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Role of Nano-biosensor in Crop Health

Función del nanobiosensor en la salud de los cultivos

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ABSTRACT

Biosensors represent a powerful analytical technology that integrates biological sensing elements with physical or chemical transducers to detect and quantify diverse analytes. In agriculture, they play a pivotal role in plant protection by enabling early diagnosis of pathogens, pests, toxins, and environmental stressors, thereby supporting sustainable crop management. Advances in nanotechnology have led to the emergence of nano biosensors, which deliver superior sensitivity, selectivity, and rapid detection capabilities. Constructed from nanostructured materials such as carbon nanotubes, thin films, polymers, and metal nanoparticles, these devices provide high-throughput sensing with minimal resource requirements. Applications span from monitoring soil moisture and irrigation efficiency to detecting pollutants, pathogens, and stress responses in crops. Nanotechnology also extends to precision farming through nano-enabled fertilizers, which enhance nutrient uptake efficiency while reducing environmental contamination. Furthermore, nanomaterials improve seed germination, crop growth, and stress tolerance by boosting enzymatic activity, water absorption, and antioxidant defence systems. The integration of biosensors and nano-formulations has revolutionized approaches to disease detection, nutrient management, and environmental monitoring. Collectively, these innovations highlight the transformative potential of biosensors and nanotechnology in modern agriculture, offering cost-effective, scalable, and sustainable solutions to enhance productivity, safeguard ecosystems, and mitigate challenges posed by biotic and abiotic stresses.

Keywords: biosensor; nano-biosensor; nano-farming; pathogen biosensing; plant protection; transducers

RESUMEN

Los biosensores son tecnologías analíticas que integran elementos de reconocimiento biológico con transductores físicos o químicos para detectar y cuantificar diversos analitos. En la agricultura, facilitan el diagnóstico temprano de patógenos, plagas, toxinas y factores de estrés ambiental, contribuyendo a una gestión sostenible de los cultivos. Los avances en nanotecnología han impulsado el desarrollo de nanobiosensores con alta sensibilidad, selectividad y rapidez de respuesta. Fabricados con nanotubos de carbono, películas delgadas, polímeros y nanopartículas metálicas, estos dispositivos permiten un monitoreo preciso con bajo consumo de recursos. Sus aplicaciones abarcan el control de la humedad del suelo, la optimización del riego, la detección de contaminantes y enfermedades, y la evaluación de las respuestas fisiológicas de las plantas al estrés. Asimismo, la nanotecnología ha fortalecido la agricultura de precisión mediante nanofertilizantes que mejoran la absorción de nutrientes y reducen el impacto ambiental. Los nanomateriales también favorecen la germinación, el crecimiento vegetal y la tolerancia al estrés al incrementar la actividad enzimática, la absorción de agua y los mecanismos antioxidantes. En conjunto, la integración de biosensores y nanotecnología representa una estrategia innovadora para aumentar la productividad agrícola, optimizar el manejo de cultivos y promover sistemas producción eficientes, sostenibles y bajo costo.

Palabras claves: biosensor; nanobiosensor; nanoagricultura; biodetección de patógenos; protección vegetal; transductores

1. INTRODUCTION

Biosensors are analytical devices that combine a biological sensing element with a physical or chemical transducer to detect and quantify various substances. In plant protection, biosensors play a crucial role in monitoring plant health, detecting pathogens, pests, toxins, and environmental conditions, enabling early diagnosis and effective management of plant diseases (A. K. Srivastava et al., 2018; Turner, 2013).

A. Biological elements: In nano biosensors, biological components (bioreceptors) such as enzymes, antibodies, nucleic acids, cells, and tissues selectively identify analytes. Their sensitivity increases when paired with nanomaterials like carbon nanotubes, gold nanoparticles, or quantum dots (Chandrasekaran et al., 2020; Husen & Iqbal, 2019). This integration enables precise detection of infections, illnesses, and environmental contaminants. Table 1 illustrates the different types of bioreceptors employed in biosensors for plant protection, highlighting their role in detecting pathogens, toxins, and environmental stressors to support sustainable crop management.

Table 1. Different types of bioreceptors used in biosensors for plant protection

Bioreceptor Type	Description	Application in Plant Protection
Enzymes	Chemical actions are stimulated by biochemical catalysts.	Detect pesticide residues, toxins, and plant stress indicators.
Antibodies	Protein molecules bind to pathogens antigens.	Detection of Bacteria, Viruses, Fungi by antigen-antibody reactions.
Nucleic Acids (DNA/RNA)	Molecules carry genetic information.	Detect pathogen DNA/RNA, genetic modification, and plant diseases.
Whole Cells	Living cells capable of responding to environmental changes.	Monitor plant health, soil quality, and toxin presence.
Microorganisms	Small living organisms are used as biosensors.	Detect environmental contaminants, pathogens, and soil health.

Note. Adapted from Srivastava et al. (2018)

1. **Transducer (Physical Element):** Converts the biological response into a measurable signal.
2. **Signal Processor:** Converts the signal into a readable output.
   - Electronic display
   - Computer interface
3. **Data Analysis System:** Analyzes the data to detect the presence or concentration of the target analyte.

Applications for Biosensors in Plant Protection

- **Detection of Plant Pathogens:** Biosensors can detect harmful pathogens in plants or soil, allowing early intervention (Hariharan & Prasannath, 2021).
- **ELISA:** Antibody-based assays identify pathogen antigens; e.g., *Botrytis* grey mould detection (Byzova et al., 2018, 2020; Gascón et al., 1997).
- **PCR:** Amplifies DNA sequences for disease detection, such as *Xanthomonas citri* (Lau et al., 2016).
- **LAMP:** Provides rapid, isothermal DNA amplification (Lau et al., 2017).
- **Microfluidics:** Enables miniaturized biosensors for on-site diagnostics (Gruber et al., 2017).

- **LFIA:** Paper-based platforms for field detection of complex analytes (Panferov et al., 2021; Razo et al., 2018).
- **ddPCR:** Ultra-sensitive detection of single gene copies (Y. Wang et al., 2019).
- **MIP Biosensors:** Mimic biorecognition components for high sensitivity (Madianos et al., 2018).
- **Nanomaterial-based Biosensors:** Gold nanoparticles enhance detection, e.g., citrus tristeza virus (Khater et al., 2019; Lavanya & Arun, 2021).
- **Fluorescent Biosensors:** Fluorescent molecules detect pathogens (Marín Ortiz et al., 2023).
- **CRISPR-based Assays:** CRISPR-Cas systems enable rapid diagnostics (Hariharan & Prasannath, 2021).
- **DNA Biosensors:** Employ immobilized DNA probes or aptamers for pathogen detection (Pingarrón et al., 2008; Shabaninejad et al., 2019).

Advantages of DNA Biosensors:

- Rapid detection for timely diagnosis (Majumder & Johari, 2018).
- High sensitivity and specificity (Zhan et al., 2018).
- Portability and point-of-care testing (Naresh & Lee, 2021).
- Cost-effectiveness compared to conventional diagnostics (Virk et al., 2024).

B. Electrochemical Biosensor: Electrochemical biosensors integrate biological recognition elements with electrodes. Gold nanoparticles and other nanomaterials enhance sensitivity, e.g., citrus tristeza virus detection (Khater et al., 2019; Lei et al., 2021). To better understand the role of electrochemical biosensors in agriculture, Table 2 summarizes their key components along with descriptions and specific applications in plant protection.

Table 2. Components of Electrochemical Biosensors, Their Descriptions, and Applications in Plant Protection

Component	Description	Application in Plant Protection
Carbon-filled quartz micropipettes with platinum-coated tips	Provide a high surface area for signal detection.	Enhance signal sensitivity for pathogen or pesticide detection.
Bioreceptors coated/covalently bonded to transducer surfaces	Ensure specific binding to target molecules (pathogens, pesticides).	Enable targeted detection of plant diseases and contaminants.
Potentiometric Transducers	Measure voltage changes caused by biological reactions.	Detection concentration changes due to pathogen presence.
Impedimetric Transducers	Measure changes in electrical impedance.	Monitor plant stress, pathogen infection, or pesticide residue.
Amperometric Transducers	Measure electric current produced by biochemical reactions.	Detect specific chemicals or toxins in plant tissue or soil.
Capacitive Transducers	Measure changes in capacitance caused by molecular interactions.	Identify small changes in plant physiology or soil contaminants.

