterials is usually very large, generally reaching tens of square meters per gram or even hundreds of square meters per gram. A large specific surface area is conducive to improving the sensitivity of the sensor. Taking nanopores gold as an example, its porous structure makes it significantly more specific surface area than ordinary gold materials. Each unit mass of nanopores gold can provide a large number of atoms or molecules exposed to the surface, providing a rich activity checkpoint for electrochemical reactions, so that more target analytes can react simultaneously, thereby enhancing electrochemical signals [7].

Another property that helps to improve the sensitivity of sensors is the excellent electron conduction properties of nanomaterials, such as carbon nanotubes. Carbon nanotubes with typical one-dimensional nanoscale features are formed by carbon atoms in a seamless hollow tubular structure. This structure allows electrons to be transported through the carbon nanotubes with less scattering while maintaining a good direction and energy of motion, as in the case of a smooth pipe with fast flow, reducing the chances of collisions of electrons with other impurities or lattice defects, which facilitates efficient electron conduction [5]. This nanomaterial has a unique one-dimensional structure and excellent electronic conductivity and high electron mobility, which can rapidly transfer electrons and reduce the electron transfer resistance, making the electron transfer in electrochemical reactions more efficient, thus enhancing the detection signal and improving the sensitivity.

The application of nanomaterials to electrochemical sensors can also help improve the selectivity of the sensor. Because of the modifiable sexuality of nanomaterials, scientists can chemically modify specific recognition molecules on the surface of nanomaterials [8]. By modifying antibodies on the surface of nano-gold, the antibodies can specifically bind to specific antigens to form stable antigen-antibody complexes making the sensors responsive only to the target antigen and unresponsive or weakly responsive to other substances. In addition, some nanomaterials have pores and mesoporous silica has a regular pore structure and a specific pore size. Depending on the molecular size and shape of the target analyte, mesoporous silica with an appropriate pore size can be selected to allow only molecules of a specific size and shape to enter the pore and interact with the active checkpoints inside, thus achieving selective detection [5]. Of course, selective screening can also be achieved by taking advantage of the fact that different nanomaterials have different chemical properties.

Enhanced stability is also one of the reasons why scientists choose to apply nanomaterials to electrochemical sensors. From two different perspectives of physics and chemistry, nanomaterials can prolong the service life of sensors. Some nanomaterials such as titanium dioxide nanotubes can form a dense nanostructure coating on the electrode surface, which acts as a physical protective barrier to prevent the electrode material from being corroded or oxidized, and at the same time, it can prevent impurities or harmful substances in the solution from contacting the active components on the electrode surface, prolonging the service life of the electrode [3,8]. Some nanomaterials such as graphene have good chemical stability and oxidation resistance and are not easy to undergo chemical reactions or structural changes in the electrochemical environment. It can be used as a modified material to improve the stability of the electrode and can maintain the stable performance of the electrode even in complex acid-base environments or high potential conditions.

Nanomaterials can also help the rapid transport of substances. For example, materials with nanopores structures, and their porous networks provide a channel for the rapid transport of analytes, enabling the analyte to quickly reach the electrode surface or active checking point. The unique electronic structure and surface properties of nanomaterials can accelerate the electron transfer process. For example, nano-palladium has good catalytic activity and electron conduction properties, which can quickly promote the redox reaction of the reactants in electrochemical reactions, accelerate the electron transfer speed, and thus shorten the response time of the sensor [7,8]. So, nanomaterials can speed up the response speed of the sensor and shorten the research time to a certain extent.

Although there are many advantages to applying nanomaterials to electrochemical sensors, there are still many problems to be solved. One of the biggest problems is the preparation and cost of nanomaterials. The preparation of nanomaterials often requires precise experimental conditions and sophisticated techniques, and the preparation of quantum dots with uniform size and regular morphology usually requires the use of a high-temperature thermal injection method, sol-gel method, etc. These methods require extremely high reaction temperatures, time and purity of raw materials, and slight deviations may lead to poor product quality. These professional and complex operations often require large equipment. For example, the preparation of carbon nanotubes by chemical vapor deposition requires the use of gases such as methane and ethylene as carbon sources, as well as transition metals as catalysts, and equipment maintenance and operation costs are also high [2-4].

