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Study on the Role of Biosensors in Food Safety Environment Based on Pesticide Residues

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Abstract: Pesticide residues in agriculture pose significant risks to food safety and public health. Traditional detection methods, such as gas chromatography (GC) and high-performance liquid chromatography (HPLC), provide high accuracy but are costly, complex, and not suitable for real-time monitoring. Biosensor technology, with its high sensitivity, rapid response, low cost, and ease of use, presents a promising alternative. By integrating biological recognition elements with signal transduction systems, biosensors enable rapid, on-site detection of pesticide residues. In the field of pesticide residue detection technology, the use of biosensors has demonstrated its unique value. The enzyme sensor, antibody and molecular imprinted biosensors demonstrate their unique selectivity and stability. This kind of detection technology has a great advantage in reducing the complexity of sample preparation, and its low detection limit has made it widely permeated the application scenarios of food safety monitoring, agricultural production and environmental detection.

Keywords: Pesticide Residues, Biosensors, Food Safety

1. Introduction

Global agriculture has changed dramatically over the past 50 years, with the use of pesticides skyrocketing. The need for large-scale crop production has driven the widespread use of pesticides, and this new technology has had a significant effect in pest control and increasing food production. A large amount of pesticides and the wrong way of use seriously threaten the ecological environment and human health. Pesticides that permeate the soil have a negative impact on the ecosystem in multiple ways, and even spread through the food chain and eventually into the human body. Data recorded by the Food and Agriculture Organization of the United Nations (FAO) reflect a dangerous situation, with pesticide consumption nearly double what it is now 40 years ago. Countries all over the world have established pesticide regulatory systems and standards, but the problem of pesticide residues continues to deteriorate in the environment of large-scale agriculture and global integration. The Chinese government has strengthened the supervision of pesticide residues, but the occurrence of agricultural products exceeding the standard is frequent, and pesticide abuse in many rural areas and small and medium-sized farms is difficult to monitor [1].

Pesticide residue detection technologies such as gas chromatography-mass spectrometry (GC-MS) and high performance liquid chromatography (HPLC) have shown corresponding detection capabilities in the laboratory environment, but these technologies are difficult to overcome the limitation of detection depth, and there are problems of slow detection speed and high cost, and various detection equipment is very limited in the application range of grass-roots. The restriction of

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traditional schemes in pesticide residue detection is particularly prominent, and the complicated sample pretreatment procedures lead to low detection efficiency, which is more prominent in practice detection. In this case, the real need for real-time monitoring and rapid identification of pesticide residues has not been met. The development of efficient and simple pesticide residue detection technology faces many technical bottlenecks, sensitivity and cost control have been the major problems restricting its development. The field of pesticide residue detection technology is in urgent need of technical breakthrough. This research plan builds a new detection method based on biosensor technology, and strives to promote the wide application of rapid detection technology in pesticide residue detection.

The application of biosensors in the field of pesticide residue detection has great potential, especially in the improvement of food safety monitoring efficiency. Efficient and real-time pesticide residue monitoring technology is being improved and optimized in the field and food production line, which can greatly improve the efficiency of food safety supervision and reduce the potential harm caused by pesticide residues. Biosensors have many positive effects on the health of consumers, such as greatly reducing the health risks caused by pesticide residues. Looking back on the previous development of biosensor technology, this research has promoted the overall detection of pesticide residues, and agricultural policies and industrial chains have also changed, the quality of agricultural products and the health of consumers are gradually guaranteed, and agricultural development is gradually becoming sustainable. The research shows that this innovative biosensor has the ability to improve the sensitivity of pesticide residue detection, work efficiency and cost are significantly improved, and the monitoring of agricultural food safety becomes more accurate and rapid. This study consists of six content blocks, including research background and purpose, existing technology and research gap analysis, research design and experimental route, experimental results display and data analysis, research summary and follow-up research direction, etc [2].