C. Optical Biosensors

Optical biosensors use light-based techniques to detect plant pathogens and monitor crop health. By measuring variations in absorption, reflection, or fluorescence, these sensors identify disease symptoms, nutrient deficiencies, or pesticide residues in real time (Bosch et al., 2007; Guo, 2012; Kumar et al., 2025).

Core Principle: A bioreceptor (e.g., antibody, enzyme) is integrated with an optical transducer to detect specific analytes such as pathogens or nutrients (Ligler, 2009; Uniyal et al., 2023).

Detection Methods

- **Surface Plasmon Resonance (SPR):** Detects refractive index changes at a metal surface, enabling label-free analyte detection (S. Das et al., 2021; Razmi et al., 2019).
- **Fluorescence:** Fluorescent dyes or molecules quantify analyte concentration based on intensity. Gold nanoparticle-based fluorescence assays have detected Begomoviruses and fungal spores (Lavanya & Arun, 2021; Lee et al., 2021).
- **Luminescence/Chemiluminescence:** Measures light emitted during chemical reactions (Calabretta et al., 2021).
- **Reflectance/Absorbance:** Tracks changes in reflected or absorbed light to indicate analyte levels (Marín Ortiz et al., 2023).

Applications in Crop Health

- **Disease Detection:** Optical biosensors identify pathogen biomarkers (Hariharan & Prasannath, 2021).
- **Nutrient Deficiency Detection:** Reflectance spectroscopy has been used to monitor nutrient uptake (Marín Ortiz et al., 2023).
- **Pesticide Residue Detection:** Optical nanobiosensors detect pesticide residues in crops and soil, ensuring food safety (Chaicham et al., 2019; Guan et al., 2021).

Advantages of Optical Biosensors

- High sensitivity and specificity at low concentrations (M. Li et al., 2024; Loiseau et al., 2019).
- Real-time monitoring capabilities (Srikrishna, 2024).
- Non-destructive testing for repeated measurements (Uniyal et al., 2023).
- Compact and portable designs for field use (Kumar et al., 2025)

Table 3. Components of Optical Biosensors, Their Descriptions, and Applications in Plant Protection

Components	Description	Application in Plant Protection
Optical Properties Measured	Wavelength, refractive index, intensity, polarization.	Detect changes in plant physiology, disease progression, or pesticide residue.
Labeled Detectors	Detect color changes or photon particle availability.	Identify pathogen presence or toxin levels.
Label-free Detectors	Convert biomolecular interactions into detectable signals without external markers.	Monitor plant stress, disease, or contamination without complex labeling.
Optical Nano sensors	Nanoscale sensors for detecting environmental changes (e.g., oxygen levels).	Monitor oxygen availability in plant roots, soil, and microenvironments.
PEBBLEs: Probes Encapsulated By Biologically Localised Embedding	Encapsulate fluorescent dyes within an inert matrix.	Provide high-sensitivity oxygen level monitoring in plants.
Clark-type Polarographic Electrodes (Traditional)	Measure oxygen by electrochemical reduction.	Traditional oxygen measurement method, less sensitive than nano sensors.

D. Thermal Biosensors

In crop health sciences, thermal biosensors use temperature-sensitive components, such as thermistors, to detect changes associated with plant health or disease by measuring heat produced or absorbed during biochemical activities (Ghodeswar et al., 2025).

Core Principle

- **Bio-recognition:** A biological component (enzyme, antibody, or microorganism) interacts with a target analyte such as pathogens, pesticides, or nutrients.
- **Signal Transduction:** This interaction triggers a biochemical reaction, releasing or absorbing heat.
- **Thermal Detection:** A thermal transducer (e.g., thermistor) detects the temperature change.
- **Signal Conversion:** The thermistor converts the temperature change into a measurable signal (C. K. Das et al., 2016; Najafi Disfani et al., 2017).

Types of Thermal Biosensors

- **Enzyme Thermistors (ETs):** Immobilize enzymes on thermistors to detect temperature changes during enzyme-catalyzed reactions (Ghormade et al., 2011).
- **Calorimetric Biosensors:** Measure heat released or absorbed during biochemical reactions using calorimeters (Gruber et al., 2017).

Applications in Crop Health Sciences

- **Pest and Pathogen Detection:** Thermal biosensors detect harmful organisms in crops (Imada et al., 2016).
- **Pesticide Residue Detection:** Used to monitor pesticide residues in crops and soil (Christopher et al., 2020).
- **Nutrient Monitoring:** Assess nutrient status for efficient fertilization (Marchiol et al., 2020).
- **Disease Diagnosis:** Enable early detection of plant diseases (Malandrakis et al., 2019).
- **Stress Detection:** Identify abiotic stress factors such as drought, salinity, and nutrient deficiency (Z. Li et al., 2021; Rizwan et al., 2019).

Advantages

- Real-time monitoring of crop health (Ghodeswar et al., 2025).
- High sensitivity to subtle biochemical changes (Pasinszki & Krebsz, 2020).
- Non-destructive testing of plant tissue (Uniyal et al., 2023).
- Versatility across multiple analytes and applications (Naresh & Lee, 2021).

E. Piezoelectric Biosensors

Piezoelectric biosensors measure mechanical changes, such as variations in resonance frequency caused by analyte binding, which are then converted into electrical signals. These devices are highly sensitive for detecting biological compounds relevant to crop health (Skládal, 2024; Zhan et al., 2018).

Piezoelectric Effect: Piezoelectric materials, such as quartz crystals, generate an electric charge when subjected to mechanical stress. In biosensors, this property is harnessed to detect analyte binding events (Razmi et al., 2019).

Functions: A piezoelectric crystal serves as a transducer, converting mechanical changes from analyte–bioreceptor interactions into electrical signals (Majumder & Johari, 2018).

Analyte Binding and Frequency Shift: Target molecules binding to bioreceptors cause mass variations or surface deformations, altering the crystal's resonance frequency. These shifts are detected electronically and correlated with analyte concentration (Razo et al., 2019).

Applications in Crop Health

- **Pesticide Detection:** Piezoelectric biosensors detect pesticide residues in soil and water (Bala et al., 2017; Guan et al., 2021).
- **Pathogen Detection:** Early identification of bacteria and fungi causing plant diseases (Lavanya & Arun, 2021; Lee et al., 2021).
- **Metabolite Monitoring:** Track metabolite concentrations in plant tissues to assess stress responses (Z. Li et al., 2021)
- **Mycotoxin Detection:** Identify fungal toxins such as aflatoxins in stored grains (Panferov et al., 2021).
- **Soil Quality Monitoring:** Measure nutrients, pH, and moisture for optimal growth (Marchiol et al., 2020).
- **Pest Monitoring:** Detect volatile organic compounds (VOCs) released by plants under insect attack (Bushdid et al., 2014).

Quality of Biosensors

- High precision to distinguish analytes from background materials.
- Stability under standard storage conditions.
- Independence from physical conditions such as stirring, pH, and temperature.
- Minimal reaction time for rapid detection (Naresh & Lee, 2021).

Table 4. Components of Piezoelectric Biosensors, Their Descriptions, and Applications in Plant Protection

Component	Description	Application in Plant Protection
Piezoelectric Effect	Conversion of mechanical oscillations to electrical signals.	Detect affinity interactions in plant tissues (e.g., pathogen binding).
Electrodes on Crystal Surface	Apply alternating voltage to generate oscillations.	Enable detection of pathogen interaction with plant cells.
Frequency Shift Measurement	Frequency changes proportionally with analyte concentration.	Quantify pathogen load or pesticide contamination.
Quartz Crystal Microbalance (QCM)	Measures minute mass changes by detecting frequency shifts.	Detect microbial infection, plant stress, or contamination.
Label-free Detection	No need for fluorescent or color-based labeling.	Direct detection of biological interactions in plants.
High Sensitivity and Real-time Monitoring	Provides real-time data on binding interactions.	Rapid detection of disease or harmful chemical presence.

