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Biosensors for Rapid Detection of Plant Pathogens in the Field and Horticultural Crops

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Plant pathogens are a major constraint to global agricultural productivity, particularly in horticultural crops where diseases can rapidly reduce yield, quality, and market value. Conventional diagnostic techniques such as culture-based identification, microscopy, serological assays, and molecular tools including polymerase chain reaction (PCR) have contributed significantly to plant disease detection; however, these approaches often require well-equipped laboratories, skilled personnel, and lengthy analysis times. Such limitations restrict their effectiveness for rapid, on-site disease diagnosis in field conditions. In recent years, biosensor technology has emerged as a promising alternative for the rapid and accurate detection of plant pathogens. Biosensors combine a biological recognition element with a physicochemical transducer to identify pathogen-specific biomolecules and convert the interaction into measurable signals. Advances in nanotechnology, molecular biology, and materials science have significantly enhanced the sensitivity, selectivity, and portability of biosensing platforms. Various types of biosensors, including electrochemical, optical, piezoelectric, nanomaterial-based, and CRISPR-based systems, have been developed for detecting viral, bacterial, and fungal pathogens in agricultural crops. These technologies enable early disease diagnosis, facilitate timely management strategies, reduce unnecessary pesticide application, and support sustainable crop production. Biosensors also offer advantages such as rapid detection, high sensitivity and specificity, portability, cost-effectiveness, and real-time monitoring capabilities. Despite these benefits, several challenges remain, including issues related to sensor stability under field conditions, sample preparation, standardization of detection protocols, and limited commercial availability. Ongoing research focusing on integrating biosensors with digital tools, artificial intelligence, and precision agriculture systems is expected to further improve their efficiency and accessibility. This review highlights the principles, types, applications, advantages, and future prospects of biosensor technology for rapid detection of plant pathogens, emphasizing its potential role in modern plant disease management and sustainable agriculture.

Keywords: Biosensors; Plant pathogen detection; Field diagnostics; Nanobiosensors; Precision agriculture.

Introduction

Plant pathogens pose a major threat to global agriculture, particularly to horticultural crops such as fruits, vegetables, ornamental plants, and plantation crops. These pathogens—

including fungi, bacteria, viruses, nematodes, and phytoplasmas—can significantly reduce crop yield, quality, and market value. Rapid globalization of trade, climate change, and intensive agricultural practices have increased the spread and emergence of plant diseases in recent decades. Consequently, early and accurate detection of plant pathogens has become essential for effective disease management and sustainable crop production. Traditional diagnostic approaches, including culture-based identification, microscopy, serological assays, and molecular techniques such as polymerase chain reaction (PCR), have contributed greatly to plant pathology research and disease diagnostics. However, these methods often require sophisticated laboratory infrastructure, trained personnel, and time-consuming sample preparation, which limit their application for rapid, on-site detection in agricultural fields. In horticultural systems, where crops are highly sensitive to pathogen attack and where rapid disease outbreaks can occur, timely detection is particularly critical. Many pathogens infect plants at early growth stages without visible symptoms, allowing the disease to spread before management measures can be implemented. For example, bacterial wilt, viral mosaics, and fungal blights in horticultural crops can spread rapidly under favorable environmental conditions, causing severe economic losses. Therefore, the development of rapid, sensitive, and portable diagnostic technologies capable of detecting pathogens directly in the field has become a priority in modern plant disease management.

Biosensor technology has emerged as a promising tool for rapid detection of plant pathogens in agricultural systems. A biosensor is an analytical device that combines a biological recognition element with a physicochemical transducer to detect specific biological molecules or organisms. The biological component—such as antibodies, nucleic acids, enzymes, aptamers, or whole cells—interacts selectively with the target pathogen or its biomolecules. The transducer then converts this biological interaction into a measurable signal, such as electrical, optical, thermal, or piezoelectric output. This integration enables biosensors to provide rapid, specific, and highly sensitive detection of pathogens, often within minutes. Recent advances in nanotechnology, molecular biology, and materials science have greatly enhanced the performance of biosensors for agricultural applications. Nanomaterials such as gold nanoparticles, graphene, carbon nanotubes, and quantum dots have improved signal amplification, sensitivity, and stability of biosensing platforms. In addition, the integration of microfluidics and portable electronics has facilitated the development of compact and user-friendly devices suitable for on-site pathogen detection. These technological innovations are transforming biosensors into powerful tools for real-time plant disease monitoring in the field.

