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Application of biosensors in the detection of plant biomolecules

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Abstract. Traditional plant research mainly relies on the observation of external performance, and it is difficult to accurately understand the internal physiological and environmental responses of plants. However, the introduction of biosensors provides different avenues to address these issues. The application of biosensors in plants is an emerging field, combining sensor technology with biology, bringing new opportunities for plant research and agricultural production. The core content of plant biosensing technology is to embed biosensors into plants to monitor and transmit information such as biomolecules, metabolites, or environmental factors inside plants. This paper introduces the design of biosensors, the research progress of biosensors, and the development trend of biosensors. Biosensors can quickly and accurately respond to changes in plants and transmit data to researchers or farmers through wireless communication. Real-time monitoring of the nutritional status and health status of plants can help to gain insight into the adaptability and stress resistance of plants to the environment and provide support for the cultivation of original varieties with greater adaptability. Farmers can accurately fertilize, water, and prevent pests and diseases based on sensor data, improve crop yield and quality, and reduce waste of resources. In general, plant biosensor research is of great significance in the fields of environmental monitoring, biological research, agricultural application, environmental protection, and sensing technology, which can help solve practical problems and promote the development and application of science and technology.

Keywords: biosensor, salt stress, phosphoproteomic analysis, pesticide detection, nanomaterials.

1. Introduction

In recent years, the field of biosensors has witnessed tremendous advancements and has emerged as a fascinating area of research at the intersection of biology, engineering, and technology. Biosensors are innovative devices that utilize biological elements to detect and quantify specific substances, ranging from simple molecules to complex biomolecules, with high sensitivity and selectivity. These bio-inspired sensors have shown great promise in various applications, including medical diagnostics, environmental monitoring, agriculture, and industrial processes.

The development of biosensors can be traced back to the early 1960s when the concept of coupling biological elements with transducers was first introduced. Since then, significant progress has been made, driven by advancements in biotechnology, nanotechnology, and microfabrication techniques. This progress has paved the way for the design of diverse and sophisticated biosensors, allowing them to cater to a wide range of analytical needs.

Biosensors can be classified based on the type of biological element used for detection. There are several major categories. 1) Enzyme-based biosensors: These biosensors utilize enzymes as the recognition element. Enzymes are highly specific catalysts that can interact with specific analytes, leading to a measurable signal. 2) Antibody-based biosensors: Antibodies, or immunoglobulins, are used as the recognition element in these biosensors. They can bind specifically to antigens, resulting in a detectable signal. 3) Nucleic acid-based biosensors: These biosensors use nucleic acids such as DNA or RNA as the recognition element. They are particularly useful in detecting genetic material and nucleic acid sequences [1]. 4) Whole-cell biosensors: In these biosensors, intact living cells are employed as the recognition element. The cells' response to target substances provides a signal that can be measured [2]. Each type of biosensor possesses unique advantages and limitations, making them suitable for specific applications. For instance, enzyme-based biosensors excel in detecting analytes with high specificity, while whole-cell biosensors offer the advantage of real-time monitoring and adaptability.The applications of biosensors are vast and continue to expand as technology evolves. In healthcare diagnostics, environmental monitoring, food safety, and bioprocessing, biosensors play a pivotal role in providing rapid, accurate, and cost-effective analytical solutions. The following sections will introduce the design, instructions, and applications of biosensors in plants.

2. Design and instructions of biosensor

2.1. Design and preparation

Based on the biological factors to be detected, researchers select appropriate recognition elements, which can be biological receptors such as antibodies, aptamers, and enzymes [1]. It is then integrated with sensors to convert biochemical signals into measurable light or electrical signals. Once a biosensor is designed, it needs to be tested and calibrated, at which point it can be tested with a known concentration of the target biomolecule. This ensures the sensitivity and accuracy of the biosensor.

2.2. Sampling

Taking the test of plant salt stress as an example, to study the response of plants to salt stress, researchers can apply different concentrations of salt solution to plants and collect plant samples at specific time points during the stress treatment. Sampling frequency can be adjusted according to the stress response of the plant to the stress, or the stability of the biomolecule being tested.

2.3. Analysis

The collected plant samples are analyzed using biosensors. The recognition elements of biosensors selectively bind target biomolecules, thereby generating detectable signals. The signals obtained from the biosensors are recorded and quantified, and the data are statistically analyzed. To ensure the reliability of the data, the experiment needs to ensure the repeatability, which is convenient for repeated experiments of biosensors.

2.4. Improvements

After completing the experiment, researchers can compare the results generated by the biosensor with those obtained experimentally using traditional methods, such as spectrophotometry. Based on the comparison results, the researchers were able to optimize the parameters of the biosensor and improve the accuracy and sensitivity of the biosensor.

