***Review Article***

**PIONEERING PLANT HEALTH: BIOSENSORS FOR EARLY AND ADVANCED PATHOGEN DETECTION**

**ABSTRACT**Plant diseases significantly threaten global food security, leading to up to 40% annual crop losses and an estimated $220 billion in financial damages. Traditional methods for detecting plant diseases such as symptomatology, microscopy, and molecular diagnostics (e.g., PCR, ELISA) are often time-consuming, labour-intensive, and difficult to scale. However, advanced technologies, particularly biosensors, have emerged as precise, efficient, and rapid tools for pathogen detection as they combine biological recognition elements (such as DNA, antibodies, or enzymes) with transducers to produce measurable signals upon interaction with target analytes. This review categorizes biosensors based on their bio-recognition elements and transducer mechanisms, focusing on key types such as electrochemical, optical, piezoelectric, and nucleic acid-based sensors. It explores specific advancements like DNA-based biosensors for molecular-level detection and antibody-based sensors for antigen specificity. Additionally, emerging technologies such as electronic noses, which detect volatile organic compounds, and phage-based biosensors, known for their high sensitivity and specificity, highlight the extensive range of biosensing applications in plant pathology. Innovations in wireless sensing and real-time data capture promise to transform bio-sensing into a cornerstone of Integrated Disease Management (IDM) systems. These advancements can reduce agrochemical usage and improve crop sustainability. Hence, biosensors represent a pivotal technology for addressing the growing challenges of global agriculture.

**INTRODUCTION**

Plant diseases cause a remarkable loss in food production and reduce species diversity, affect people's livelihoods, increase mitigation costs, and thereby negatively influence human health as well as worldwide food availability and stability. Plant pathogens are a significant challenge to agriculture, impacting the economy and food security. Up to 40% of crop yield is lost annually due to these pathogens and pests, creating huge financial consequences leading to estimated losses reaching $220 billion each year (Baldi and La Porta 2020). Beyond the economic implications, the socioecological consequences are considerable, particularly with the world population by 2050 is expected to touch 9.7 billion (FAO 2024). Hence, effective strategies for management of plant diseases are extremely imperative to ensure safety, security and sustainability in food production.

Plant diseases impact not only the yield of crops but also cause financial instability to agriculture and industries worldwide. It is critical to monitor and detect diseases in plants at an early stage for sustainable agriculture. (Sankaran et al., 2010). As economic crop production is mainly oriented in larger farms relying on less manpower, the farm manager has to reduce the requirement for manual labour by depending more on automated types of equipment. For this purpose, platforms with autonomous robotics equipped with explicit weeding techniques and self-driven tractors have already been developed (Bak and Jakobsen 2004). Manual inspection in fields and greenhouses is labour-intensive and demands skilled personnel, as identifying and distinguishing plant diseases based solely on visual symptoms can be quite challenging (Skotturup et al., 2008).

**PLANT DISEASE DETECTION METHODS**

The primary step in plant disease management is the identification of diseases using various detection techniques which is the most crucial part in plant health monitoring. This can be achieved through direct and indirect detection methods, each offering unique advantages for timely and accurate diagnosis. Direct detection of diseases includes symptomatology in which we observe symptoms of the pathogen on a diseased sample, culture the pathogen in its nutrient-specific media, and observe the spores under a microscope. Molecular and serological methods are preferred when enormous samples are to be analyzed. Here, the biotic stress-causing agents like viruses, fungi, and bacteria are detected directly providing precise identification of the biotic agent/disease within a limited period. Alternatively, the indirect methods of identifying diseases are through various parameters such as variation in temperature, change in transpirational rate, volatile organic compounds(VOCs) released by infected plants as well as the morphological changes exhibited by the diseased plants which are time-consuming. (Fang and Ramaswamy 2015).