Biosensors for plant pathogen detection operate through various detection mechanisms, including electrochemical, optical, piezoelectric, and thermal sensing. Electrochemical biosensors measure changes in electrical properties such as current, voltage, or impedance following interaction with the target pathogen. Optical biosensors detect variations in light absorption, fluorescence, or surface plasmon resonance caused by pathogen recognition events. Piezoelectric biosensors measure changes in mass or frequency on sensor surfaces when pathogens bind to the recognition element. Each of these platforms offers distinct advantages in terms of sensitivity, speed, portability, and cost-effectiveness, making them suitable for different agricultural applications. In horticultural crop production, biosensor-based diagnostics can significantly improve disease surveillance and management strategies. Early detection allows farmers and agricultural professionals to implement targeted control measures, reducing unnecessary pesticide use and minimizing crop losses. Furthermore, rapid pathogen identification supports precision agriculture approaches by enabling timely decision-making regarding irrigation, chemical treatments, and quarantine measures. This capability is particularly important for high-value horticultural crops, where even minor disease outbreaks can lead to substantial economic damage. Another important advantage of biosensor technology is its potential to support sustainable agriculture. By enabling early and accurate pathogen detection, biosensors help reduce the excessive use of chemical pesticides and fungicides that are often applied as preventive measures. Lower

chemical inputs not only reduce production costs but also minimize environmental contamination and protect beneficial organisms within agroecosystems. Thus, biosensors contribute to environmentally friendly plant disease management practices.

Despite these promising developments, several challenges remain in the widespread adoption of biosensors for field-level plant pathogen detection. Sensor stability under variable environmental conditions, standardization of detection protocols, and large-scale commercialization are among the key issues that need to be addressed. Additionally, the detection of multiple pathogens simultaneously, often referred to as multiplex detection, remains an area of active research. Integrating biosensor platforms with digital technologies, such as smartphone-based analysis and wireless data transmission, is also being explored to improve accessibility and real-time monitoring capabilities.