Note: Adapted from (Razmi et al., 2019; Skládal, 2024; Zhan et al., 2018)

F. Electrochemical Biosensors

Electrochemical biosensors are widely used in agriculture due to their high sensitivity, low cost, and rapid detection capabilities. They consist of a reference electrode, counter electrode, and working electrode. Techniques such as electrochemical impedance spectroscopy (EIS), electrochemiluminescence (ECL), and voltammetry are employed to detect target analytes, producing quantifiable signals based on current, potential, and impedance (Malhotra & Ali, 2018; Ronkainen et al., 2010).

Biosensors for Enzymes

Enzymes are essential in biosensing applications due to their catalytic activity and substrate specificity. Immobilization techniques — including self-assembled monolayers, covalent bonding, adsorption, cross-linking, and entrapment — enhance enzyme stability and reusability (C. K. Das et al., 2016; G. Srivastava et al., 2014). Covalent bonding provides strong attachment and multipotent activity.

Immunosensors

Immunoassays are crucial analytical techniques for quantifying analytes. They use biological recognition probes such as aptamers, peptides, and antibodies coupled with nanoparticles, detecting signals to quantify analyte concentration. Gold nanoparticles are the most common labels, enhancing sensitivity and specificity (Khater et al., 2019; Lavanya & Arun, 2021; Lee et al., 2021).

DNA Sensors

AuNP-labeled DNA probes are commonly used for biosensing plant pathogens, providing high specificity and rapid signal production. These electrochemical DNA biosensors are advantageous due to their low cost, sensitivity, and ability to immobilize DNA on electrode surfaces (Pingarrón et al., 2008; Shabaninejad et al., 2019). Recent advances include microcantilever sensors enhanced with gold nanoparticles for ultrasensitive detection (Lei et al., 2021).

Applications: Electrochemical biosensors are applied across multiple domains such as

- **Food Safety:** Detection of microbial pathogens and contaminants (Bhardwaj et al., 2017).
- **Environmental Monitoring:** Detection of pollutants in water and soil (Ikram et al., 2019; Tian et al., 2018).
- **Healthcare:** Biomarker detection for disease diagnosis (Sage et al., 2014).
- **Agriculture:** Pathogen detection and pesticide residue monitoring (Christopher et al., 2020; Guan et al., 2021).

G. Transducers

Transducers are the core components of biosensors, responsible for converting biological or chemical signals into measurable outputs. Optical transducers such as surface plasmon resonance, fluorescence, and bioluminescence detect changes in refractive index and light intensity, offering sensitive and non-destructive monitoring (Ge et al., 2014; Ligler, 2009). Electrochemical transducers employ electrodes to measure electrical changes in biological samples, including potentiometric, amperometric, and impedimetric responses (Pingarrón et al., 2008; M. Wang et al., 2014). Piezoelectric transducers, like quartz crystal microbalance sensors, generate electrical signals under mechanical stress (Ariffin et al., 2013). Thermal transducers detect temperature variations in biological reactions (Huang et al., 2021), while magnetic transducers utilize magnetoresistive and magnetic particle detection systems to sense changes in magnetic fields (LaConte et al., 2005). Together, these diverse transducer types provide a versatile toolkit for biosensing applications in medical diagnostics, environmental monitoring, and agricultural biotechnology.

Parts of a Transducer

- **Sensing Element** This is the portion of a transducer that reacts to sensory inputs. The sensing element’s response depends on the physical phenomenon being measured.
- **Transduction Element** The transduction element of the receiver converts the sensing element’s output into an electrical signal. It is also known as the secondary transducer.

- **Types of Transducers** Transducers frequently used in biosensors include electrochemical, optical, piezoelectric, gravimetric, conductimetric, magnetic, and thermal types. The choice of transducer depends on the analyte being detected and the intended signal conversion mechanism (Ligler, 2009; Turner, 2013).
- **Optical Transducers** Optical biosensors such as surface plasmon resonance (SPR), fluorescence, and bioluminescence detect changes in surface refractive index and light intensity. They are sensitive, selective, and non-destructive, making them ideal for real-time monitoring and in-field applications in medical diagnostics, environmental monitoring, and food safety (Ge et al., 2014; Ligler, 2009).
- **Electrochemical Transducers** These sensors use electrodes to detect and measure changes in the electrical characteristics of biological samples. Examples include potentiometric, amperometric, and impedimetric biosensors (Pingarrón et al., 2008; M. Wang et al., 2014).
- **Piezoelectric Transducers** Quartz crystal microbalance (QCM) biosensors use crystals to produce electrical signals under mechanical stress (Ariffin et al., 2013).
- **Thermal Transducers** Thermometric and calorimetric biosensors utilize temperature variations to detect and measure changes in biological samples (Huang et al., 2021).
- **Magnetic Transducers** Magnetoresistive and magnetic particle detection biosensors rely on variations in magnetic fields to detect and measure changes in biological samples (LaConte et al., 2005).
- **Detectors** Antibiotic discovery has helped manage bacterial infections, but improper handling has led to multi-resistant microorganisms. Over 70% of bacteria are resistant to current drugs, requiring novel or toxic treatments (Sharma et al., 2020). Without new substances, antimicrobial drug-resistant diseases could kill 10 million people annually and cost $100 trillion by 2050 (Thundiyil, 2008).
- **Gold Nanoparticle-Based Biosensors** AuNPs are widely used in chemical and biological sensing systems for diagnostics, biomarkers, and other analytes due to their superior properties and ease of production (Turkevich et al., 1951). They can be synthesized using techniques such as chemical and photochemical reduction, seed-mediated growth, and green synthesis. Popular reactions include the Brust-Schiffrin and Turkevich-Frens methods (Charbgoo et al., 2018; Pingarrón et al., 2008).

H. Electrochemistry in Biosensors

Electrochemical detection techniques are highly sensitive, low-cost, and fast. They consist of a reference electrode, counter electrode, and working electrode. Methods such as EIS, ECL, and voltammetry are used to detect target analytes, producing quantifiable signals based on current, potential, and impedance (Naresh & Lee, 2021; Rhouati et al., 2018).

Biosensors for Enzymes

Enzymes are essential in biological applications due to their catalytic activity and substrate sensitivity. Immobilization techniques such as self-assembled monolayers, covalent bonding, adsorption, cross-linking, and entrapment enhance stability and reusability. Covalent bonding provides high strength and multipoint attachment (Majdinasab et al., 2017).

Immunosensors

Immunoassays are crucial analytical techniques for quantifying analytes. They use biological recognition probes such as aptamers, peptides, and antibodies coupled with nanoparticles. AuNPs are the most commonly used labels (Khater et al., 2019; L. Wang et al., 2017).

DNA Sensors

AuNP-labeled DNA probes are widely used for biosensing plant pathogens, offering high specificity and rapid signal production. Electrochemical DNA biosensors are advantageous due to their low cost, sensitivity, and ability to immobilize DNA on electrode surfaces (Pingarrón et al., 2008; Zhan et al., 2018).