Currently, the plant disease detection techniques available are enzyme-linked immunosorbent assay (ELISA), based on proteins produced by the pathogen, and polymerase chain reaction (PCR), based on specific deoxyribose nucleic acid (DNA) sequences of the pathogen (Ruiz-Ruiz et al. 2009). Diagnosis of plant disease have evolved from traditional methods to more advanced techniques like electron microscopy, serological diagnostics, and PCR-based methods. These advancements have revolutionized plant diagnostics, allowing for faster, precise as well as simultaneous detection of fungal pathogens without the need for expert taxonomists. The integration of traditional and modern methods is essential for effective disease management, and the future challenge lies in selecting the most suitable technique for specific pathogen detection. Hence, nanotechnology, biosensors, and other innovative tools offer promising solutions concerning the future of disease diagnostics in plants (Khakimov et al., 2022). Pests and diseases have been found as most important factors involved in most of the agricultural losses. Therefore, a comprehensive approach is needed to tackle the devastating impact on food security and sustainability. A collaborative effort has been put forth by the International Plant Protection Convention (IPPC) to reduce the spread of pests and diseases across the nations but they may remain a threat in agricultural production systems within the borders.

**WHY EARLY DETECTION IS NECESSARY**

Prompt identification of the pathogens affecting the plants is crucial for effective health monitoring in plants. It enables disease management in greenhouse systems and the field at various stages of disease development. This proactive approach helps minimize the spread of infections, prevents the introduction of new plant diseases particularly quarantine pathogens at country borders and supports agricultural sustainability. Additionally, it reduces economic losses caused by crop damage (Lopez et al., 2003; Miller et al., 2009)

**BIOSENSORS**

These are devices that combine a biological sensing element with a physicochemical transducer for analysing the pathogen. They generate an electronic signal proportional to the specific interaction between analytes and the sensing element (Turner 2000). They can detect the analytes comprehensively, from minute molecules to entire pathogenic microorganisms. While biosensors can also operate both inside and outside living organisms, the parameters they measure or detect typically originate from living organisms or ecosystems (Kaur et al., 2019).

The first biosensor, known as the Clark electrode, was created by LeLand Clark for oxygen detection, earning him the title "father of biosensors" (Heineman and Jensen 2006). The first commercially available biosensor, developed by Yellow Springs Instruments in 1975, was designed to measure glucose levels in blood (Yoo and Lee 2010).

Biosensors possess great potential for on-site care applications because of their affordability, simplicity, and rapid results. They have become advanced detection tools across various research domains, including environmental surveillance, diagnosis of airborne pathogen, real-time human blood components analysis, pathogen identification, and the detection of pesticide residues in beverages and foods (Liu et al., 2018).

**COMPONENTS OF BIOSENSOR**

A biosensor detects a specific biomarker (analyte) associated with a particular pathogen through an immobilized sensing element known as a bioreceptor. The bioreceptor can be a monoclonal antibody, RNA, DNA, enzyme, tissue, or whole cell, and it plays a critical role in ensuring the biosensor’s high sensitivity and selectivity for the target biomarker. This selective recognition minimizes interference from other microorganisms or molecules present in the sample. The transducer is an essential part of a biosensor. A chemical sensor transforms the recognition event into measurable electrical signals, that correlate with the quantity of a chemical or biological target present. Transducers generate signals that are either electrical or optical, in proportion to the interactions between analytes and bioreceptors. The amplitude of the signal output is also proportional to the concentration of the analyte which is further amplified and processed by the electronic device. (Vidic 2017). The processed signal is then presented on a display unit, which interprets the data using an output device such as a computer or printer. This system generates output in a format that is readable and understandable by the user. Depending on the user's requirements, the output can take the form of numerical data, graphical representations, tabular values, or figures. Biosensors offer superior selectivity and sensitivity compared to other existing diagnostic tools (Sadanandom and Napier 2010).