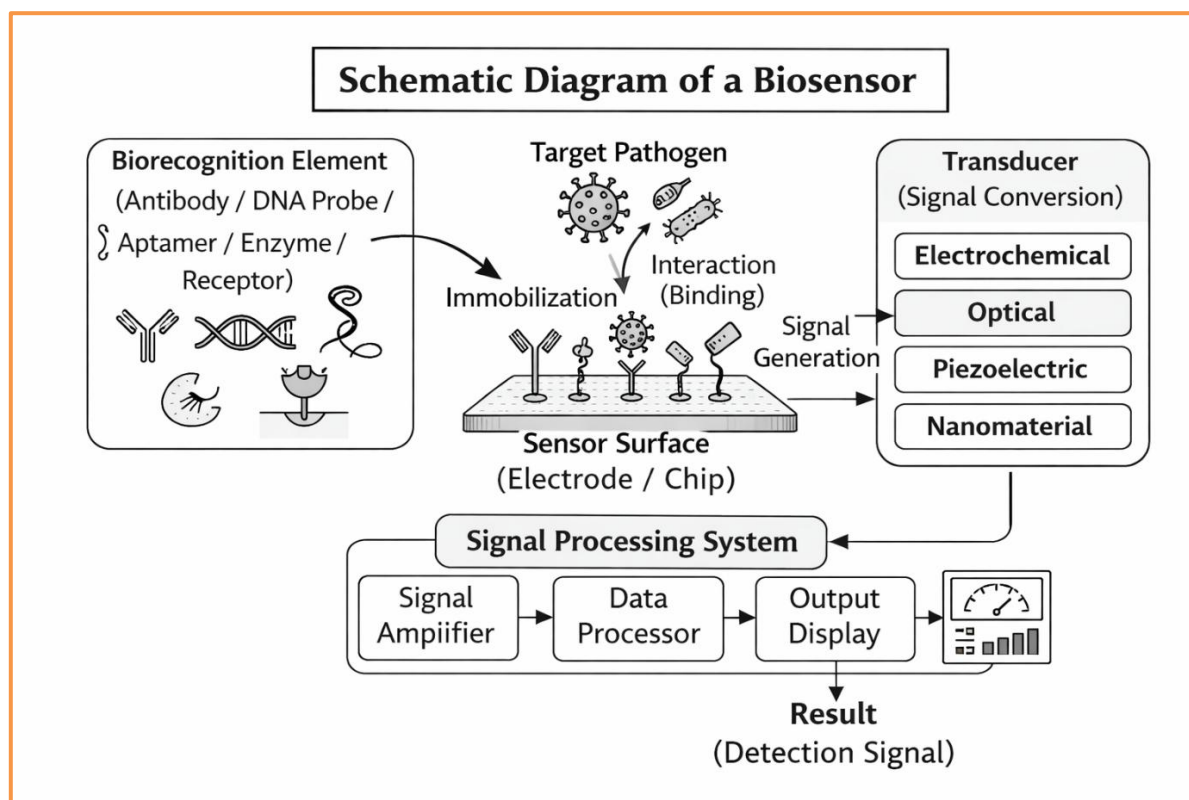


Figure 1. Schematic well labelled diagram of Biosensors

Modern biosensors integrate advances in nanotechnology, molecular biology, and microelectronics to create portable and user-friendly diagnostic tools. These technologies allow the detection of pathogens directly in plant tissues, soil, or irrigation water without complex sample preparation. As a result, biosensors are increasingly considered essential components of precision agriculture and plant disease management systems. This article discusses the principles, types, applications, advantages, and future prospects of biosensors for rapid detection of plant pathogens in field conditions.

Plant Pathogens and the Need for Rapid Detection

Plant pathogens include a wide range of microorganisms that infect crops and cause disease. The major groups include fungi, bacteria, viruses, phytoplasmas, and nematodes. These pathogens can spread rapidly through seeds, soil, air, water, or insect vectors, making early detection critical for effective control. Plant diseases often remain asymptomatic during early stages of infection. By the time visible symptoms appear, the pathogen may already have spread extensively within the crop. Early detection therefore plays a crucial role in preventing epidemics and minimizing crop losses.

Rapid detection technologies are particularly important for several reasons:

1. **Early disease management:** Timely identification allows farmers to apply control measures before the disease spreads.

- Reduction in pesticide use:** Accurate diagnosis helps avoid unnecessary chemical applications.
- Improved crop productivity:** Early detection ensures healthy crop development and higher yield.
- Prevention of pathogen spread:** Quick diagnosis helps prevent the introduction of invasive pathogens into new regions.

Because of these advantages, research efforts are increasingly focused on developing portable diagnostic technologies such as biosensors that can detect pathogens directly in the field.

Principles of Biosensor Technology

A biosensor is an analytical device designed to detect biological molecules or pathogens. It typically consists of three main components:

Biorecognition Element

The biorecognition element is responsible for specifically interacting with the target pathogen or its biomolecules. Common biological recognition elements include:

- Antibodies
- Enzymes
- DNA or RNA probes
- Aptamers
- Whole cells

These biological molecules bind selectively to pathogen markers such as proteins, nucleic acids, or toxins.

Transducer

The transducer converts the biological interaction into a measurable signal. This signal can be electrical, optical, or mechanical depending on the type of biosensor used.

Signal Processing System

The signal generated by the transducer is amplified, processed, and displayed in a readable format such as a digital output, color change, or fluorescence signal.

