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Advanced Biological Sensing for Real Time Crop Intelligence

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A B S T R A C T

The growing demand for sustainable and effective farming techniques has made it critical to monitor crops and environment in a real-time manner, with the help of precise and fast sensors. Currently, biosensors become more and more popular as an effective tool for contemporary agriculture owing to combining biological receptors with transducers and processors of biological and chemical signals. This paper gives an account of the basic elements and principle of operation of biosensors including bioreceptors, transducers, amplifiers, processors and display units. More attention is given to the new trend in biosensing technology – nano biosensors, which combine nanotechnology with biological sensing for improvement of detection sensitivity and efficiency and reduction of the size of sensors. The work describes the principle of operation of nano biosensors, which include sampling, recognition of the analyte, conversion and processing of the signal obtained and its output to a display. Some major types of nano biosensors such as enzyme, aptamer-, electrochemical and optical are characterized together with their principle of operation and possible applications in agriculture. The role of nano biosensors in early disease detection, nutrient assessment, plants' stress detection, pesticides' presence identification, contaminants detection, and in precision agriculture in general is also outlined in the paper. Problems with field testing, reliability, high cost, calibration and ecological safety are mentioned as major issues. The combination of nano biosensors with smart farming can provide many new possibilities in precise and timely control of the process of crop cultivation.

Keywords: *Biosensors, Bioreceptors, Crop Health Monitoring, Nano biosensors, Precision Agriculture, Signal Processing, Smart Farming*

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1. INTRODUCTION

In modern-day agriculture, there is a growing need for accurate information regarding the condition of crops, fertility of soil, availability of water, nutrients and presence of pests/diseases. Conventionally, farmers rely on visual inspection and soil testing for detection of any problem with their crops. However, while these techniques continue to have value, they can be lengthy and also involve sample transportation and laboratory equipment. Biosensor refers to a bioanalytical tool that incorporates the use of a biological sensing element together with a signal transducer for detection of a particular substance (Nimhan *et al*., 2025). The type of biosensor determines what substances can be detected, including but not limited to plant growth regulators, nutrients-related

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substances, pesticides, disease indicators, and stress indicators. Combining the use of biosensors with electronic processing, wireless technology, and display screens can help make faster decision-making processes in agriculture. The new technology is helping make crop intelligence a reality through provision of relevant crop and soil information.

2. STRUCTURE OF A BIOSENSOR

The working mechanism of the biosensor is based on the use of a bio-sensing system coupled with the electronic information processing system. The biosensor detects a particular analyte, encodes the sensing process into information and displays it in a way that can be read by humans. The structure of a typical biosensor includes a bioreceptor, a transducer, a processor and a display system (Tetyana *et al*., 2021).The bioreceptor and transducer form the core sensing unit, while the electronic components process and communicate the information (Figure 1).

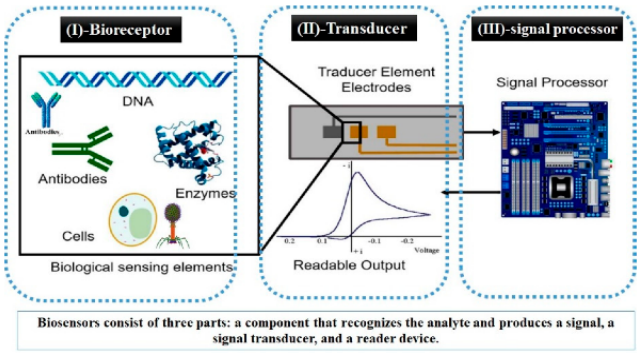


Figure 1. Structure of Biosensor

2.1 Bioreceptor

The bioreceptor is the biological recognition component interacting specifically with the target known as the analyte. For example, an enzyme or antibody may recognize a pesticide or a substance that belongs to a microorganism in the plant - pathogen connection.

2.2 Transducer

The transducer is the part of the sensor allowing change of the state of analyte interacting with the bioreceptor into a measurable signal. The type of signal may be either change in electric current or voltage, change in resistance or something else.

2.3 Signal-processing unit

The signal produced by the transducer may be too weak or noisy to interpret directly. An amplifier strengthens the signal when required, while the processor filters unwanted interference, analyses the data and converts the response into a meaningful reading.

2.4 Display and communication system

The final result is displayed as a concentration, numerical value, colour change or warning. In connected systems, the reading can also be transmitted to a mobile phone or farm-monitoring platform.

3. APPLICATIONS OF BIOSENSORS IN AGRICULTURE

Biosensors can provide information about several aspects of crop production, from soil and plant health to food safety. Their value lies in detecting specific targets rapidly, potentially reducing the time between identifying a problem and taking corrective action.

3.1 Soil health and nutrient management

Biosensors can be developed to detect selected nutrients, nutrient-related compounds, soil contaminants and indicators of microbial activity (Vashishth *et al*., 2024). When calibrated for the target and soil type, their readings may help guide fertilizer decisions and complement conventional soil testing.

3.2 Early detection of pests and diseases

Biosensors designed for pathogen-specific DNA, proteins or other biomarkers can help identify disease-causing organisms (Mahmoudi *et al*., 2026). Earlier identification can support timely scouting, targeted treatment and improved disease management.

