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Botanical Guardians: Unveiling Plant Health Secrets with Biotech Biosensors

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Abstract

Advancements in biotechnology have revolutionized the field of plant health monitoring, leading to the development of innovative biosensors capable of unveiling the secrets of plant health. These biosensors, equipped with cutting-edge biotechnological tools, offer rapid, sensitive, and specific detection of plant pathogens, enabling timely disease diagnosis and precise management strategies. These abstract highlights the significance of biotech biosensors as botanical guardians, elucidating their pivotal role in safeguarding plant health and maximizing agricultural productivity. With a focus on real-time, in-field applications, we discuss the challenges and opportunities associated with implementing these biosensors, including validation, affordability, and user-friendliness. Additionally, we explore the potential of biotech biosensors in deciphering plant-pathogen interactions, shedding light on the intricate mechanisms governing plant defense and pathogen evasion. By embracing the power of biotechnology, these botanical guardians empower farmers, agronomists, and researchers to unlock the mysteries of plant health and protect global food security. As we delve into the future of biotech biosensors, we envision a world where these cutting-edge technologies form an integral part of sustainable agricultural practices, fostering a harmonious coexistence between humans, plants, and their microbial counterparts.

Introduction

A biosensor is a specialized analytical tool used to detect and analyses certain biological or chemical compounds. It combines biological components (such as enzymes, antibodies, or live cells) with a physicochemical sensor. It works by transforming an easily measurable and quantifiable biological reaction into an electrical or optical output. Biotechnology, environmental monitoring, food safety, and plant pathogen diagnosis are just a few of the industries where biosensors have found use. Three primary parts are commonly found in biosensors for pathogen detection: a transducer, a biological identification element, and a signal processing unit.

- **Biological Recognition Element:**

The biological recognition element is a key component of the biosensor that provides specificity and selectivity in detecting the target pathogen. It can be an antibody, DNA probe, enzyme, aptamer, or any other biomolecule that exhibits a strong binding affinity to the pathogen of interest. When the pathogen comes into contact with this recognition element, a specific biochemical interaction occurs.

- **Transducer:**

The transducer is responsible for converting the biochemical interaction between the pathogen and the biological recognition element into a measurable signal. The type of transducer used depends on the biosensor's design and the nature of the interaction. Common transducer types include:

Electrochemical Transducer: In an electrochemical biosensor, the binding event between the pathogen and the biological recognition element causes a change in electrical properties, such as current or voltage. This change is proportional to the concentration of the target pathogen.

Optical Transducer**:** Optical biosensors use light as the detection mechanism. The interaction between the pathogen and the recognition element leads to a change in the optical properties of the biosensor, which can be measured and quantified.

- **Signal Processing Unit:**

The signal processing unit is responsible for converting the output from the transducer into a meaningful and quantifiable result. This unit may include electronic circuits, microcontrollers, or software algorithms that analyze the sensor's response and provide a numerical value or a visual representation of the pathogen's presence or concentration.

Working Principle:

When a sample containing the target pathogen is introduced to the biosensor, the biological recognition element selectively binds to the pathogen. This binding event triggers a response in the transducer, leading to the generation of an electrical, optical, mechanical, or thermal signal. The signal processing unit then interprets the signal and provides the desired output, such as the pathogen's concentration or the presence/absence of the pathogen.