**CLASSIFICATION OF BIOSENSORS**

Biosensors can be broadly categorized based on the type of bio-recognition element or the transducer utilized. When classified by the recognition element, biosensors include whole-cell sensors, enzyme sensors, nucleic acid sensors and immunosensors. Additionally, when classified by the transducer type, biosensors are divided into piezoelectric optical, and electrochemical sensors (Arora 2013; Srinivasan et al., 2015). It is grouped as enzyme sensors, immunosensors, nucleic acid sensors, and whole-cell sensors based on the recognition element, and they. are again categorised into optical, electrochemical, and piezoelectric biosensors based on the type of transducer used (Arora 2013; Srinivasan et al., 2015)

 For effective analyte detection, a bioreceptor must be activated to ensure its attachment to the transducer or electrode, allowing for specific interaction with the target analyte. Bioreceptors can include proteins (such as antibodies or enzymes) (Song et al. 2021), cellular materials (e.g., cells, tissue cultures) (Soleymani et al., 2018; 2021), nucleic acids (such as DNA or RNA) (Saadati et al., 2019) or nanomaterials (Zamora-Galvez et al., 2017). Strategy based on sensing, biosensors were identified as seven, major types to be utilized in plant pathology viz., optical sensors, piezoelectric sensors, electrochemical sensors, nucleic acid sensors, antibody sensors, phage based sensors, and e-nose (Akognullu and Denizli 2022). There is one novel category such as nano biosensors derived from nano materials (Sharifi et al., 2020).

**ELECTROCHEMICAL BIOSENSOR**

A chemical sensor perceives the information which is of chemical in nature and converts the concentration of a specific element or the overall composition of a sample, into a signal in measurable form (Thevenot et al., 2001). Electrical and electrochemical techniques are often favoured for plant disease monitoring due to their advantages over traditional methods. These techniques offer ease of use, high selectivity and sensitivity for detecting specific pathogens, and the potential to develop portable, commercial devices for real-time, on-site measurements (Khater et al., 2017; Khaled et al., 2018). Electrochemical ways for plant disease detection predominantly rely on biosensors for the recognition of pathogens (Martinelli et al., 2015).

Specifically, when biochemical reactions occur between a functionalized electrode and the analyte, electron transfer is generated. This transfer is detected and measured using methods such as amperometric, voltammetric, potentiometric, or impedimetric techniques. (Fang and Ramaswamy 2015). Amperometric biosensors measure the electric current generated from the binding event, while a voltage signal is generated by converting analyte biorecognition in the case of potentiometric biosensors. Impedimetric biosensors measure changes in impedance that occur when the analyte interacts with a specific antibody (Leonard et al., 2003). There are two primary components in an electrochemical biosensor viz., a molecular recognition layer and an electrochemical transducer. The transducer transforms biological information from a binding analyte into an electrical signal, which is then presented on a display device (Ronkainen et al., 2010). These sensors are capable of detecting pathogens in diverse conditions, such as air, water, and seeds. They are also versatile, making them suitable for various environments, including greenhouses, fields, and storage facilities. (Fang and Ramasamy 2015).

**DNA/RNA based biosensor**

 For the plant pathogens detection, DNA-based electrochemical sensors present, significant potential particularly for on-site environmental monitoring. These sensors, which detect specific DNA sequences, have applications in clinical diagnostics, environmental monitoring, horticulture, and food analysis. The primary advantage of DNA-based biosensors is their ability to detect at the molecular level, hence facilitating early disease detection, often before visible symptoms appear. They are extensively utilized for identifying fungi, bacteria, and genetically modified organisms. Usually, this method uses single-stranded DNA (ssDNA) probes on electrodes, with electroactive indicators detecting the hybridization between the probe DNA and its complementary target DNA (Eun and Wong 2000).

The core principle in the case of DNA-based biosensors is hybridization or the hydrogen bonding between the target DNA sequence and the immobilized DNA probe on the sensing platform. A probe is a specific DNA fragment designed to bind to a chromosomal region of interest. Although DNA-based biosensors can quantify pathogens even down.to a single cell, but it degrades rapidly in the environment thereby limiting its sensitivity (Xu et al., 2009). To enhance precision, nanostructured substances with excellent electronic or chemical properties such as silver, gold, or cadmium sulfide nanoparticles are used. These may act as substrates for the attachment of DNA and function by amplifying the signal, thereby increasing the quantity of immobilized DNA and significantly improving the diagnosis speed, accuracy, and sensitivity. Hybridization between the target and probe DNA is detected through electroactive indicators or by measuring the signal from electroactive DNA bases (Asal et al., 2018).