2. Literature Review

2.1. Overview of the existing research

Pesticide residue detection technology plays a vital role in ensuring food safety and environmental protection. Traditional pesticide residue detection methods, such as high performance liquid chromatography(HPLC)and gas chromatography(GC),have high sensitivity and accuracy, but their expensive equipment, complex operation and the need for professional personnel limit their application in rapid on-site detection. In recent years, enzyme-based optical biosensors have become a hot topic of research due to their advantages such as rapid response, high sensitivity and low cost. Peng Zoujun et al. [3]reviewed the research progress of organophosphorus pesticide biosensors based on acetylcholinesterase (AChE)inhibition, pointing out that these sensors have good prospects in detecting organophosphorus pesticides, but still face challenges such as stability and reusability [4].Yang Song et al. [5]used a new mesoporous material-QuEChERS-ultra-high performance liquid chromatography-tandem mass spectrometry to detect 10 pesticide residues in tea, and achieved good detection results, but this method still requires complex sample pretreatment, which limits its application in rapid on-site detection [6].These studies provide valuable references for this article, but also reveal the shortcomings of existing technologies, such as poor stability, slow detection speed and high cost, which urgently need to be solved through innovative sensor technology

2.2. Identification of gaps in the literature

The activity of enzymes in existing enzyme-based sensors is easily affected in complex environments, making it difficult to maintain long-term stable performance. Traditional detection methods require a long time for sample preparation and experimental analysis, which is difficult to meet the needs of

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rapid on-site detection. Existing detection equipment and reagents are expensive, limiting their popularization and application in developing countries. Existing technologies usually require complex laboratory equipment and professional personnel to operate, and lack simple equipment suitable for a wide range of applications. These gaps provide a clear direction for the research of this article, which aims to solve the above problems through innovative MOF-based optical biosensor technology [7].

2.3. Relevance to the current study

The current research results provide a valuable theoretical basis and technical reference for this article, but there are also some unresolved issues. For example, although traditional enzyme-based sensors have been proven to be able to achieve high-sensitivity detection of pesticide residues in laboratory environments, problems in practical applications are still prominent. This study aims to overcome the shortcomings of existing technologies in terms of stability, sensitivity, detection depth, and rapid on-site detection by combining the high stability of MOFs materials with the specific recognition ability of enzymes. The difference from existing research is that this article will focus on how to improve the stability and sensitivity of sensors in practical applications, especially the detection capabilities under complex matrices, and how to achieve portable and on-site rapid detection to fill the gaps in existing technologies [8].

2.4. Theoretical framework

The theoretical framework of this paper is based on the combination of optical biosensing technology and metal organic framework (MOFs)materials. MOFs materials provide an ideal carrier for enzyme immobilization due to their high specific surface area, adjustable pore structure and excellent chemical stability. By immobilizing enzymes in MOFs materials, the stability and catalytic performance of enzymes can be effectively improved, and their application effect in pesticide residue detection can be enhanced. At the same time, the combination of MOFs materials and optical probes can further improve the sensitivity and detection accuracy of sensors. This theoretical framework provides a scientific basis for the design and experimental verification of this study, and is expected to provide a new and efficient solution for pesticide residue detection [9].

3. Methodology

3.1. Research design

Biosensors can make up for the shortcomings of pesticide residue detection technologies such as gas chromatograph-mass spectrometry (GC-MS) and high performance liquid chromatography (HPLC), which are reflected in the high cost, long time and complex instruments of traditional detection methods, and it is not easy to carry out large-scale detection work in agricultural environment. The addition of new substances such as metal-organic frameworks (MOFs) and nanomaterials has enhanced the detection effectiveness of biosensors, and relevant studies have covered the various indicators of these sensors, including specificity, sensitivity and speed requirements, as well as the analysis of ease of operation. A systematic summary of the identification of pesticide residues by biosensors can be made to understand the configuration parameters and data indicators of relevant experiments. Such research is very necessary to judge the application prospects of such sensors, and the combination of theory and practice is easier to promote the technological breakthrough of pesticide residue inspection, which is of great significance to the protection of food safety and natural environment.

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3.2. Materials and Equipment

Biosensors in pesticide residue detection technology involve the use of various technologies and materials. Enzyme-based biosensors detect pesticide residues through the interaction between enzymes and substrates, antibody biosensors rely on antigen and antibody binding to achieve pesticide molecular detection, and molecular imprinted sensors use preset molecular cavities to identify pesticide substances. These biosensors have been widely used in agricultural food safety monitoring and environmental protection.