Nanomaterials are also susceptible to environmental influences. For example, nano-metal oxides may undergo surface oxidation or hydrolysis in a humid environment, changing their surface properties and affecting sensor performance. Taking zinc oxide nanowires as an example, in a high humidity environment, their surface will absorb water molecules, form hydroxyl groups, and interfere with electron transmission, resulting in a decrease in the response stability of the sensor [6,7]. In practical use, nanomaterials may undergo structural and performance changes due to interactions with the tested substance or long-term electrochemical cycling.

Practical application challenges also include the potential toxicity and environmental damage of some nanomaterials. They may have potential toxicity to organisms. For instance, nanometer silver particles may release silver ions in living organisms, which combine with groups such as thiol groups in biomolecules, interfere with the normal metabolism and physiological functions of cells, and cause harm to human health. Some sensors for medical testing also need to consider whether the nanomaterials used have the ability to elicit an immune response in an organism. For example, when carbon nanotubes enter the human body, they may be recognized by the immune system as foreign objects, triggering an inflammatory response or immune rejection, which may interfere with the detection results in biomedical testing applications and may also have adverse effects on the human body.

In today's society, the term nanomaterials is more like a gimmick. It is undeniable that it can indeed enhance the function of sensors to a certain extent and extend their lifespan, but it still has many unsolved problems. Take the enzyme-free electrochemical biosensor mentioned at the beginning as an example. Compared with traditional enzyme-based biosensors, because of the use of nanomaterials, enzyme-free electrochemical biosensors have high stability and short response time. This is because nanomaterials make the sensor unnecessary to consider the denaturation and inactivation of enzymes and the rate of enzyme-catalyzed reactions. However, Enzymes are highly specific to substrates, and the selectivity is usually very good. As long as the activity of the enzyme is not affected, it can generally accurately detect the target. Enzyme-based biosensors also have extremely high sensitivity, and the efficient catalysis of enzymes can produce significant electrical signal changes in trace substrates. These advantages, at least until now, are unmatched by nanomaterials.

Therefore, the utilization of nanomaterials in a sensor does not inherently ensure superior performance compared to alternative sensor technologies. While noting the advancements that nanomaterials bring to electrochemical sensors, it is also necessary to be aware of the drawbacks they bring. Therefore, the problem facing material scientists is how to expand the advantages of nanomaterials in various ways while making up for its shortcomings.

The future development prospects of nanomaterials in electrochemical sensors should be based on the development and application of new materials and the integration of multiple technologies and disciplines. Improvement of sensors with new nanomaterials with special properties, and preparation of enzyme-free electrochemical biosensors with excellent performance by compositing with other nanomaterials. It is also possible to try to reduce production costs by combining with emerging artificial intelligence. Overall, nanomaterials will need to cooperate with other fields and technologies in the future to reduce costs and achieve promotion.

3. Conclusion

Taking enzyme-free electrochemical biosensors as an example, this study explores the various application modes of nanomaterials in electrochemical sensors and their advantages and disadvantages. The results show that nanomaterials can enhance the performance of electrochemical sensors in multiple aspects. It improves sensitivity through high specific surface area and excellent electron conduction characteristics, enhances selectivity through chemical modification and unique physical structure, enhances stability through physical protection and good chemical stability, and accelerates response speed by promoting substance and electron transport. However, the application of nanomaterials in electrochemical sensors has limitations. Its preparation method is complex, requiring sophisticated instruments and cutting-edge technology. The high cost of nanomaterials fabrication also makes it difficult to scale up production. In the actual use of sensors, the potential toxicity of nanomaterials also needs to be considered. The significance of this study is to clarify the advantages and disadvantages of nanomaterials in electrochemical sensors and provide guidance for future research directions. The future development of nanomaterials in electrochemical sensors should focus on the development of new materials, the integration of artificial intelligence and other technologies to reduce costs, overcome existing problems, and further promote the development and application of electrochemical sensors.

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