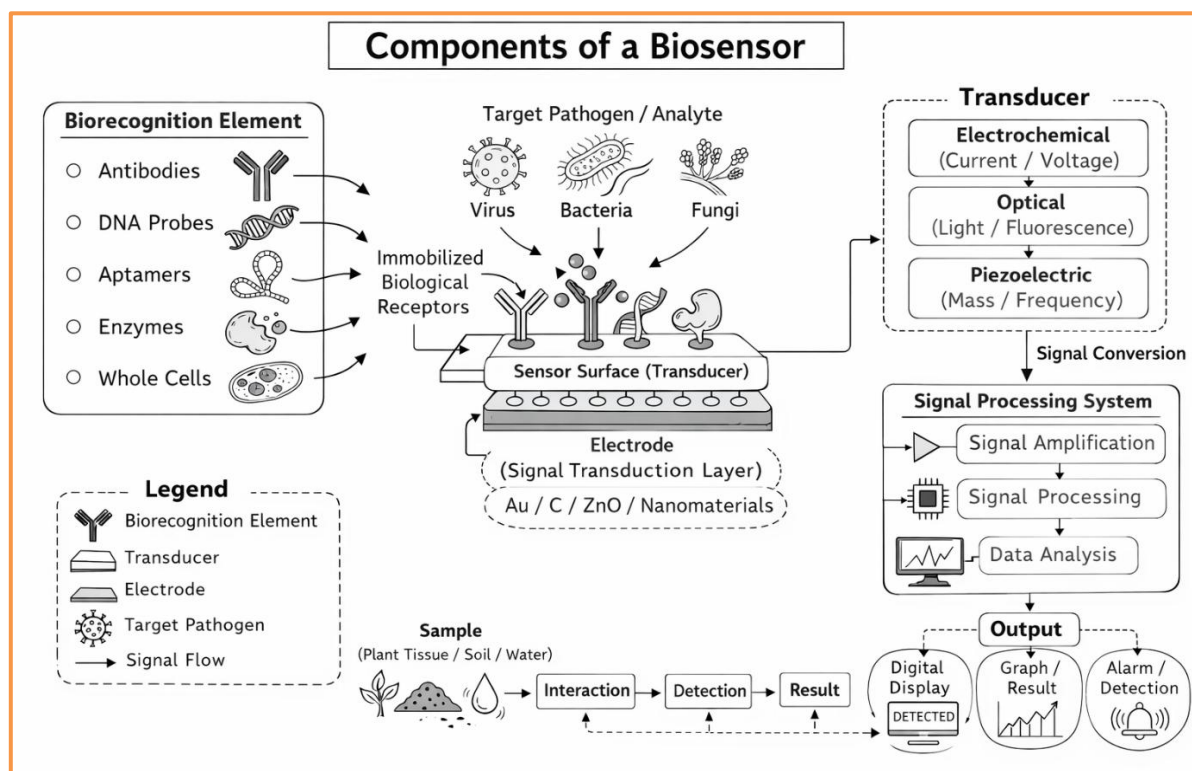


Figure 2. Components of biosensors used in pathogen detection

When the pathogen interacts with the biosensor, the biological recognition element binds to the target molecule, triggering the transducer to produce a detectable signal. This mechanism enables rapid identification of plant pathogens with high sensitivity and specificity.

Types of Biosensors Used for Plant Pathogen Detection

Various types of biosensors have been developed for agricultural diagnostics to enable rapid and accurate detection of plant pathogens. These biosensors differ mainly in their detection principles and signal transduction mechanisms. The most commonly used biosensors for plant pathogen detection include electrochemical, optical, piezoelectric, nanobiosensors, and CRISPR-based biosensors.

Electrochemical biosensors detect pathogens by measuring changes in electrical signals such as current, voltage, or impedance that occur when the target pathogen binds to the sensor surface. These sensors usually contain electrodes coated with biological recognition elements like antibodies, enzymes, or DNA probes that specifically interact with pathogen molecules. Once the pathogen binds to the recognition element, an electrochemical reaction generates a measurable electrical signal. Electrochemical biosensors are widely preferred because they are highly sensitive, provide rapid results, are relatively inexpensive, and can be easily miniaturized for portable devices. They have been successfully used for detecting plant pathogens such as *Plum pox virus*, *Pseudomonas syringae*, and *Xanthomonas* species.

Optical biosensors operate by detecting changes in optical properties such as fluorescence, absorbance, or refractive index during pathogen interaction. Techniques such as fluorescence detection, surface plasmon resonance (SPR), colorimetric assays, and Raman spectroscopy are commonly employed. Optical biosensors provide high sensitivity and enable real-time monitoring of pathogen detection.