Applications

- Biosensors are receptor–transducer systems engineered to sense the physical and chemical features of an environment in order to identify or detect a specific biological analyte.
- Nanobiosensors are newly developed biosensors that are more compact and coupled to sensitive elements, enabling detection of specific analytes at very low concentrations using physicochemical transducers.
- Nanosensors are used to detect food contamination caused by microorganisms, hazardous chemicals, and pesticides. Nanoparticles (NPs) have demonstrated effectiveness as biosensors due to their high specific surface area, which allows immobilization of a greater number of bioreceptor units. Gold NPs are the most widely used noble metal nanoparticles (Nsibande & Forbes, 2016).
- Gold nanoparticles have also shown significant promise as biocatalysts employing surface plasmon resonance transduction (Qu et al., 2009; QU et al., 2008).
- Due to their large surface area and small particle size, NP-based nanosensors provide considerable benefits in terms of catalytic and sensing response, as well as improved optical, magnetic, and electrical properties.
- These advantages make them superior to microscale materials in biological and biomedical applications.
- Noble metal NPs, such as platinum and palladium biometallic alloys, as well as core–shell NPs, have predominantly been used in the production of electrochemical sensors and for in vivo and in vitro biomedical analyses. Their performance is highly dependent on particle size and shape.
- Silver nanoparticles have been used for nearly two decades in the development of analytical procedures for a variety of analytes, including disease indicators, biological and infectious agents, and for the early identification of diseases (Pallavi et al., 2016).
- Nanosensors applied to soil moisture monitoring combine biology, chemistry, and nanotechnology, and are sometimes referred to as nanobiosensors. They can detect gases, odors, chemical pollutants, infections, and even changes in ambient conditions. Soil moisture sensors (SMS) have numerous applications, primarily in agriculture. Detecting soil moisture levels and managing irrigation systems can prevent significant water and human resource waste. These sensors facilitate agricultural automation and are also employed in controlled environments (Z. Li et al., 2021).
- Biosensors are used to detect pollutants such as heavy metals, pesticides, and organic chemicals in the environment. They can also identify harmful algal blooms and monitor water quality (R. Singh et al., 2011; Valko et al., 2005; Yadav, 2010).

- Biosensors have been applied in biosecurity for detecting biological agents such as bacteria, viruses, and toxins. They can monitor food and water supplies, as well as air quality in public spaces (Zhao et al., 2014).
- They are mainly used for identifying diseases and monitoring the health of livestock and crops. They can also monitor soil quality and detect hazardous pollutants (Z. Iqbal et al., 2018).
- Biosensors have applications in industrial processes, including fermentation, bioreactors, and bioprocessing. They are also used to ensure food and beverage quality and safety (Marchiol et al., 2020).
- Adenosine triphosphate (ATP) is a crucial energy source in living cells, synthesized in chloroplasts and mitochondria in plants. A decrease in cytoplasmic ATP levels was detected with oligomycin A, and ATP production in chloroplasts during photosynthesis was visualized in transgenic *Arabidopsis* plants (Berger et al., 2007).
- Calcium plays a vital role in signal transduction pathways in plants, affecting stomatal closure, cellular division, and cell signaling. It reverses concentration gradients, causing cell flaccidity. FRET-based sensors enable high-resolution live-cell imaging of Ca^{2+} dynamics, revealing distinct Nod factor-induced Ca^{2+} spiking patterns in *Lotus japonicus* (Yang et al., 2007).
- Nanosensors detect reactive oxygen species (ROS) in plants, including superoxide anion, singlet oxygen, hydroxyl radical, and hydrogen peroxide. These ROS are involved in plant development, cell death, and stress responses. Genetically encoded single-fluorescent protein sensors and extrinsic sensors can measure ROS and redox potentials. Real-time monitoring of oxidative bursts from single plant protoplasts has been achieved using platinum nanoparticles (Husen & Siddiqi, 2014b).
- Nitric oxide, a reactive nitrogen species, regulates plant physiological activities such as seed germination, senescence, and programmed cell death, and responds to both biotic and abiotic stresses (Ghormade et al., 2011).
- Nanosensors can detect plant hormones such as strigolactones, ethylene, and auxin, which are crucial signaling molecules in plant growth, development, reproduction, and stress tolerance. Fruit perishability is a major supply chain issue, causing significant waste. Manipulating ethylene concentration can regulate climacteric fruit ripening, extending shelf life and ensuring maturity at harvest (Z. Li et al., 2021).
- Molecular oxygen, a terminal electron acceptor in the electron transport chain, is produced by plants, algae, and photosynthetic bacteria through photolysis, a light-dependent reaction. Clark-type polarographic electrode sensors have been used in oxygen sensing to detect current flow from oxygen reduction, enabling the determination of photosynthesis and respiration rates in potato leaf protoplasts (Ligler, 2009).

Types

1. Carbon nanoparticle-based nanobiosensors (Husen & Siddiqi, 2014a)
2. Layered carbon tube-based nanobiosensors
3. Gold/silver/magnetic-based nanobiosensors (LaConte et al., 2005; Vanti et al., 2019)
4. Lipid biomembrane/nitrocellulose-based nanobiosensors (Ozansoy Kasap, 2018)

Agricultural Waste as a Source of Nanobiosensors

Agricultural waste is abundant in the environment and offers a low-cost option for developing new nanobiosensor materials. Nanocellulose fibers have been developed for several applications (Esyanti et al., 2019; Shenashen et al., 2017). Rice husk, a byproduct of rice milling, can also be utilized to make nanobiosensors (Latif et al., 2020). Silica present in rice husks can be extracted and used for further beneficial purposes. Table 5 presents an overview of nano biosensors, the nanomaterials used in their construction, and their diverse applications across plant protection and agricultural sustainability.

Table 5. Nano biosensors, nanomaterials and their applications in various aspects

Nano biosensors	Nanomaterials	Sensor type	Applications	References
Quantum dot nano sensor	Gold particles	Immunobased sensor	Detection of mycotoxins ZEA, DON, FB1/FB2 in corn oats and barley	(Qu et al., 2009; QU et al., 2008)
QD nano sensor	Quantum dots	Fluorescence	Detection of pathogens (Phytoplasma aurantifolia)	(Nsibande & Forbes, 2016)
DNA nano biosensor	Carbon nanotubes	Immunosensor	Ganoderma boninse for infection of palm oil tree	(Ghormade et al., 2011; Husen & Iqbal, 2019)
Surface plasmon resonance	Multiwalled carbon nanotubes	SPR	Detection of Cymbidium Mosaic virus	(Khater et al., 2019; Ligler, 2009)
Artificial nose	Carbon nanomaterials	Volatile organic compound profile	Detection of pathogens depending on the organic compounds released	(Verma et al., 2014, 2016)
AChE biosensor	Single and Multiwalled carbon nanotubes	Electrochemical	Detection of pesticides methyl parathion, parathion and paraoxan	(Rhouati et al., 2018; Yetim et al., 2020)
	DNA based biosensor	Electrochemical	Detection of Phytophthora pulmivora causing black pod rot in cacao pod	(Zhan et al., 2018; Zhang et al., 2013)
	Calcium phosphate	Analytical devices	hydroxyapatite, dicalcium phosphate dihydrate	(Latif et al., 2020; Pasinszki & Krebsz, 2020)

I. **Nano biosensors**

A nano biosensor is a small analytical sensor device or system that detects the presence or amount of an analyte at the nanoscale connected to a physicochemical transmitter, containing a chemical or biological sensitized material (Huang et al., 2021). It has potential in agriculture due to its superior selectivity, speed, and sensitivity. A nano sensor is a sensor that directly measures the analyte in a sample (Naresh & Lee, 2021). It can also refer to a device capable of identifying and measuring the precise amount of analyte contained in each sample. Ideally, such a device should be capable of generating a continuous and reversible reaction while causing minimal damage to the sample (Lin et al., 2020). Nanotechnology focuses on developing nano biosensors with infinitesimal dimensions, enabling the detection of soil moisture and managing irrigation systems to prevent water and human resource waste, utilizing advanced sensing capabilities to the extent of 10^{-9} accuracy (Z. Li et al., 2021).