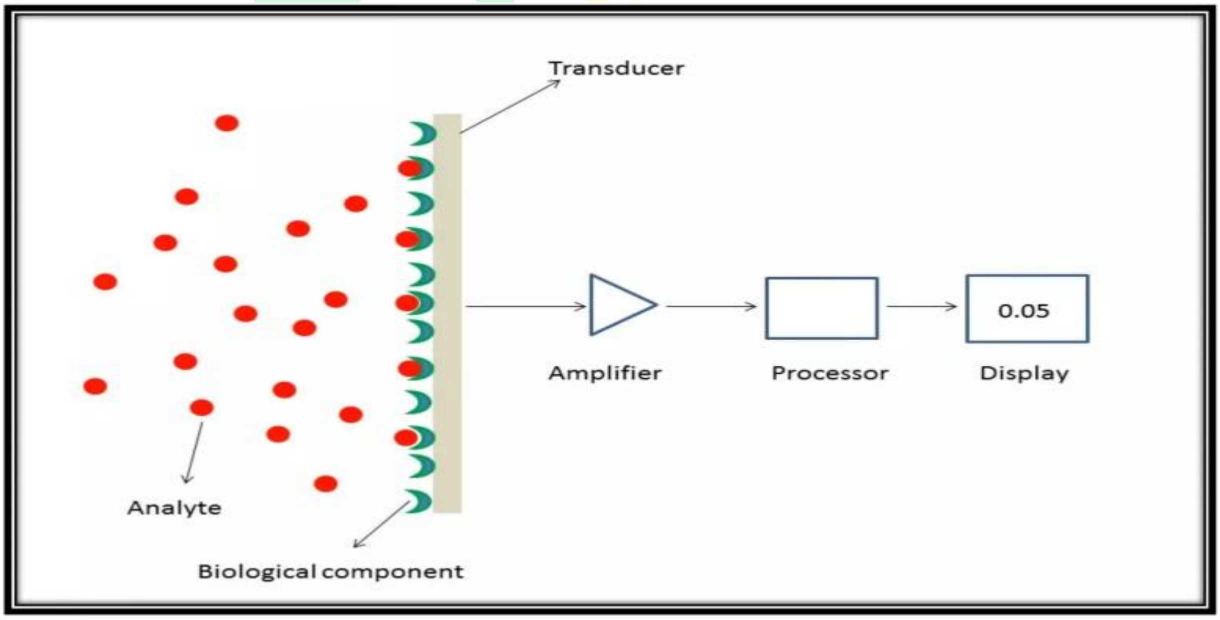

Figure 1 -Working principle of Biosensor (Liu *et al*.,2018)

Why Biosensors are Important:

Sensitivity and Selectivity: Biosensors exhibit high sensitivity and specificity, allowing for accurate detection of target substances even at low concentrations. This attribute makes them valuable in various applications, especially in agricultural fields.

Real-time Monitoring: Biosensors enable real-time, continuous monitoring of biological and chemical processes. This feature is essential for timely responses in critical situations, such as detecting medical emergencies or environmental hazards.Miniaturization and Portability: Advances in technology have allowed for the miniaturization of biosensors, making them portable and suitable for point-of-care testing. Portable biosensors provide rapid results, reducing the need for complex laboratory setups and improving accessibility to healthcare in remote areas.

Cost-effectiveness: Biosensors can be cost-effective compared to traditional laboratory techniques, primarily due to their ability to use smaller sample volumes, lower reagent consumption, and simplified testing procedures.Environmental Benefits: In environmental monitoring, biosensors can detect pollutants and toxins in real-time, helping to prevent environmental degradation and facilitate timely intervention to protect natural resources

Advancements in Biosensor Technologies for Plant Pathogen Detection

In a variety of scientific domains, including environmental monitoring, real-time plant pathogen detection, and pesticide residue analysis in foods and drinks, biosensors have become an increasingly useful tool for enhanced detection. When a particular analyte or pathogen in solution comes into contact with a biosensor, a physicochemical transducer and a biological sensing element, an electrical signal is produced. The biomolecular interaction is subsequently transformed into a digital output by the transducer. The biological component that functions as a bioreceptor might be in the form of tissues, entire cells, DNA, enzymes, antibodies, or DNA. Through particular molecular interactions, these bioreceptors give the biosensor recognition specificity. Biosensors can be categorized as electrochemical, optical, thermal, or piezoelectric devices depending on the type of transducer they use.

Over the past few decades, biosensing techniques for plant pathogen detection have demonstrated practicality in achieving significant diagnostic results for real-life applications. For instance, Regiart developed a microfluidic electrochemical immunosensor for early detection of *Xanthomonas arboricola* in walnut plant samples. This in-situ diagnostic method was three times faster than traditional enzyme-linked immunosorbent assay (ELISA) and provided significantly higher specificity and sensitivity. In another study, a DNA-probe based bioassay was employed for the detection of Plum Pox Virus (PPV). The researchers used an ion-channel electrochemical biosensor to monitor the interaction between single-stranded PPV DNA probes on a glassy carbon electrode surface, achieving a detection limit of 12.8 pg of PPV ssDNA/mL. Additionally, they developed an electrochemical immunosensor with the same sensitivity to detect the PPV virus using anti-PPV polyclonal antibodies attached to gold electrodes.

These biosensors have proven to be effective in in-field plant pathogen detection, offering advantages such as low cost, ease of use, and rapid detection of target pathogens. Moreover, they exhibit high specificity and sensitivity. For instance, a nanoparticle electrochemical biosensor detected Pseudomonas syringae more sensitively than conventional PCR, enabling the diagnosis of infected plants even before any disease symptoms appeared.