The biosensor preparation process requires specific material support. Metal-organic frameworks (MOFs) have the advantages of strong stability, good adjustability and large surface area, which have a significant impact on the sensitivity and selectivity of sensors. Biosensor manufacturing employs nanoparticles, carbon nanotubes, graphene and other nanomaterials, which exhibit excellent electrical properties, optical characteristics and catalytic effects. The integration of these materials with biosensor platforms has enabled highly sensitive detection, accurate data analysis and rapid response to pesticide residues, and these materials have played a crucial role in the development of equipment. Research and analysis in the field of biosensor technology demonstrate that the relevant pesticide residue detection materials and instruments show a diversified development trend.

3.3. Data collection methods

The data collection for biosensor research in pesticide residue detection includes a comprehensive collection and sorting of various research literature, review articles and investigative reports. The research quality is controlled according to specific evaluation criteria. The data detected by biosensors is mainly classified into the technical implementation system of various sensors such as enzyme sensors, antibody sensors and molecular imprinting sensors. The evaluation index system of different sensors in the detection of agricultural residues focuses on the performance of sensitivity, specificity, detection limit and response time standards. Limited by the analysis methods of pesticide types and agricultural environment, the detection ability of pesticide residues by biosensors has certain practical differences. The biosensor technology in the field of food safety monitoring and environmental protection reflects the real inspection capability. The systematic processing of data reflects the technical advantages of biosensors in dealing with pesticide residue detection, and analyses and points out the improvement direction of biosensor research and development technology. This review explores the technical support of biosensor technology for pesticide residue detection, and explores its ability to cope with agricultural and food safety issues.

3.4. Experimental or Simulation Setup

As a literature review study, this project focused on synthesizing experimental setups related to biosensor pesticide residue detection from published research results. In the research process, many kinds of biosensor manufacturing processes are deeply discussed, including enzyme carrier sensor, antibody sensor and sensor prepared by molecular imprinting etc., and their materials and technologies are systematically reviewed. The part of detection parameters covers all kinds of sample preparation. The concentration range of pesticide residues detected, the test substrate soil or aqueous solution, and the test ambient temperature and pH value are all compared to determine the degree to which these key variables have an impact on the test accuracy results. The biosensor analysis technology part involves the response measurement scheme, data calibration index, and relies on the photometric detection system, electrochemical analysis device or colorimetric analysis and judgment platform. As a whole, the full text examines the experimental procedures and implementation methods, and explains in detail which scheme is the most suitable for biosensor pesticide residue detection procedures. The detector can repeat the work performance and obtain the reliability of the

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data to show the reader a relatively systematic and complete result. The record of actual problems encountered in the laboratory research process has significant value for the construction of biosensor detection system in agricultural food safety monitoring.

3.5. Data Analysis Techniques

In view of the performance of pesticide residue detection by biosensors in the field of food safety monitoring, the data processing involved requires the comparison of a large number of research results in different dimensions. Sensitivity reflects the sensor's detection accuracy for low concentrations of pesticides, and the biosensor also has the ability to clearly identify the target pesticide rather than other substances. The ability to maintain performance during repeated use demonstrates the stability of the sensor, and the characteristics of rapid response determine whether the biosensor can meet the inspection requirements of agricultural environment. The performance of biosensors for detecting pesticide residues is different. Data summary analysis, based on the average value and statistical calculations, examines the reliability of various biosensors for detecting pesticide residues. Data analysis shows that certain technologies show promise for large-scale use, and the future development of biosensor technology for pesticide residue detection will focus on optimizing and improving overall sensor performance.

4. Results

4.1. Presentation of Key Findings

Biosensors are used in the field of pesticide residue detection and contribute to food safety inspection and environmental pollution analysis. Biosensors developed based on enzyme, antibody and molecular imprinting technology show unique detection effects, and the detection effects of various types of biosensors on pesticide residues under agricultural production conditions have been verified by special analysis.

4.1.1. Enzyme-Based Biosensors

High specificity and high sensitivity give enzyme biosensors a unique advantage in the field of pesticide residue detection, and many scientific research teams have invested in related research. The reaction signals generated by the enzyme molecules in response to target pesticides constitute the signal detection basis of this kind of sensor. This sensing technology is excellent for the detection of organophosphate and carbamate pesticides, and the detection limit is nanomolar level. The working performance of the enzyme biosensor is controlled by the change of pH value and temperature fluctuation in the environment, and the detection process is easily affected by interfering substances. The high fat or protein content of food samples poses a challenge to sensor detection, and the sensitivity is difficult to meet the needs of real-time food safety monitoring, even if such detection methods are fast and low-cost.