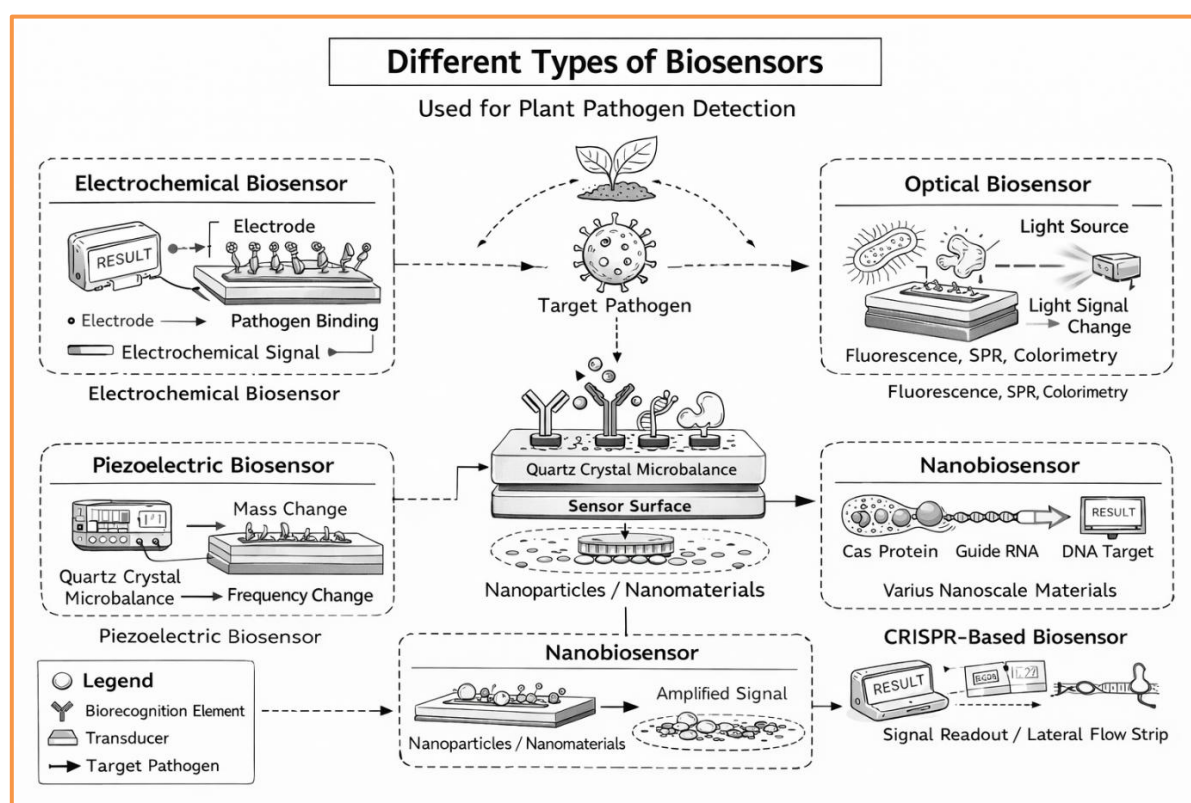


Figure 4. Different types of biosensors have been developed for agricultural diagnostics which differ based on the detection mechanism and signal transduction method

Piezoelectric biosensors function by measuring mass changes on the sensor surface. These sensors commonly use quartz crystal microbalance (QCM) technology, where pathogen binding increases the mass on the sensor surface and alters the vibration frequency of the crystal. This change in frequency indicates the presence of the pathogen.

Nanobiosensors utilize nanomaterials like nanoparticles, nanotubes, or quantum dots to enhance detection sensitivity and signal amplification. These sensors can detect pathogens at extremely low concentrations.

CRISPR-based biosensors represent a recent advancement that uses CRISPR-Cas systems to detect pathogen DNA or RNA with high specificity and speed, often producing results within minutes, making them suitable for field diagnostics. These technologies represent the next generation of rapid diagnostic tools in plant pathology.

Applications of Biosensors in Plant Disease Detection

Biosensors have emerged as powerful tools for the rapid and accurate detection of plant pathogens in agricultural systems. These devices enable early identification of disease-causing organisms directly in the field, allowing farmers and researchers to take timely preventive measures. By detecting pathogens before visible symptoms appear, biosensors help reduce crop losses and improve disease management strategies. Their ability to provide quick and reliable results makes them highly valuable for monitoring plant health and ensuring sustainable agricultural production.

Table 1. Applications of Biosensors in Detection of Plant Pathogens

Pathogen Type	Example Pathogens	Biosensor Detection Target	Importance of Detection
Viral Pathogens	Tobacco mosaic virus, Plum pox virus, Maize chlorotic mottle virus	Viral RNA/DNA or viral proteins	Enables early diagnosis and removal of infected plants to prevent disease spread
Bacterial Pathogens	<i>Xanthomonas</i> spp., <i>Pseudomonas syringae</i> , <i>Erwinia amylovora</i>	Bacterial DNA, enzymes, or surface proteins	Helps manage bacterial diseases quickly and reduces excessive pesticide use
Fungal Pathogens	<i>Fusarium</i> spp., <i>Phytophthora infestans</i> , <i>Aspergillus niger</i>	Fungal spores, DNA, or metabolites	Allows timely application of fungicides and improves crop protection

Detection of Viral Pathogens

Plant viruses are responsible for substantial yield losses in many economically important crops. Traditional virus detection techniques often require laboratory facilities and may take several hours or days to confirm the presence of the pathogen. Biosensors provide a faster alternative by detecting viral particles or their nucleic acids directly from plant tissues. This allows for early diagnosis of viral infections before the appearance of visible symptoms. Biosensors have been successfully used to detect viruses such as Tobacco mosaic virus, Plum pox virus, and Maize chlorotic mottle virus. Early identification of viral pathogens enables farmers to implement control measures such as removal of infected plants, use of resistant varieties, or vector management, thereby preventing further spread of the disease.