Over the decades, there has been significant growth in the use of electrochemical nucleic acid sensing in disease diagnosis. These sensors provide high sensitivity, cost-efficiency, and swift DNA analysis, effectively addressing the limitations of traditional techniques such as gel electrophoresis and membrane blots. (Liu et al., 2018). However, challenges remain, including selecting and synthesizing specific DNA probes and the difficulty in detecting short DNA sequences within long double-stranded DNA, which poses an obstacle in DNA detection using biosensing systems (Fang and Ramasamy 2015; Hushiarian et al., 2015).

A sensitive method to detect *Pseudomonas syringae* using a colloidal gold nanoparticle DNA probe combined with recombinase, polymerase amplification (RPA), and electrochemical detection via differential pulse voltammetry (DPV) was developed by Lau et al., (2017) The assay when applied to infected *Arabidopsis thaliana* samples, demonstrated high sensitivity and specificity, detecting pathogen DNA with a limit of 214 pM, which is 100 times more sensitive when compared to gel electrophoresis. The use of RPA allowed rapid DNA amplification within 60 minutes, significantly enhancing the assay's capability for early pathogen detection.

**Antibody-based biosensor**

This type of biosensor operates on the principle of coupling the transducer with the specific antibody. This configuration transforms the interaction between the antibody immobilized on the biosensor and the target analyte (such as the particular interest pathogen) into a measurable signal. Antibodies are anchored onto the electrode surface, where they selectively attach to the target analyte present in the sample material. This binding event alters the electrochemical properties of the system, with changes in current, voltage, or impedance being measured. The resulting signal is directly correlated with the concentration of the antigen (Wang et al., 2022). Although many antibody-based biosensors focus on specific binding to a particular antigen, measurement errors can arise due to environmental factors such as pH and temperature. Additionally, antibodies are sensitive and prone to denaturation, necessitating specific storage conditions to maintain their functionality; without proper conditions, the performance of antibody-based sensors can degrade over time (Byrne et al., 2009). However, DNA-based biosensors offer advantages, primarily related to superior sensitivity to their antibody-based counterparts.

Freitas et al., (2019) designed a biosensor for detecting the Citrus tristeza virus (CTV) capsid protein using a disposable microfluidic electrochemical device (DμFED) with gold nanoparticles (AuNPs), magnetic beads, and specific antibodies. The sandwich-type immunoassay is the principle followed here, where CTV capsid protein (CP-CTV) is captured by antibodies immobilized on a gold electrode, followed by detection with a secondary antibody conjugated to horseradish peroxidase (HRP), which catalyzes hydrogen peroxide reduction in the presence of hydroquinone, generating a current proportional to CP-CTV concentration. The readings were measured by differential pulse. voltammetry. This method demonstrated a broad linear range (1.95–10,000 fg/mL) and a detection, limit (0.3 fg/mL), with successful application to citrus samples and agreement with ELISA results.

**ELECTRONIC NOSE**

An electronic nose (e-nose) is a device built to detect flavors or odours by mimicking the human olfactory system. It comprises a signal collection unit, a sensing element, and an effective pattern recognition. Algorithm. The e-nose technique identifies volatile organic compounds (VOCs) released by isolated microorganisms, while indirect methods assess changes in VOCs emitted from infected plants inoculated with specific bacteria or fungi. By detecting gaseous emissions with abnormal VOCs from diseased host tissues in the sampled headspace, e-noses offer a non-invasive approach for identifying specific diseases associated with distinct combinations of volatile metabolites.

From both healthy and diseased plant samples, the database for the aroma specific to various plant samples is established from prior analyses of known clinical samples, often obtained from specific healthy or diseased plant parts (such as roots, stems, leaves, or flowers). Neural networking or similar training algorithms are used to create these databases. These databases include diagnostic patterns derived from the outputs of a multisensory array, forming a unique "smell print" pattern, with each sensor's response depicted in a bar graph. (Wilson et al., 2004). The strength of each sensor's response, depicted in the smell print pattern, reflects the combined effects of all VOC components in the sampled headspace E-nose training databases validation can be done using previously untrained samples is crucial to ensure that classification algorithms effectively discriminate between sample types (Li et al., 2009; Ghaffari et al., 2012).