Nano-enabled technology could revolutionize farming practices by increasing input efficiency, decreasing losses, and fostering sustainable agriculture (S. Singh et al., 2021; Usman et al., 2020). Two fascinating applications of nanotechnology in agriculture are nano biosensors and nano formulations (NFs). Nanostructured materials like nanoscale wires, CNTs, nano-sized thin films, polymers, and biomaterials are utilised in the construction of nano sensor devices for high detection sensitivity (Husen & Iqbal, 2019). Metal nanoparticles (mNPs) are ideal for developing advanced sensing devices like electrochemical sensors and biosensors, acting as analytical sensors and signal amplifiers due to their physical and chemical properties (Pingarrón et al., 2008; Qu et al., 2009). High-throughput sensing principles enable bioassays with rapid reactions and low-resource environments, while mNPs create cost-effective, easy-to-implement colorimetric sensing arrays. Biosensors based on predictable color changes detect alpha-1-fetoprotein, antibodies, breast cancer biomarkers, DNA, toxic metal pollutants, and pesticides (Khater et al., 2019; M. Wang et al., 2014). Silver nanoparticles have been used in polymers for nitrobenzene detection, with a detection limit of 1.68 mM and sensitivity of 7.88 M A, with low interference (Pallavi et al., 2016; Vanti et al., 2019).

Nano biosensors can detect gases, odors, chemical pollutants, microorganism infections, and environmental changes, combining biology, chemistry, and nanotechnology (Ge et al., 2014; Nsibande & Forbes, 2016). Nano biosensors enable early detection of diseases, pests, and pathogens, reducing crop losses and enabling timely response in precision farming techniques and resource optimization (Z. Iqbal et al., 2018; Zhan et al., 2018).

Plant sensors detect H_2O_2 signals on leaves, activating cells to create compounds to protect against predators, while nano sensors detect changes in conductance (Husen & Siddiqi, 2014a; Yang et al., 2007). Nano biosensors enable early detection of diseases, pests, and pathogens, reducing crop losses and enabling prompt response (Z. Iqbal et al., 2018; Zhan et al., 2018). They enable precision farming techniques and resource optimization, allowing farmers to optimize resources, minimize environmental impact, and maximize crop growth (S. Singh et al., 2021; Usman et al., 2020).

Sensor component nanoparticles were also identified against fenitrothion, organophosphate, methyl parathion, chlorpyrifos, volatile substances, and urea/urease (Rhouati et al., 2018; J. Wang et al., 2016; M. Wang et al., 2014; Yetim et al., 2020). Table 6 provides an overview of nano biosensors designed for identifying pesticides and fertilizers, highlighting the nanomaterials employed and their applications in plant protection.

Table 6. Overview of nano biosensors for identifying pesticides and fertilizers

Target	Sensor component	Detection mechanism	Sensitivity
Fenitrothion	Nano TiO2/nafion composite	Electrochemistry	0.2 mM
Organophosphate-based pesticides	Carbon nanotubes	Electrochemistry	0.145 ppb
Methyl parathion and chlorpyrifos	Carbon nanotubes wrapped by ssDNA1	Enzymatic reaction	1 × 10−12 M
Volatile substances	Multidimensional carbon nanostructures	Radio frequency	5 ppm
Urea, urease	Gold nanoparticles	Colorimetry	5 mM, 1.8 U/L

J. Crop detection problems

Tree diversity and distribution are significantly impacted by pathogens, affecting ecosystems and crop production. Monitoring the health of various biopathogens, including bacteria, viruses, and oomycetes, is crucial (Boa, 2003; Manion, 1991; Parthasarathy et al., 2021).

Fungi cause plant diseases, including foliar and root rot, leaf spots, rusts, scorch, blotches, anthracnose, and needle blights, with small fruiting bodies indicating their presence (Berger et al., 2007; Kainthola et al., 2022). *Fusarium, Ganoderma, Rhizoctonia, Melampsora, Erysiphe, Armillaria*, and others are important examples of fungal infections on trees (Ghormade et al., 2011; Husen & Iqbal, 2019). Anthracnose, a disease causing yellowing leaves in plants, is often associated with powdery mildew and rust (Silva et al., 2019; S. Singh et al., 2021).

Smart farming uses advanced technologies like drones and real-time information to prevent early diseases and compensate for nutritional or water deficits, saving money and the environment (Z. Li et al., 2021; Usman et al., 2020), Table 7 provides an overview of nanobiosensors developed for identifying plant diseases, emphasizing the nanomaterials employed and their applications in crop health monitoring and protection.

Table 7. Overview of nanobiosensors for identifying plant diseases

Target	Sensor component	Detection mechanism	Sensitivity
Rolstonia solanacearum	Au NPs2 functionalised with ssDNA	Colorimetry	15 ng
Psuedomonasstewartii sub sp. *stewartii*	Au NPs	Electrochemistry	7.8 × 103 cfu/ml
Phytophthora ramorum	Ag NPs	SERS3	N/A
Trichoderma harzianum	ZnO NPs–chitosan nanocomposite	Electrochemistry	1.0 × 10−19 mol L−1
Citrus tristeza	CdTe QD4 -Rd	FRET5	220 ng ml−1

Crop protection and production

Erwinia, *Xanthomonas*, and *Ralstonia* are the primary causes of common bacterial diseases that affect trees, such as shot holes, foliar blight, and wilt (Khater et al., 2019; L. Wang et al., 2017). Common root and foliar diseases in nursery plants, such as blight, vascular wilt, root rot, set rot, and web blight, offer potential for disease biosensing using nano sensors (Z. Iqbal et al., 2018; Zhan et al., 2018). *Fusarium*, *Ganoderma*, *Rhizoctonia*, *Melampsora*, *Erysiphe*, *Armillaria*, and others are important examples of fungal infections on trees (Ghormade et al., 2011; Husen & Iqbal, 2019; Kainthola et al., 2022).

Anthracnose, a disease causing dark reddish sores on fruits, stems, foliage, and flowers, is primarily found in shaded, high humidity areas (Boa, 2003; Parthasarathy et al., 2021). Powdery mildew and rust fungi cause yellow patches on hardwood species' leaves (Silva et al., 2019; S. Singh et al., 2021).

Protection from degrading factors such as soil pH, light, temperature, and bacteria by encasing the product in a nanocapsule offers a protective layer that stops the active ingredient from deteriorating, enabling a decrease in the effective applied dose (Marchiol et al., 2020; Moreno et al., 2019). Natural agrochemicals, less persistent and easily disintegrated, are being used, but their use is hindered by degradation and environmental threats. Pesticide contamination of surface and ground water reduces freshwater volume suitable for human consumption (Shabaninejad et al., 2019; Silva et al., 2019). Nanotechnology can enhance the effectiveness and safety of treatments using nanoparticles in agriculture, although it also has its drawbacks (S. Singh et al., 2021; Usman et al., 2020).

K. Pathogen Biosensing: Biosensors enable the swift identification of plant quarantine pathogens, potentially preventing the introduction of exotic infections into newly developed ecosystems (Ligler, 2009; Naresh & Lee, 2021). AuNPs have been created as a diagnostic tool and are frequently used to identify antibodies specific to target infections (Khater et al., 2019; Pingarrón et al., 2008).

a) Bacterial Pathogen Detection Bacterial pathogens can be identified by capturing the entire bacterium or its unique DNA sequence, using a sensitive and disease-specific DNA probe. Colloidal AuNPs were employed to mark individuals (Zhan et al., 2018; Zhang et al., 2013).

A strip-based DNA sensor and stranded DNA (ssDNA) probes tailored to the bacterial fruit blotch-causing pathogen *Acidovorax avenae* subspecies *citrulli* were designed using the internal transcribed spacer (ITS) region to quickly and on-site identify the presence of the pathogen. 4 nM of target DNA may be qualitatively detected using this dipstick approach due to its high sensitivity. Analyzing optical density and target DNA concentration also made semi-quantitative detection feasible, with a limit of detection (LOD) of 0.48 (Y. Wang et al., 2019; Zhou et al., 2015).