Detection of Bacterial Pathogens

Bacterial diseases are another major threat to crop production, often spreading rapidly under favorable environmental conditions. Biosensors designed with specific antibodies or DNA probes can detect bacterial pathogens with high sensitivity and specificity. Pathogens such as *Xanthomonas* species, *Pseudomonas syringae*, and *Erwinia amylovora* have been successfully identified using biosensor-based techniques. These sensors can analyze plant sap, leaf extracts, or environmental samples, providing rapid results that assist in early disease management and help reduce the misuse of chemical pesticides.

Detection of Fungal Pathogens

Fungal pathogens are among the most widespread and destructive agents affecting crops worldwide. Biosensors have been developed to detect important fungal pathogens such as *Fusarium* species, *Phytophthora infestans*, and *Aspergillus niger*. Rapid detection allows farmers to apply fungicides or other management strategies at the correct time, minimizing disease spread and protecting crop yield and quality.

Advantages of Biosensors for Field Detection

Biosensor technology has emerged as a valuable tool for rapid plant disease diagnosis in modern agriculture. Compared with conventional laboratory-based diagnostic methods, biosensors offer several practical advantages, particularly for field-level monitoring of plant pathogens. These devices combine biological recognition systems with electronic or optical signal detection, enabling fast and accurate identification of disease-causing organisms. As agriculture increasingly moves toward precision farming and digital monitoring, biosensors provide a reliable approach for early disease detection and timely crop management. One of the most important advantages of biosensors is **rapid detection**. Traditional methods such as culturing pathogens, polymerase chain reaction (PCR), and enzyme-linked immunosorbent assay (ELISA) often require several hours to days to produce results. In contrast, biosensors can identify pathogens within minutes or a few hours. This rapid response allows farmers and researchers to take immediate control measures, preventing the spread of diseases across crop fields. Another significant advantage is **high sensitivity and specificity**. Modern biosensors are capable of detecting extremely small concentrations of pathogen molecules, including DNA, proteins, or toxins. By using specific biological recognition elements such as antibodies, enzymes, or nucleic acid probes, biosensors can accurately distinguish between different pathogens. This high level of precision reduces the chances of false results and ensures reliable diagnosis. **Portability** is also a major benefit of biosensor technology. Many biosensor devices are compact and lightweight, allowing them to be used directly in agricultural fields. Portable biosensors eliminate the need for transporting samples to distant laboratories and enable farmers or plant pathologists to perform on-site analysis. This feature is particularly useful in remote rural areas where laboratory infrastructure may not be available. Biosensors also offer **cost-effectiveness**. Once the technology is developed and optimized, biosensors can be produced in large quantities at relatively low cost. The ability to conduct rapid tests without expensive laboratory equipment helps reduce diagnostic expenses. As a result, biosensors have the potential to become accessible tools for farmers, agricultural extension workers, and crop protection specialists. Another important advantage is **real-time monitoring**. Biosensors can continuously monitor plant health and detect the presence of pathogens in crops, soil, or irrigation water. Real-time monitoring allows early detection of disease outbreaks and helps farmers apply preventive measures at the right time. This capability supports sustainable crop production and reduces excessive use of chemical pesticides.

Challenges and Limitations

Despite their numerous advantages, biosensors also face certain challenges that limit their widespread adoption in agricultural systems. One of the primary concerns is **sample preparation**. Plant tissues contain complex biochemical compounds such as pigments, enzymes, and organic molecules that may interfere with sensor performance. Proper sample preparation techniques are therefore required to obtain accurate results. Another limitation is related to **environmental conditions**. Field environments often involve fluctuating temperature, humidity, dust, and sunlight, which can affect the stability and performance of biosensors. Designing sensors that can function reliably under diverse environmental conditions remains an important research challenge. **Standardization** is another issue that needs attention. Many biosensor technologies are still in the experimental stage, and standardized protocols for calibration, validation, and quality control are not yet widely established. Developing uniform testing standards will help ensure reliability and reproducibility across different agricultural applications. Additionally, **limited commercial availability** remains a barrier. Although numerous biosensors have been developed in research laboratories, only a small number have reached large-scale commercial production. More efforts are needed to translate laboratory innovations into practical tools that farmers can easily use.