The primary advantages of e-nose for early disease detection include non-invasive diagnostic sampling, the ability to assess large host samples, the detection of several diseases, adjustable detection levels through training, and targeted sensor array selection can be done for specific disease-related VOCs. Furthermore, various classes of pathogens can be identified using the same e-nose instrument by referencing different databases. (Cellini et al., 2017).

Markom et al., (2009) developed an e- nose (Cyranose 320) with artificial neural networks (ANN) to detect basal stem rot (BSR) disease caused by, *Ganoderma boninense* in oil palm trees. Odour samples were collected from healthy and infected trees at FELDA Besout plantation, Malaysia. The sample odour was collected from three points in the tree 1) the base of the trunk, 2) soil near the base, and 3) bored trunk. The collected odour sample was then compared with the existing smell print and identified. They have also determined that healthy and diseased samples exhibit different odour profiles.

Falasconi et al., (2005) utilized an electronic olfactory system (EOS835) to detect and classify toxigenic *Fusarium verticillioides* strains in maize based on fumonisin B1 production. Principal component analysis (PCA) was applied in initial experiments on cultured pathogen, while linear discriminant analysis (LDA) and k-nearest neighbours (kNN) were used for classification in harvested maize grains. The results demonstrated the e-nose's ability to differentiate between fumonisin-producing and non-producing strains, highlighting its potential as a rapid, cost-effective tool for detecting mycotoxin contamination in maize.

**PHAGE BASED SENSOR**

 Bacteriophages are viruses infecting bacteria which consist of a protein capsid that houses a RNA or DNA genome. It replicates within bacteria after infecting, ultimately lysing the host to propagate. Bacteriophages have been extensively studied and utilized in phage therapy for treating bacterial infections by targeting and lysing specific bacteria. Phage therapy has been applied for human as well as plant disease control. Besides phages for curing diseases, they are also emerging as a promising option for the detection of pathogens due to their high selectivity, sensitivity, superior thermostability, and low cost (Brigati and Petrenko 2005). The phage biosensor works by detecting the signal produced by the change in impedance of charge transfer reactions at the interface, caused by the interaction between the bacteriophage and the target analyte.

A bacteriophage-based biosensor for detecting *Pseudomonas cannabina* pv. *alisalensis*, the causal agent of bacterial blight in cruciferous plants, using a recombinant "light-tagged",reporter phage, PBSPCA1:luxAB was developed by Schofield et al. (2013). This phage assay detects the pathogen via bioluminescence by integrating the *luxAB* genes into the phage genome, relying on viable cells for signal production. The biosensor rapidly identifies the pathogen in plant samples within 20 minutes, enabling quick and specific disease diagnosis with a detection limit of 10³ CFU/mL.

**QUARTZ CRYSTAL MICROBALANCE (QCM) BASED BIOSENSORS**

The quartz crystal microbalance (QCM) biosensors are utilized for detecting plant diseases by coating a quartz crystal disc with antibodies specific to pathogens. These sensors consist of a thin quartz disc with plated electrodes. It works by generating an acoustic wave with a specific resonance frequency through the piezoelectric effect when an oscillating electric field is applied to the disc (Webster et al., 2004). The disc is coated with antibodies, nucleic acids, receptors, or small molecules, depending on the target analyte which forms a sensing layer, when the analyte accumulates on the disc's surface, it causes a change in mass, resulting in a change in resonance frequency. This change in the frequency can be directly proportional to the interaction of biomolecules. (Thies et al., 2017; Chen et al., 2018).

Singh et al., (2010) developed a QCM based biosensor to detect *Tilletia indica*, the causative agent of Karnal bunt, using a SPR or the surface plasmon resonance immunosensor approach. This method involves generating anti-teliospore antibodies that attach to the QCM plate, interacting with pathogen-specific antigens, leading to a measurable change in resonance frequency. The QCM immunosensor exhibited high sensitivity for *T. indica* detection, and for rapid on-site testing showing clear positive and negative results, a nano-gold-based lateral flow immuno-dipstick assay was also created. This system enables real-time monitoring and rapid diagnosis, aiding in seed certification and management of this quarantine pathogen.