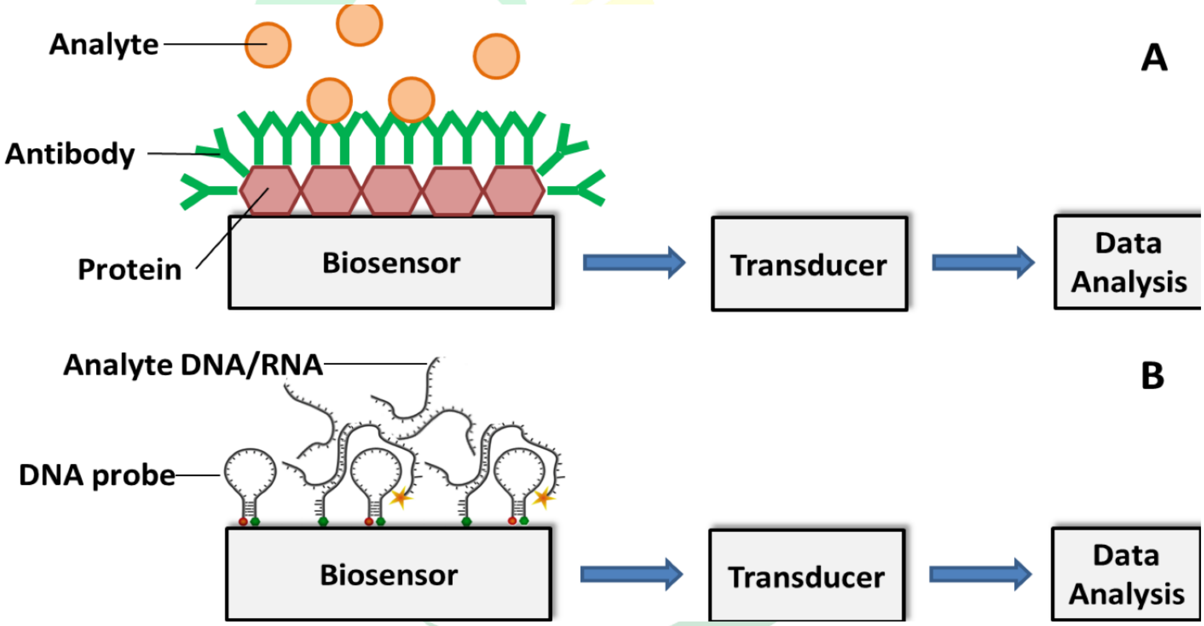

Figure 2. (A) antibody-based and a (B) DNA/RNA-based biosensor for analyte detection (Fang and Ramasamy, 2015)

Challenges in Achieving In-Field Detection and Quantification of Plant Pathogens

Conventional methods such as ELISA, PCR, and LAMP have been widely used for plant pathogen detection, but they have certain limitations that need to be addressed. For instance, ELISA, which relies on antigen-antibody binding reactions, can suffer from low specificity and cross-reactivity due to the complex design of antibodies. Moreover, producing relevant bioreceptors, such as monoclonal antibodies, can be expensive. Similarly, PCR-based technology requires costly instruments and reagents, making it less suitable for point-of-care detection. Additionally, nucleic acid-based assays often involve multiple steps to disintegrate target cells before the detection process, requiring skilled labor and professional laboratory workers.

Recent advances in micro- and nanotechnologies have led to the development of biosensor-based assays that are highly specific, sensitive, and provide rapid results. However, their broad adoption and implementation in agricultural settings require further considerations and validation. Biosensors are likely to become a common tool within Integrated Disease Management (IDM) packages, but each biosensor will need careful validation for its specific application in a particular crop, location, or pathosystem. Their use for decision support purposes in disease management must be complemented by reliable knowledge of plant phenology, pathogen biology, and disease epidemiology. Pathogen detection information must be integrated with other factors in each farming system, including cultural cropping practices, climate, and current disease management strategies. This integration may lead to predictive tools for epidemics and enhance IDM strategies to safeguard crop productivity and quality.

The accuracy of biosensor-based detection relies heavily on the in-field sampling strategy. Informed sampling methods should be guided by climatic, host, and farming system knowledge, considering factors that influence pathogen distribution and dissemination. Detection limits for target pathogens can be impacted by their biological concentrations in plant materials or environmental samples, as well as the presence of non-target molecules that interfere with probe binding. The complexity of sample matrices containing ions and cells may disrupt the optimization of biosensor amplifiers.

In-field sample preparation methods remain relatively unexplored but are crucial for overall diagnostic procedures and interpretation. The initial separation of the target analyte from sample backgrounds is essential for improved detection. However, conventional sample preparation techniques like centrifugation and precipitation are less suitable for in-field applications due to their reliance on powered equipment and time-consuming processes. For DNA-based diagnostics, PCR inhibitors present in plant and fungi tissues, such as polysaccharides and phenolic compounds, must be removed during sample preparation.

Magnetic properties of metal nanoparticles can be utilized to separate and concentrate bound target analytes, offering potential solutions for faster and higher-quality DNA extractions. Magnetic bead-based DNA extraction and purification methods are promising alternatives that reduce dependency on toxic reagents and powered equipment. These approaches enhance the efficiency of DNA extractions and improve biosensor performance. Timely results are crucial for effective disease management on farms, necessitating rapid diagnostics. Efforts have been made to reduce costs and achieve multi-target detection in biosensor devices. However, implementing portable sensors in-field requires specialized hardware, posing challenges for non-specialized users. Determining minimum inoculum levels is vital to estimate disease risk based on biosensor-quantified pathogen levels.

Conclusion

In conclusion, nano biosensors offer promising solutions for plant pathogen detection, paving the way for a proactive and efficient approach to disease management in agriculture. With further advancements and validation, these tools will play a crucial role in safeguarding crop health, reducing chemical inputs, and enhancing the overall sustainability and productivity of agriculture in the future.

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