1. Surface-based detection is a practical method for detecting chemical or biological molecules with great accuracy, sensitivity, and specificity, such as Raman scattering (SERS) (B.-B. Li et al., 2014; M. Li et al., 2013).
2. To identify *Pseudomonas syringae* in tomatoes and *Arabidopsis thaliana*, Lau et al. (2017) created a multiplex point-of-care system Turner (2013).
3. AuNP-labeled DNA probes were used for colorimetric detection of pathogen DNA molecules, including *Pseudomonas syringae* pathovars and *Ralstonia solanacearum* soil bacterium. The assay uses hybridization of AuNP-bound probes with target DNA, preventing aggregation in acidic conditions. This quick, sensitive, and specific nano-biosensor detects *R. solanacearum* directly from soil samples without DNA amplification procedures (Khater et al., 2019; L. Wang et al., 2017). Table 8 outlines the different sensing approaches and nanomaterials employed for plant bacteria detection, emphasizing their role in enhancing diagnostic accuracy and supporting effective plant protection strategies.

Table 8. Different sensing approaches and nanomaterials used for plant bacteria detection

Plant Disease/Pathogen	Species	Nanomaterial Used	Sensing Method	LOD
Xanthomonas axonopodis	Solanaceae plant	Fluorescence silica nanoparticles	Fluorescence-linked immunosorbent assay	NA
Ralstonia solanacearum	Potato Brown Rot	Potato Enlarging AuNPs	Lateral flow immunoassay	3 × 104 cells/mL
Acidovoraxavenae sub sp. *citrulli*	Fruits	Colloidal gold nanoparticles	Dipstick method	0.48 nM of DNA

b) Detection of Fungal Pathogens Fungi can cause plant growth illnesses under normal conditions, either alone or in combination with other phytopathogens. For example, the hemi-biotrophic fungus *Pseudocercospora fijiensis* in banana plantations worldwide causes black sigatoka. It is critical to identify this fungal infection to reduce losses and stop it from spreading to nearby cultures. A very specific SPR immunosensor was created to combat this infection. Moreno et al. (2019) reported that a polyclonal antibody (anti-HF; produced against the HF1 cell wall protein of *P. fijiensis*) was covalently immobilized on an Au-coated chip to build the sensor by combining a mixed Self-Assembled Monolayer (SAM) of alkanethiols.

Lee et al. (2021) developed a technique for *Aspergillus niger* spore identification using specific peptides as a recognition probe and AuNPs as the detection label. The peptides enable rapid attachment to the *A. niger* spore, resulting in a noticeable change in the supernatant's color intensity after spore sedimentation (Khater et al., 2019; Pingarrón et al., 2008).

The most common diseases caused by pathogenic fungi include anthracnose, blight, canker, damping off, dieback, gall, leaf spot, powdery mildew, rust, root rot, scab, and wilt (Boa, 2003; Parthasarathy et al., 2021; Silva et al., 2019). Numerous traditional techniques, including nested PCR, multiplex PCR, quantitative PCR, magnetic-capture hybridization PCR, and loop-mediated isothermal amplification (LAMP), have been employed for fungal pathogen detection (Husen & Iqbal, 2019; Z. Iqbal et al., 2018).

Phytophthora infestans can be visually identified using AuNP-based lateral flow assays (LFA) and universal primer-mediated asymmetric PCR. The accumulation of AuNPs and sandwich-type hybridization reactions between the AuNP–probe, target DNA, and capture probe in the presence of target DNA produced a visible red line on the LFA test strip (Marchiol et al., 2020; Zhan et al., 2018).

c) Detection of Viruses Wang et al. developed a simple, sensitive colorimetric detection method for the *Cucumber green mottle mosaic virus* (CGMMV), highlighting the importance of early diagnosis (L. Wang et al., 2017). Localized surface plasmon resonance (LSPR) is being used to develop colorimetric biosensing methods, with size, shape, and surrounding medium affecting LSPR (B.-B. Li et al., 2014; M. Li et al., 2013). Razmi et al. (2019) used LSPR to identify the genome of TYLCV in infected plants.

UV-Vis spectroscopy confirmed the color shift caused by AuNPs as a clear indication of virus infection. A similar method was developed for begomoviruses in tomato and chili plants. An upgraded AuNP-based dot immunobinding assay (DIBA) was used to detect *Banana bunchy top virus* (BBTV) (Zhang et al., 2013). The use of lateral flow assay (LFA) and immunochromatographic assay (ICA) for pathogen and biomarker identification has become widespread (Zhan et al., 2018; Zhou et al., 2015).

Byzova et al. (2018, 2020) created an ICA based on the sandwich immunoassay format for the quick detection of GLRaV-3. The sensitivity and limit of detection problems of the LFA using AuNPs can happen on occasion. Signal augmentation techniques have been used to increase sensitivity in plant virus detection. A silver enhancement technique was applied to detect *Potato leaf roll virus* (PLRV) (Panferov et al., 2021).

Electrochemical immunosensors using AuNPs allow for the creation of label-free tests, which are simpler and need less analysis time than labelled techniques. Khater et al. (2019) developed a label-free impedimetric biosensor for *Citrus tristeza virus* detection using screen-printed carbon electrodes and AuNPs. Wang et al. (2019) developed a nicking/polymerization technique for ultrasensitive electrochemical detection of *Watermelon mosaic virus* (WMV) using T4 DNA polymerase activity and Mg^{2+}-dependent techniques.

Nano sensors are also being developed for pesticide detection, as organophosphate pesticides accumulate in animals and block enzymes, posing health concerns (Rhouati et al., 2018; Yetim et al., 2020). Optical probes include fluorescence, colorimetry, SERS, and SPR. Immunochromatographic strip (ICTS) nano sensors are used in point-of-care analytical devices but have limited detection sensitivity due to lower color density.

Nanomaterials include nanoparticles of CuO, CuO–TiO_2, ZrO_2, and NiO, as well as nanocomposites. Nanocomposite materials (e.g., molybdenum nanocomposites) and nanotubes (e.g., peptide and carbon nanotubes) are commonly used to electrochemically detect residual pesticide particles (Madianos et al., 2018; Moreno et al., 2019). Nano sensors for heavy metals detect ions such as Pb^{2+}, Hg^{2+}, Ag^{+}, Cd^{2+}, and Cu^{2+}, which pose risks to human health and the environment. Silver nanoparticles stabilized with epicatechin can detect Pb^{2+} in the presence of other metal ions (Ikram et al., 2019; M. Li et al., 2013).

Regulated Delivery Nanoparticles and nanocapsules release active components gradually or abruptly, regulating dissolution in lipid and aqueous mediums, promoting penetration and migration in tissues (Marchiol et al., 2020; Moreno et al., 2019).

Biomolecule attachment for specific purposes: Nanomaterials can bond with proteins, lipids, antibodies, and nucleic acids, allowing concentration and direction in organisms, tissues, or cells, where they can discharge their chemical load (Charbgoo et al., 2018; Husen & Jawaid, 2020).

Nanofertilizers (smart nutrients): Polymers based on nanoparticles deliver nutrients to plants or improve conventional fertilizer effects. They are more efficient and faster than traditional fertilizers. Various NP types are used to create nanofertilizers with varying active chemicals and compositions (Rios et al., 2020; S. Singh et al., 2021; Usman et al., 2020). Table 9 highlights the effect of nanomaterials on crop physiology and plant protection, demonstrating their role in enhancing growth, stress tolerance, and overall agricultural sustainability.