4.1.2. Antibody-Based Biosensors

There is a unique selective binding characteristic between pesticide molecules and antibodies, which constitutes the basis for antibody biosensors to achieve targeted detection. Antibody biosensors are very powerful when detecting pesticide residues. The test results show that the sensor has a very low detection limit and can detect pesticide molecules in concentrations as low as one part per billion. A variety of detection platforms such as lateral flow analysis support the operation of such sensors, and pesticide detection work can be carried out on-site to complete the instrument. Antibodies are costly

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and prone to degradation, and once they encounter harsh conditions, the sensor life will be affected, adding difficulty to the long-term monitoring of pesticides.

4.1.3. Molecular Imprinting Biosensors

The technology of molecularly imprinted biosensors is mainly based on the design and construction of specific pesticide molecular cavities, offering excellent selectivity and stability. These sensors are highly sensitive for pesticide detection and can detect complex matrix samples such as soil and plant tissue. Molecularly imprinted biosensors demonstrate robust performance and long-term stability compared to enzyme and antibody sensors. The study data shows that these molecular imprinting sensors are extremely sensitive to pesticide detection, with detection limits reaching sub-picogram per milliliter levels. The preparation of molecularly imprinted biosensors requires a long period of time, and the high cost of specialized materials still limits their practical applications. However, advancements in material science and sensor miniaturization are expected to address these challenges and enhance the scalability of molecular imprinting-based sensors.

These findings highlight the potential of biosensors to overcome the limitations of traditional pesticide residue detection methods, providing faster, more cost-effective, and real-time monitoring solutions in food safety and environmental protection.

4.2. Interpretation of Results

The application of biosensors to the detection of pesticide residues in food safety monitoring shows that this kind of technology has various differences in monitoring effect and performance in agricultural practical application, and its advantages and disadvantages should be weighed from the perspective of technical applicability.

4.2.1. Strengths of Biosensors in Pesticide Residue Detection

Biosensors based on enzymes and antibodies demonstrate high sensitivity and specificity, with detection limits of pesticide residues as low as one part per billion (ppb) and even extending to one part per trillion (ppt). Biosensors are suitable for agricultural field monitoring applications, where gas chromatography-mass spectrometry (GC-MS) and high performance liquid chromatography (HPLC) sample processing is time-consuming and expensive. Compared with traditional detection methods, biosensors have obvious advantages, including low manufacturing cost, small size and convenient use, and are widely used in agricultural environments. The on-site requirements of pesticide residue monitoring align well with the performance of biosensors, providing technical support for enhancing large-scale food safety monitoring.

4.2.2. Limitations and Challenges

Biosensor technology needs to overcome many bottlenecks before it can be widely used in real industry. Harsh environmental conditions will cause the stability of biosensors to decay and affect their long-term performance. The sensitivity of biosensors for soil analysis or detection of high-fat, high-protein samples is abnormally reduced. The biosensor has obvious effect on the inspection of specific pesticide indexes in agricultural products, but the identification efficiency of complex pesticide mixtures does not meet the requirements of industrial application, and the application in agricultural environment is limited.

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4.3. Future Directions and Recommendations

For biosensors to be fully integrated into the current food safety systems, further research is needed to enhance their scalability and robustness. Future studies should focus on improving sensor stability, reducing production costs, and expanding detection capabilities to cover a broader spectrum of pesticide residues. Additionally, there is a need for sensors that can operate effectively in diverse environmental conditions and be suitable for both large-scale agriculture and small farming operations. Integrating biosensors with automated systems and mobile technologies could improve the efficiency of pesticide monitoring and ensure better compliance with food safety regulations.

5. Conclusion

For biosensors to be fully integrated into the current food safety systems, further research is needed to enhance their scalability and robustness. Future studies should focus on improving sensor stability, reducing production costs, and expanding detection capabilities to cover a broader spectrum of pesticide residues. Additionally, there is a need for sensors that can operate effectively in diverse environmental conditions and be suitable for both large-scale agriculture and small farming operations. Integrating biosensors with automated systems and mobile technologies could improve the efficiency of pesticide monitoring and ensure better compliance with food safety regulations.

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