**OPTICAL BIOSENSORS**

These are devices for detecting and measuring variations in the optical properties of a material and converting these changes into a measurable electronic signal. These biosensors measure the interaction between a target analyte and ligand. It consists of a light source, an optical transmission medium, an immobilized bio-recognition element, and a signal detection system. A change in the amplitude, frequency, and phase, of the given light in response to physicochemical conversion (change) generated by the bio-recognition process is observed. The sample analyte is measured by plotting a graph with incidence angle and reflectance the shift in the curve gives the concentration of the analyte in the sample (Ray et al., 2017). Among the optical biosensors created for plant pathogen detection, the most common types are colorimetric biosensors, surface plasmon resonance-based biosensors, and fluorescence-based assays (Yan et al., 2018).

1. **Colorimetric biosensors**

Colorimetric biosensors are devices designed for the quantitative and qualitative detection of analytes through colour variations that can be observed with the naked eye and the optical signals are measured using the photodetector. (Song et al., 2011). For immediate detection of pathogenic microorganisms in a small number of samples, this is the most widely used tool. The result can be obtained within l0-15 minutes via a colour change. This type of sensor is widely available on the market. There are two types of tests: flat-based and solution-based. The lateral flow assay, a widely used paper-based sensor in laboratories, is an affordable and easy-to-use tool for rapid diagnosis. It features a flat, colorimetric format and consists of four distinct pads. The first pad, made of cellulose, is where the sample containing the analyte is placed. The second pad, composed of glass fibre, is saturated with a bioconjugate solution. The third and fourth pads are the detection and absorption pads, where a test line and a control line are printed, respectively (Khater et al., 2017). In commercial lateral flow immunoassays as reported by Koczula and Gallotta (2016) colloidal gold is frequently used as a label due to its intense colour, which eliminates the need for additional visualization methods.

The advantages of this method include its operational simplicity, rapid result delivery, immediate point-of-care diagnosis, and minimal sample requirement. However, lateral flow immunoassays are not as accurate when compared to other nanotechnology-based techniques as reported by De Puig et al., (2017). This may be due to various potential inorganic-biological issues that can lead to the destruction of target analytes and non-specific adsorption.

The main applications in agriculture are they facilitate continuous monitoring of asymptomatic plants to prevent the spread of pathogens before visible symptoms appear. It can be integrated with disease forecasting systems to optimize spray events, reducing unnecessary pesticide use and improving crop management. This provides a portable tool for agricultural extension workers to assist farmers in diagnosing plant health issues on-site as it supports studies on host-pathogen interactions and the effectiveness of strategies related to disease management- in various environmental conditions.

1. **Surface plasmon resonance (spr) based biosensor**

 Liedberg et al., (1983) reported that surface plasmon resonance (SPR) is a highly sensitive technique which provide a high signal-to-noise ratio and excellent precision without the need for any labeling. Even, its use in biosensing began in the 1980s it has since been recognized as one of the most sensitive techniques available.

 It works on the principle that two surfaces with opposite dielectric properties generate a surface plasmon wave (SPW), typically one being a metal like gold and the other being silver. The principle of SPR detection is widely used in optical biosensors and enables to monitor the molecular interactions in real time. It measures changes in the surface refractive index on the surface that do not require the labelling of molecules and provides real-time data on biomolecular interactions on the surface. Apart from this, direct label-free detection of pathogens is also achievable (Skottrup et al., 2008). It consists of a sensor chip which is made of a glass surface coated with thin gold creating the necessary conditions for the SPR reaction. One molecule (ligand) is immobilized on the chip surface, while the other (analyte) is delivered via a microfluidic system. The polarized light is directed onto the underside of the chip, generating an electron charge density wave on the metallic film surface. This wave extends beyond the sensor surface and detects mass changes. As molecules bind to and dissociate from the chip surface, variations in the resonance signal occur, resulting in a sensorgram that is measured by a detection unit.

