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A Biosensor-Based Device for the Detection of Soil-Borne Fungal Diseases in Agricultural Soils.

M. S. Desai
Department of Botany, Karmaveer Hire Arts, Commerce and Education College, Gargoti, Dist. Kolhapur.

Abstract
Soil-borne fungal diseases have a major issue in agriculture because they are not readily detected until the onset of symptoms in plants. Although conventional methods of diagnosis are effective, they are time consuming and not ideal for use in the rapid diagnosis of the condition in the field. The use of biosensor-based devices appears to be a viable alternative in the rapid detection of pathogenic fungi in soil. This review highlights the problem of soil-borne fungal diseases in agriculture, the limitations of conventional diagnosis, and the potential of biosensors. The review highlights the various sensors in use, their mechanisms of functioning, and advancements made in biosensor research.

Keywords: *Soil-borne fungal diseases, biosensors, plant pathogen detection, agricultural soils, early disease diagnosis.*

I. Introduction

Soil quality is an important aspect when considering agricultural production, but on the other hand, soil is home to many plant pathogens. Soil-borne fungi, such as *Fusarium, Rhizoctonia, Pythium, and Phytophthora*, causing wilt disease and root rot, account for substantial crop loss (Oerke, 2006). Conventional methods will determine the pathogens either by observing the plants or by means of a lab, thereby resulting in substantial delay in detecting plant pathogens (Chen et al., 2024). But biosensor methods have been proved to have great potential and enhanced sensitivity for the detection of plant pathogens, which will assist in analyzing at a quicker pace at the site itself (Nguyen et al., 2024).

The Impact of Soil-Borne Plant Pathogenic Fungi on Plants:

Soil-borne fungal pathogens can infect the roots of plants and therefore cannot as easily absorb water and nutrients from the soil to help maintain their health, yield, and growth. Some examples of these fungal pathogens are *Fusarium oxysporum*, which can infect bananas and tomatoes and lead to vascular wilt; and *Rhizoctonia solani*, which can infect cereals and vegetables and lead to root rot (Schaad et al., 2001). The increasing visibility of soil-borne diseases has caused farmers to be affected for many years with no clear control measures. Farmers can lose significant amounts of income due to soil-borne disease from year to year (Oerke, 2006).

Conventional Methods for Detecting Soil, Borne Fungi:

- Culture, Based Techniques: Culture, based techniques are the primary means by which soil borne fungi are isolated for diagnostic purposes. Despite the fact that culture, based methods offer reliable identification (Schaad et al., 2001), they are relatively slow and demand the user to have knowledge of fungal taxonomy.
- Microscopy Techniques: Fungi can be visually inspected through the aid of microscopy, which enables the researchers to see the cellular features of the fungi. However, microscopy methods of viewing fungi usually have low resolution and thus lack the specificity for the identification of closely related pathogens (Lazcka et al., 2007).
- Molecular Detection Techniques: Molecular methods for detecting soil, borne fungi, such as PCR and qPCR, lead to correct identification, but the methods are costly, require well, equipped laboratory facilities, and are generally not suitable for on, site use (Chen et al., 2024).

II. Principles of Biosensor Technology:

A biosensor is an analytical device, which couples antibodies, nucleic acid probes, or enzymes with a transducer to convert a specific biological interaction into a measurable signal. The components of a biosensor include: A bio receptor that specifically binds the target analyze. A transducer that converts this biological event into an electrical or optical signal. A signal processing unit to interpret and display the result.

Types of Biosensors for Site, Specific Fungal Detection:

- Electrochemical biosensors: Electrochemical biosensors detect changes in electrical signals depending on the target binding. These sensors have gained a lot of attention because they can be easily miniaturized and offer high sensitivity and low detection limits. New studies point to their use as the most effective for nucleic acid detection and also the identification of certain fungal biomarkers providing early pathogen identification (Nguyen et al., 2024).
- Optical biosensors: Optical biosensors sense the changes in the light properties like absorbance, fluorescence, or refractive index. Although the optical biosensors indicate high sensitivity, complex soil matrices sometimes hinder the signal readings. Research that is still going on focuses on enhancing the signal discrimination under field conditions.
- Immunosensors: Immunosensors take advantage of specific antigen antibody binding. They are perfect for reasons of detecting fungal proteins or spores with high specificity. With the nanomaterial introduction, antibody immobilization has been improved which results in higher signal stability and longer lifetime of the sensor in the field (Nguyen et al., 2024).
- Molecular and DNA, Based Technologies: DNA biosensors use one strand of DNA as a probe to hybridize with the target DNA of the pathogen. These sensor devices utilize the specificity of molecular diagnostics combined with the rapidness of the signal generation thus are perfect for the detection of fungal pathogens in the pre, symptomatic phase (Nguyen et al., 2024).

III. Recent Advances and Current Research:

Recent literature reports rapid growth in biosensor research for plant pathogen detection: A comprehensive review of biosensor technologies for plant pathogens was published in Analytical Methods in 2024, highlighting latest developments and types of sensors being explored (Nguyen et al., 2024). A 2024 review in Frontiers in Microbiology summarized detection technologies for vegetable soil-borne pathogens, underscoring the need for rapid, field-deployable methods (Chen et al., 2024). A 2024 review in Nanoscale discussed biosensors for fungal spore detection, showing advances in micro–nano sensor integration and rapid detection capability (Memon et al., 2024). These studies confirm that biosensing is emerging as a viable strategy for early disease identification, potentially transforming how crop diseases are monitored and managed.

Challenges and Limitations:

Organic matter and mineral components in soil can dampen sensor signals. Occasionally, biosensor components do not maintain their stability over a long period under natural conditions. Several advanced biosensor systems are only research concepts and have not been commercialized. Price and requirement of user training are still a couple of obstacles that limit the adoption of the technology by farmers.

Future Perspectives:

Nanotechnology and microfluidics are becoming more efficient, allowing the development of more sensitive and portable biosensors. Besides that, machine learning integration could make signal interpretation easy and thus, predict the disease. Fostering cooperation between the public and private sectors is facilitating the production of fungal infection detection instruments for field workers, thereby encouraging early intervention and sustainable practices.

IV. Conclusion

Biosensor, based tools are a breakthrough in the early identification of fungal diseases in the soil. By rapidly, sensitively, and conveniently detecting the presence of pathogens in the field, these innovative technologies have the potential to enhance disease management practices and cut crop losses. Several recent reviews and studies have pointed out that biosensor research is very active, however, more efforts are required to tackle the issues and make these systems a part of daily farming life.

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