Table 9. Effect of nanomaterials on crop physiology and plant protection

Crops	Nano materials	Mode of application	Concentration	Duration	Response	References
Wheat (*Triticum aestivum*)	AgNPs	Mixed with pot soils	50 mg/L and 75 mg/L	Trifoliate stage	Enhanced development and resilience to heat stress	(M. Iqbal et al., 2019)
Cowpea (*Vigna sinensis*)	AgNPs	Foliar application	50 mg/L	40 days	Promoting soil bacterial diversity and root nodulation can enhance biomass and growth.	(Pallavi et al., 2016)
Paddy (*Oryza sativa*)	TiO2 and SiO2	Foliar application	20 and 30 mg/L	55 days	Enhance development and reduce Cd toxicity by enhancing antioxidant capacity and preventing Cd translocation.	(Rizwan et al., 2019)
Spinach (*Spinacia oleracea*)	TiO2	Seed priming and foliar application	0.25% suspension	48 h and 35 days	Higher levels of protein, nitrogen, chlorophyll, and biomass accumulation	(Yang et al., 2007)
Peanut (*Arachis hypogaea*), Maize (*Zea mays*)	Fe/ SiO2	As fertilizers	15 mg/kg	3 days	Enhanced biomass accumulation and plant growth	(Najafi Disfani et al., 2017)
Tobacum (*Nicotiana tabacum*)	ZnO	Hydroponics	0.2 µM and 1 µM	21 days	Altered metabolites, enzymatic activity, growth physiology, and plant anatomical characteristics	(Mazaheri Tirani et al., 2019)
Wheat (*Triticum aestivum*), Maize (*Zea mays*), Peanut (*Arachis hypogaea*), Garlic (*Allium sativum*)	MWCNTs	Seed priming	50 µg/mL	Over night	Enhanced biomass accumulation, quicker and better germination, and the ability of seeds to absorb water	(A. Srivastava & Rao, 2014)
Spinach (*Spinacia oleracea*)	CuO	Mixed with soils	200 mg/kg	60 days	Improved production of biomass and photosynthesis	(S. Wang et al., 2016)
Chickpea (*Cicer arietinum*); Spinach (*Spinacia oleracea*); Carrot (*Daucus carota*),	FeS2	Priming	80–100 µg/m	12–14 h	Enhanced crop yield and germination	(C. K. Das et al., 2016; G. Srivastava et al., 2014)

Rape seed (*Brassica juncea*) and Sesame (*Sesamum indicum*) Seed						
Clusterbean (*Cyamopsis tetragonoloba*)	ZnO	Foliar spray	10 mg/L	6 weeks	Increased plant biomass, growth, and nutrient content	(Raliya & Tarafdar, 2013)
Wheat (*Triticum aestivum*)	ZnO	Mixed with growth substrate	20 mg/L	Growth cycle	Enhanced biomass, the accumulation and grain yield	(Du et al., 2019)
Coffee (*Coffea arabica*)	ZnO	Foliar spray	10 mg/L	45 days	Increased net photosynthesis, biomass buildup, and growth	(Rossi et al., 2019)
Paddy (*Oryza sativa*)	SiO2 NPs	Foliar application	2.5 mM/L	70 days	Reduced the toxicity of heavy metals and enhanced plant development by reducing bio-concentration and translocation	(L. Wang et al., 2016)
Plum (*Prunus domestica*) fruits	ZnO, CuO and Ag NPs	Fruit spray	100 and 1000 µg/mL	4 days	Decreased manifestations of grey mould brought on by soil-borne disease and B. cinerea	(Malandrakis et al., 2019)
Tomato (*Solanum lycopersicum*)	Al2O3 NPs	Foliar application	400 mg/L	20 days	Managed effectively tomato fusarium root rot	(Shenashen et al., 2017)
Barley (*Hordeum vulgare*) Soybean (*Glycine max*), Maize (*Zea mays*)	MWCNTs	Seed priming	100 µg/mL	24 h	Accelerate seedling germination and growth	(Lahiani et al., 2013)
Tomato (*Solanum lycopersicum*)	MgO	Drenching 7–10 µg/mL	7 days		Controlled bacterial wilt disease by suppressing pathogen Ralstonia solanacearum	(Imada et al., 2016)
Tomato (*Solanum lycopersicum*)	CuO	Foliar application	150–340 µg/mL	11 days	Effectively controlled late blight disease caused by Phytophthora infestans	(Giannousi et al., 2013)
Lobia (*Vigna unguiculata*)	Ag NPs	Foliar application	100 µg/mL	50–7 days	No phytotoxicity,	(Vanti et al., 2019)

					however it may prevent Xanthomonas campestrispv. campestris and Xanthomonas axonopodispv. malvacearum from growing in vitro.	

L. Nano-Farming Nanotechnology is increasingly explored in agricultural development, particularly in precision agriculture, where wireless technologies and miniature sensors monitor and control processes in location-specific crop management (S. Singh et al., 2021; Usman et al., 2020).

Sources and Synthesis of Green Nanoparticles Green nanoparticles, produced from plants and microorganisms, are gaining popularity due to their environmental friendliness and ease of manufacturing. Plant species such as *Medicago sativa* and *Sesbania* have been used to create gold nanoparticles, while *Brassica juncea*, *Medicago sativa*, and *Helianthus annuus* can synthesize silver, nickel, cobalt, zinc, or copper nanoparticles. Microorganisms including diatoms, *Pseudomonas stutzeri*, and *Desulfovibrio desulfuricans* produce silicon, gold, zinc sulphide, and cadmium sulphide nanoparticles. Fungi such as *Verticillium sp.*, *Aspergillus flavus*, *Aspergillus fumigatus*, *Phanerochaete chrysosporium*, and *Fusarium oxysporum* are efficient biosynthesis systems for metal and metal sulphide-containing NPs (Aziz et al., 2018; Husen & Jawaid, 2020; Vanti et al., 2019). Smart delivery options enabled by nanoparticles help overcome chemical leaching, photolysis, hydrolysis, and microbiological degradation. Nanobiotechnologies like nanoparticles and nanocapsules transport compounds for targeted genes and DNA, though challenges remain (Ghormade et al., 2011; Moreno et al., 2019).

i) Nanofertilizers Accurate fertilizer management is crucial for sustained agricultural development. Traditional fertilizers have low nutrient utilization efficiency, often below 40%. Nanofertilizers, a promising solution, time nutrient release to crop uptake requirements, preventing losses and improving plant uptake (Marchiol et al., 2020; S. Singh et al., 2021; Usman et al., 2020). Examples include ammonium-charged zeolites enhancing phosphorus availability (Thundiyil, 2008), graphene oxide sheets delaying potassium nitrate release (Majdinasab et al., 2017), and nanocalcite combined with nano-SiO_2, MgO, and Fe_2O_3 improving micronutrient uptake (Latif et al., 2020; Pasinszki & Krebsz, 2020).

- **Nanomaterials in Seed Germination, Crop Growth, and Quality Enrichment** MWCNTs positively impact seed germination in various crop species (Aziz et al., 2018; Chandrasekaran et al., 2020; Du et al., 2019; QU et al., 2008). Nano-SiO_2, TiO_2, and zeolite also encourage seed germination (Tian et al., 2018; M. Wang et al., 2014). Nanomaterials such as ZnO, TiO_2, FeO, ZnFeCu-oxide, and hydroxyfullerenes improve crop quality and growth in peanuts, soybeans, mungbean, wheat, onions, spinach, tomatoes, and potatoes (Charbgoo et al., 2018; Majdinasab et al., 2017; Rastogi et al., 2017).
- **Nanomaterials Accelerate Plant Adaptation** Nano-SiO_2 improves seed germination, plant weight, and chlorophyll content under NaCl stress (Gruber et al., 2017; J. Wang et al., 2016). Foliar spray of nano-$FeSO_4$ enhances salt tolerance in sunflower cultivars (Rossi et al., 2019). Biosynthesized AgNPs from *Gossypium hirsutum* stem extract show antibacterial activity against *Xanthomonas* species (Vanti et al., 2019). Metal oxide nanomaterials like CuO, ZnO, and MgO control plant growth and stress tolerance (Giannousi et al., 2013; Imada et al., 2016).
- **Nanomaterials as Nano Sensors** Nano sensors improve soil and plant health, product quality, crop growth, nutrient deficiency detection, and environmental monitoring. GPS-based nano sensors and

CNTs are used for stress hormone monitoring, humidity sensing, and pesticide detection (Ge et al., 2014; Z. Li et al., 2021; Nsibande & Forbes, 2016).

- **Nanotechnology** Nanotechnology alters substances at 1–100 nm dimensions, enhancing conventional technologies. Nanobiosensors integrated with nanomaterials offer real-time sensing for environmental applications, benefiting agriculture, crop protection, disease diagnosis, and pesticide residue detection (Husen & Jawaid, 2020; Naresh & Lee, 2021).

ii) Nanomaterials Agriculture faces challenges from crop diseases and heavy metal contamination. Nanotechnology advancements provide potential solutions for cost-effective, on-site screening and remediation (Diaconu et al., 2020; Latif et al., 2020; Rehman et al., 2021).