Vinusri (2016) developed gold nanorods (GNRs) based LSPR or a solution-phase lateral surface plasmon resonance biosensor for detecting Banana bunchy top virus (BBTV). GNRs synthesized via seed-mediated growth were functionalized by conjugating BBTV-specific antibodies, forming a GNR probe that interacts with BBTV antigens from infected banana samples. This interaction caused a noticeable colour change from pinkish-red to pale grey in infected samples, enabling visual detection for field applications. The LSPR-based GNR biosensor demonstrated higher sensitivity compared to ELISA, detecting BBTV antigens at 20 ppm, whereas ELISA detected them at 80 ppm.

**APPLICATIONS AND ADVANTAGES OF BIOSENSOR**

The biosensors are equipped for detecting and quantifying specific pathogens causing various diseases in plants on-site, which can be linked with global positioning systems (GPS) to enable precise, targeted pesticide applications, optimizing and reducing agrochemical use. Moreover, biosensors offer significant potential across various stages of the food production chain. This includes detecting pathogens in the seeds, identifying mycotoxins in storage facilities, and also pathogen detection at the ports of entry. Hence, developing biosensors that are specific and rapid has become a crucial research area, with plant pathogen biosensors being developed since 1992. (Skottrup et al., 2008). Key advantages of biosensors include their ability to perform rapid and continuous measurements, quick response times, the capability to measure non-polar molecules, reduced reagent use, no requirement for calibration or re-calibration, and high precision, which traditional devices cannot.

**LIMITATION OF BIOSENSORS**

While integrating biosensors into Integrated Disease Management (IDM) systems shows great potential, several challenges must be overcome to ensure their widespread adoption in agricultural and horticultural practices. This includes the need for thorough validation through agro-economic and agro-ecological modelling to confirm their relevance for specific crops, locations, and patho systems. An effective decision support system requires a thorough understanding of plant phenology, disease epidemiology, and pathogen biology. Additionally, detection and quantification of the pathogen need to be assessed in association with various factors residing in each farming system, including climatic conditions, cultural and cropping practices as well as current disease management strategies. Although microfluidics and biosensor platforms provide opportunities for on-site diagnosis, challenges like sample evaporation, limited reagent lifetimes, packaging and storage difficulties, weak selectivity in complex matrices, and high costs associated with detecting multiple pathogens per chip pose significant obstacles (Ruiz-Altisent et al., 2010; Dutse and Yusof 2011). Although progress in developing portable devices for identifying new pathogens has been slow (Boonham et al., 2008), ongoing advancements in nanotechnology and biosensor technology are expected to improve sensor sensitivity and address these challenges in the near future.

**CONCLUSION**

Traditional methods and diagnostic tools are rapidly replaced by bio-sensing technologies and devices. With continued optimization for diverse environments and fields, they can be made highly sensitive and swift, rapid in identifying the cause of plant disease malady enabling widespread adoption. Once validated, they could play a pivotal role in disease modelling, becoming an integral part of a proactive, preventive suite of Integrated Disease Management (IDM) strategies for growers and agronomists, helping to anticipate and mitigate epidemics. Their implementation would significantly diminish both pre- and post-harvest application of pesticides in terms of frequency and volume, thereby lowering production costs, hence preventing yield and quality losses due to biotic stress.

**FUTURE THRUST**

There is an imminent need for biosensors that are capable of simultaneous detection of multiple pathogens and they should be sensitive, portable, eco-friendly, cost-effective, and sustainable. Further research should aim to refine these biosensors for multiplexing, allowing the simultaneous detection and monitoring of pathogens capable to causing multiple infections. The emergence of technologies that can wirelessly and remotely sense, capture, and communicate data regarding the quantity and frequency of pathogenic organisms holds immense promise for the advancement of agriculture. These innovations can potentially revolutionize our monitoring and managing plant health, ensuring higher yields and more sustainable farming practices.

**Declarations**

 **Conflict of interest**

The authors declare that they have known competing financial interests or personal relationships that could have appeared to influence the review paper.

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