Future Prospects of Biosensor Technology

The future of biosensor technology in agriculture is highly promising. Rapid developments in nanotechnology, molecular diagnostics, and digital agriculture are expected to improve the performance and accessibility of biosensors for plant disease detection. One important area of development is the **integration of biosensors with smartphone-based detection systems**. Mobile applications can be used to analyze sensor signals and provide instant diagnostic results. Such systems will allow farmers to monitor plant health using portable devices. Another emerging concept is the **development of wearable plant sensors**. These sensors can be attached to plant surfaces to continuously monitor physiological changes and detect early signs of infection. The use of **artificial intelligence (AI)** is also expected to enhance biosensor-based disease diagnostics. AI algorithms can analyze sensor data, identify disease patterns, and predict potential outbreaks before symptoms become visible. Furthermore, biosensors are likely to become key components of **precision agriculture systems**. When combined with remote sensing technologies, drones, and Internet of Things (IoT) platforms, biosensors can contribute to automated crop monitoring and decision-support systems. Advanced technologies such as **CRISPR-based biosensors and nanobiosensors** are also gaining attention for their exceptional sensitivity and rapid detection capabilities. In the future, integrating biosensors with digital agriculture platforms could enable automated disease surveillance networks that support sustainable crop production and improved food security.

Table 2: Advantages and Challenges of Biosensors for Field Detection

Aspect	Description	Impact on Agriculture
Rapid Detection	Identifies pathogens within minutes or hours	Enables early disease control and prevents crop loss
High Sensitivity and Specificity	Detects very low concentrations of pathogen molecules	Provides accurate and reliable diagnosis
Portability	Compact and easy to use directly in the field	Allows on-site disease monitoring without laboratories
Cost-Effectiveness	Lower diagnostic costs after development	Makes technology accessible to farmers
Real-Time Monitoring	Continuous detection of pathogens	Helps prevent disease outbreaks
Sample Preparation Challenges	Plant compounds may interfere with sensor function	Requires proper sample handling techniques
Environmental Sensitivity	Temperature and humidity affect sensor stability	Needs robust sensor design
Standardization Issues	Lack of uniform testing protocols	Limits widespread adoption
Limited Commercial Availability	Few sensors available in the market	Requires further technology transfer

Conclusion

Rapid and accurate detection of plant pathogens is essential for protecting crop productivity and ensuring sustainable agricultural practices, particularly in horticultural systems where diseases can spread quickly and cause significant economic losses. Traditional diagnostic methods have played an important role in plant pathology; however, their dependence on laboratory infrastructure, specialized equipment, and skilled personnel limits their suitability for real-time field applications. In this context, biosensor technology has emerged as a powerful and innovative tool for plant disease diagnostics. Biosensors integrate biological recognition elements with advanced signal transduction systems to enable rapid, sensitive, and specific detection of pathogens. Different biosensor platforms, including electrochemical, optical, piezoelectric, nanobiosensors, and CRISPR-based systems, have demonstrated

significant potential in identifying viral, bacterial, and fungal pathogens at early stages of infection. Their ability to provide quick results directly in field conditions allows farmers and researchers to take timely disease management actions, reducing crop losses and minimizing unnecessary pesticide use. Despite these advantages, certain challenges still need to be addressed to facilitate large-scale adoption of biosensor technologies in agriculture. Issues such as environmental stability, sample preparation complexity, lack of standardized protocols, and limited commercial availability remain barriers to widespread implementation. Continued research and technological advancements are therefore necessary to improve sensor durability, reliability, and affordability for practical agricultural use. Future developments in nanotechnology, digital agriculture, artificial intelligence, and Internet of Things (IoT) platforms are expected to further enhance biosensor performance and accessibility. Integration of biosensors with smartphone-based detection systems, automated monitoring networks, and precision farming tools could transform plant disease surveillance and management strategies. Overall, biosensor technology holds significant promise for improving plant health monitoring, supporting sustainable crop production, and strengthening global food security in the coming decades.

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