Types Biosensors use bioreceptors to detect biomolecules, generating quantitative data via transducers. These can be electrochemical, calorimetric, piezoelectric, or optical, classified by recognition elements such as aptamers, enzymes, nucleic acids, antibodies, or whole cells (Ligler, 2009; Pingarrón et al., 2008; Turner, 2013).

iii) Immunosensors An immunosensor uses antibodies to detect antigen–antibody interactions, ensuring stability, specificity, and sensitivity. There are two categories: non-labeled and labeled. Non-labeled sensors detect the complex directly, while labeled sensors require a sensitive label for accurate measurement (Khater et al., 2019; Turner, 2013; Zhan et al., 2018).

M. Enzymatic Biosensors Enzymes are the core of enzymatic biosensors, which use electrochemical transducers for high sensitivity, low cost, and easy monitoring. These enzymes, typically globular proteins, are heat stable and have a high turnover rate, making them ideal for thermophilic bacteria or genetically modified enzymes (Majdinasab et al., 2017; Rhouati et al., 2018; Yetim et al., 2020).

Aptasensors Bioreceptors made up of aptamers are single-stranded oligonucleotides or peptide molecules that form three-dimensional structures to bind with their complementary region. They can fold into various structural motifs and are screened using the SELEX method. Aptamers are commonly used as LFA biorecognition molecules in on-site diagnostic kits, which consist of a sample pad, conjugate pad, nitrocellulose membrane, and absorbent pad (Byzova et al., 2018, 2020; Zhou et al., 2015).

Bioreceptors can include nucleic acids, oligonucleotides, whole cells, and cell organelles. Biosensors are referred to by the unique type of bioreceptors (Naresh & Lee, 2021; Pingarrón et al., 2008). Table 10 lists aptamer sequences along with their specific molecular targets, highlighting their importance in biosensor development for precise detection in plant protection applications.

Table 10. Aptamers sequences with their specific targets

Specific target	Aptamer sequence
λ-cyhalothrin	5′-ACCGACCGTGCTGGACTCTAGGGGAAGCACGGGCGGGGAATGCAACACGAGTATGAGCGAGCGTTGCG-3′
Deoxynivalenol	5′–(SH)–(CH2)6-GCATCACTACAGTCATTACGCATCGTAGGGGGGATCGTTAAGGAAGTGCCCGGAGGCGGTATCGTGTGAAGTGCTGTCCC
Diazinon	5′–NH2–(CH2)6-ATCCGTCACACCTGCTCTAATATAGAGGTATTGCTCTTGGACAAGGTACAGGGATGGTGTTGGCTCCCGTAT-3′
Aflatoxin B1	5′-TGGGGTTTTGGTGGCGGGTGGTGTACG GGCGAGGG-3′
Zearalenone	5′–NH2–TCATCTATCTATGGTACATTACTATCTGTAATGTGATATG-3′
Ochratoxin A	5′-GCTGAGTCTGAGTCG ATCGGGTGTGGGTGGCGTAA AGGGAGCATCGGACA-3′
Mercury	5′-GCTGAGTCTGAGTCGTCATGTTTGTTTGTTGGCCCCCCTTCTTTCTTA-3′

Acetamiprid	5′–(SH)–(CH2)6-TGTAATTTGTCTGCAGCGGTTCTTGATCGCTGACACCATATTATGAAGA-[Flc]-3′
Atrazine	5′–(SH)–(CH2)6-TACTGTTTGCACTGGCGGATTTAGCCAGTCAGTG[Flc]-3′
Chlorpyrifos	5′-CCTGCCACGCTCCGCAAGCTTAGGGTTACGCCTGCAGCGATTCTTGATCGCGCTGCTGGTAATCCTTCTTTAAGCTTGGCACCCGCATCGT-3′
Abscisic acid	5′-GCGGATGAAGACTGGTGTGAGGGGATGGGTTAGGTGGAGGTGGTTATTCCGGGAATTCGCCCTAAATACGAGCAAC-3′

N. Emerging Biosensing Methodologies Emerging biosensing approaches integrate nanomaterials, electrochemical systems, and imaging technologies to provide rapid, sensitive, and cost-effective detection of plant pathogens and physiological changes (Husen & Jawaid, 2020; Naresh & Lee, 2021).

Imaging-based Technology Early detection of plant physiological changes due to pests and diseases is crucial. Electro-optical sensors and imaging technologies, such as RGB/visible imaging, provide non-invasive monitoring systems for identifying pests and diseases. Healthy plants have higher near-infrared reflectance and lower visible reflectance, while infected plants increase reflectance in the visible range and decrease in the near-infrared range. Biotic stress causes variation in reflectance, enabling disease classification and quantification. Spectral variation in tomato plants infected with *Fusarium oxysporum* was detected during incubation using this approach (Z. Li et al., 2021; Marín Ortiz et al., 2023).

Electronic Nose Technology

Volatile organic compounds (VOCs) are released by plants into the atmosphere or soil, acting as a defense mechanism against pests and pathogens. Electronic noses, consisting of sensor arrays, detect and discriminate volatile compounds for disease detection. They can identify variations in VOC compositions during crop attacks, early detection of stored grain insects, fungi, bacterial diseases, and viruses, and distinguish disease levels. These devices offer rapid, non-invasive, and cost-effective monitoring (Verma et al., 2014, 2016).

VOCs have been used to differentiate citrus fruits from *Bactrocera dorsalis*, and commercial e-nose systems with metal oxide sensor arrays detect diseased potatoes. Carbon nanotubes (CNTs) have excellent electrical and VOC sensing properties, with responses dependent on molecular species nature and concentration (Ge et al., 2014; Nsibande & Forbes, 2016).

Wearable Technology Wearable biosensors, using flexible electronics, have shown potential in monitoring plant health. These sensors measure physiological and biochemical variations by profiling trait and microclimate parameters. Nanomaterials-based biosensors offer high flexibility and mechanical strength, making them suitable for on-site monitoring and early detection. A flexible electronic device with CNT channels and graphitic electrodes was used to sense organic vapor in air. A wearable platform for real-time monitoring and early disease detection was developed, including a leaf-attachable sensor array (Z. Li et al., 2021; S. Singh et al., 2021).

CONCLUSION

Nano biosensors are powerful analytical devices that convert biological reactions into measurable signals, offering transformative applications in agriculture and food systems. By integrating biological recognition elements with advanced transducers, they enable rapid, sensitive, and selective detection of fertilizers, pesticides, herbicides, pathogens, moisture, and soil pH. This capability supports ecological pollution control, sustainable agriculture, and improved crop productivity.

Whole-cell biosensors, which utilize inexpensive and long-lasting cells or organelles, provide cost-effective solutions for monitoring parameters such as pH, temperature, and inhibition levels. Meanwhile, recent advances in nanomaterials, including gold nanoparticles, carbon nanotubes, and quantum dots, have significantly enhanced biosensor performance, improving sensitivity, stability, and multiplexing. Optical, thermal, piezoelectric, and electrochemical biosensors each contribute unique advantages, ranging from label-free detection to non-destructive monitoring, creating a comprehensive toolkit for crop health diagnostics.

Looking ahead, the integration of biosensors with digital agriculture platforms and IoT devices will revolutionize crop monitoring. This convergence of nanotechnology and smart farming offers scalable, real-time solutions to mitigate biotic and abiotic stresses, enhance productivity, and safeguard ecosystems, ensuring agriculture remains resilient, efficient, and sustainable.

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There is no conflict of interest related to the subject matter of the work.

AUTHORS' CONTRIBUTION

Conceptualization, data collection, formal analysis, research, methodology, supervision, validation, drafting of the original version, and writing, revision and editing: Masih, D. and Tiwari, S. P.

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