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3. Research project of biosensor

3.1. Biosensors for salt stress detection

Salt stress refers to the stress that plants experience when they grow in a high-salt environment. Salt stress will lead to physiological water shortage in plants, which will lead to the formation of active oxygen in plants, interfere with the normal metabolism of plants, destroy the membrane structure of plant cells, and make the osmotic regulation system of plants out of balance, thereby affecting the growth and development of plants [3]. Excessive Na+ entry into plant cells under salt stress will lead to loss of cell membrane system composition, channel activity, and channel regulation mechanism, resulting in decreased plant growth rate, increased energy consumption, decreased photosynthetic efficiency, and accelerated aging.

To detect salt stress in plants, the biosensor can use a fluorescent probe on the recognition element, such as an aza-IR780-based cyanine probe Cy-CO2Bz with near-infrared (NIR) emissions [4], the fluorescent biosensor is based on fluorescence resonance energy transfer (FRET). The change in the concentration will affect the fluorescence intensity on the probe, thus reflecting the intensity of the salt stress suffered by the plant.

In addition to fluorescent probes, researchers have also designed biosensors based on organic electrochemical transistors (OECTs). Biosensors designed based on OECT have been applied in various places before, such as redox reactions, ion-sensing, enzymatic sensing, etc. [5]. For salt stress, this biosensor can be improved based on the principle of electrochemical impedance spectroscopy (EIS), aiming at early detection of salt stress in plants.

Biosensors have several advantages over traditional methods for detecting salt stress in plants. Its main advantage is that it is non-invasive, and it can continuously detect the state of plants in real time without damaging plants or samples. Compared with traditional methods which usually involve destroying samples, biosensors have the advantages of being non-destructive, which will not interrupt plant growth or prevent researchers from fully understanding plant salt stress. At the same time, this biosensor is also portable, and it can be used in the field. Its portability and ease of use make it a tool for on-site application in the field. Farmers can timely assess the salt stress status of crops so that they can take timely intervention measures and improve management methods to minimize losses.

However, this type of biosensor also has certain defects, including the high cost of recognition components, short service life, and the specificity of the components, which prevents them from being widely used. At the same time, FRET is distance- and direction-dependent, and its effectiveness rapidly declines in nanoscale spaces smaller than the light-scattering limit [6].

3.2. Plant phosphoproteomic analysis

Plant phosphoproteomic is a method to study the plant proteome, which mainly focuses on phosphorylation modifications in plants. Phosphorylation is a common protein modification that regulates protein activity, stability, and interaction. Phosphoproteomic can study biological issues such as signal transduction, metabolic pathways and growth, and development in plants by isolating, enriching, and analyzing phosphorylated proteins. Plant phosphoproteomic plays a crucial role in understanding the complex signaling pathways and regulatory mechanisms that control plant growth, development, and responses to various environmental stimuli. Traditionally, the analysis of phosphoproteomic relies on methods such as nuclear magnetic resonance and electron microscopy. These methods are often time-consuming and labor-intensive. At the same time, the obtained data results are poor and may be harmful to samples. These obstacles often prevent researchers from in-depth research. With the advent of biosensor technology, researchers have been able to overcome these limitations. In the detection of plant phosphorylated proteins, biosensors are based on various principles and have developed many types, such as fluorescent biosensors, nano-biosensors, and so on.

3.3. *In-situ pesticide analysis of plants*

Pesticides play a vital role in modern agriculture, protecting crops from pests and increasing yields. However, excessive, or inappropriate use of pesticides can lead to environmental pollution and pose risks to human health. Precise, continuous monitoring of pesticide levels in plants is therefore required to ensure sustainable and safe agricultural practices. Nano-biosensors can achieve this very well. The miniaturization of biosensors realized by nanotechnology means the feasibility of wearable biosensors, which can be easily attached to plants, and the non-invasiveness of biosensors also ensures that they will not cause damage to plant growth (Figure 1) [7]. At the same time, being able to wear it for a long time also means that the biosensor can realize continuous monitoring of plants, and farmers can observe the pesticide levels of plants in real time.

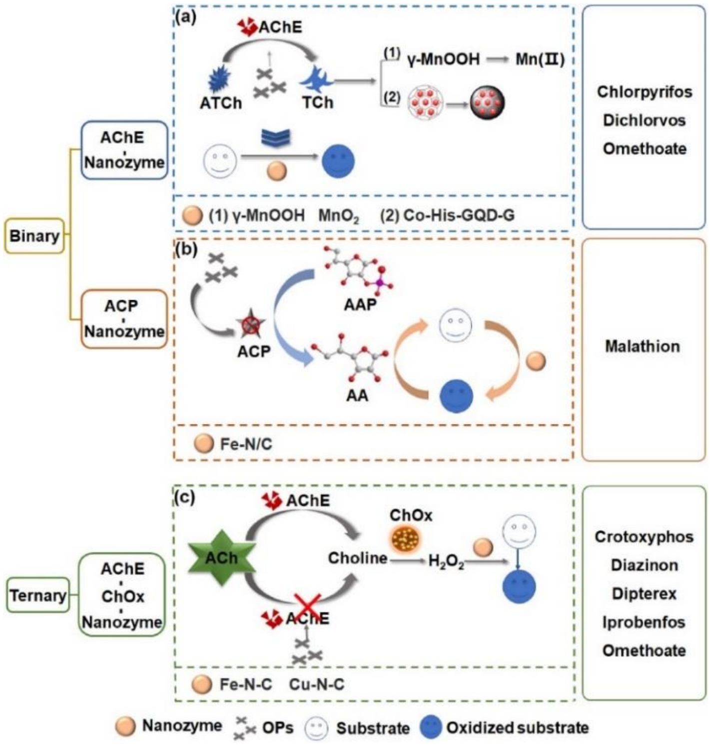

Figure 1. Mechanism diagram of organophosphorus pesticides detection in enzyme-nanozyme strategy [8].

Unlike traditional methods of laboratory analysis, this method is convenient, and rapid, minimizing damage to plants and maximizing yields. Smart plant wearable biosensors are expected to revolutionize pesticide management strategies. By continuously monitoring pesticide levels, farmers can optimize the application, use it wisely, and minimize environmental impact. The technology provides a proactive approach to pest management, ensuring plants are adequately protected and chemical exposure is minimized.

4. Development trend of biosensors

In the past few years, the development of nano-biosensors has become one of the mainstream trends in the field of biosensors. It has shown great potential in fields such as biomedicine, environmental monitoring, and food safety.

Nano biosensors are a class of biosensors that utilize the unique properties of nanomaterials to enhance themselves, and an important feature of it is the use of quantum dots (QDs) [9]. Quantum dots are semiconductor nanocrystals that emit light at different wavelengths depending on their size. They have found application in plant biosensors due to their remarkable fluorescence properties, making them ideal for detecting specific molecules and ions in plants [10]. In addition, Carbon nanotubes have excellent electrical conductivity and mechanical strength and are suitable for converting signals in biosensors, so they can also be integrated into the design of biosensors. Biosensors will also obtain higher sensitivity and faster response speed. Another important feature is the utilization of nanoscale enzymes, which are integrated into plant biosensors to enhance their selectivity and efficiency. These nanoscale enzymes can catalyze specific reactions and recognize target molecules more efficiently than bulk enzymes, making them important components in biosensor systems [11]. The application of nanotechnology in biosensors is not only at present, it may also be a trend of future development. Such as the miniaturization of biosensors, nano-biosensors can be directly deployed in plant tissues, enabling real-time monitoring of biochemical processes and stress responses at the cellular level. Furthermore, nanotechnology can even facilitate the development of label-free biosensors, which can eliminate complex and time-consuming labeling procedures, simplify the detection process, and reduce the risk of detection interference. The integration of nanomaterials can also facilitate the development of multiple biosensors, eliminate the specificity of biosensors, and enable the simultaneous detection of multiple analytes, enabling researchers to obtain multiple sets of data on plants in one experiment.

There is no doubt that the combination of nanomaterials and biosensors can reduce many of the original defects. Traditional biosensors have shown limitations in sensitivity and accuracy, which is where nanotechnology comes into play.

5. Conclusion

In this paper, the design process of plant biosensors and their applications in salt stress, phosphoproteomics analysis, and continuous detection of pesticides are summarized, and the development trends in this field are discussed.

Biosensors are a technology with great potential to detect target substances by exploiting the sensitivity and selectivity of living organisms. Despite remarkable progress, limitations remain. Stability and selectivity are the main challenges that limit sensor accuracy and reliability. The complexity of storage and maintenance increases the application cost and threshold. Some sensors have a lengthy response time and are not suitable for scenarios that require quick monitoring. However, the future remains promising. Stability and selectivity can be improved through gene editing and nanotechnology, among others. Microfluidics promises to shorten response times. The development of a multifunctional integrated sensing platform will improve detection efficiency. In the future, biosensors may have wider applications in fields such as medicine, environmental protection, and food safety, contributing additional possibilities to solve practical problems. Although there are limitations at this stage, with the continuous evolution of technology, biosensors will become an essential tool to promote scientific and technological progress.

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