3.3 Crop stress and physiological monitoring

Specialised sensors can detect plant signalling molecules, metabolites and other indicators associated with drought, salinity, heat or nutrient stress. Some wearable plant sensors can monitor changes over time without repeatedly collecting and transporting samples to a laboratory.

3.4 Pesticide residues and food safety

Selective biosensors can be developed to detect specific pesticide residues, toxins and contaminants from agricultural produce, irrigation water or soil (Dhar *et al*., 2026). Biosensors provide a quick means of detecting but further confirmation methods may be required.

3.5 Precision and digital agriculture

Biosensors can be linked to wireless technology to provide regular data collection. This data combined with weather information, remote sensing

and crop monitoring can help farmers make more timely decisions based on specific areas.

Research is continually being conducted about biosensors in agriculture. These include pathogen, plant nutrients and pesticide detection. The biosensor will depend on what you are looking for, how you are collecting the samples, detection limits and validation in real situations.

4. NANOBIOSENSORS: THE NEXT STEP IN BIOLOGICAL SENSING

- Nano biosensors are advanced biosensors based on a biological component combined with nanotechnology. Nanomaterials or nanostructures are used for enhanced detection of specific bio/chemical targets (Darwish *et al.*, 2024). These can be made using gold nanoparticles, carbon nanotubes, graphene, quantum dots and metal oxide nanostructures.
- Greater surface area – many nanostructures have a large surface area to volume ratio. This makes it possible to add further recognition sites to the sensor.
- Increased signal output – Some nanomaterials can increase conductivity, electron exchange, fluorescence or other outputs.
- Increased sensitivity – The right combination of nanomaterials and bioreceptors can allow low amounts of a target analyte to be detected.
- Miniature design – Allows smaller sensing elements to be designed as part of handheld devices, test strips and wearable devices.
- Can be used in electronics – Can be used in electronic circuits and connected systems.

Nanomaterials do not automatically make every sensor more accurate. Their performance depends on how they are designed, functionalised and combined with the recognition element. Nevertheless, they offer promising opportunities for faster and more sensitive detection in agricultural and environmental monitoring.

5. WORKING PRINCIPLE OF NANOBIOSENSORS

The working principle of a nano biosensor can be understood as a sequence of events that begins with collecting a sample and ends with obtaining a readable result (Nestor *et al.*, 2021). The sample may be soil extract, irrigation water, plant sap, a leaf surface wash or another material containing the target substance (Figure 2).

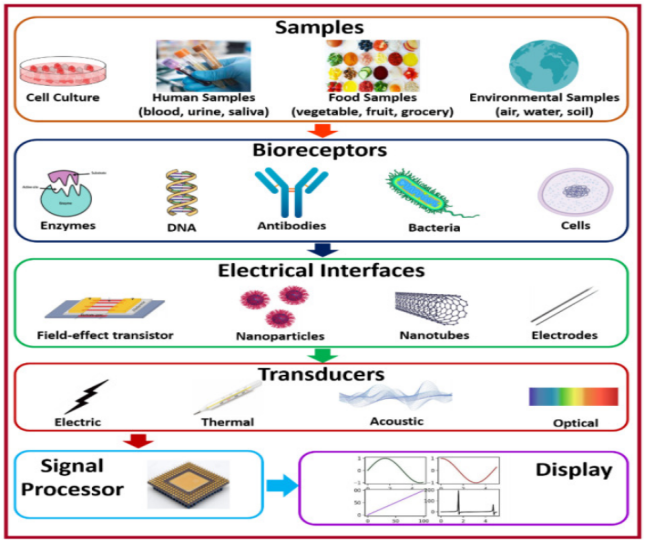


Figure 2. Working principle of nano biosensors

A nanobiosensor designed to detect a specific pesticide residue in water used for irrigation. After a suitable sample is introduced, a recognition element interacts with the target pesticide. The interaction changes a measurable property of the sensing layer. Nanomaterials may enhance the response, and the transducer converts it into a signal that the electronic system can process. The final reading indicates the presence or estimated concentration of the target, within the sensor's validated operating range.

6. CLASSIFICATION OF NANOBIOSENSORS

Nano biosensors can be classified according to their biological recognition elements or their signal-detection mechanisms.

6.1 Enzyme-based nano biosensors

Enzyme-based nano biosensors use enzymes as biological recognition or catalytic elements. Enzymes act on specific substrates and produce changes that can be measured through electrical, optical or other sensing methods. Nanomaterials such as gold nanoparticles, graphene and carbon nanotubes may improve enzyme immobilisation, electron transfer or signal strength (Hamza *et al.*, 2022).

Agricultural applications: Detection of selected pesticide compounds, plant metabolites, soil-related analytes and contaminants. For example, enzyme inhibition can be used in certain sensor designs to screen for pesticide groups that interfere with the enzyme's activity. Their performance depends on enzyme stability, temperature, pH and the composition of the sample. Enzyme-based sensors are particularly useful when the target participates in a suitable enzyme-catalysed reaction.

6.2 Aptamer-based nano biosensors

Aptamers are short, single-stranded DNA or RNA sequences selected for their ability to bind particular target molecules. They can fold into specific three-dimensional structures that recognise a target, somewhat like a molecular key fitting a suitable lock. When the target binds, the aptamer may change its shape or alter a measurable property of the sensing surface (Ji *et al*., 2023). Nanomaterials can help convert these changes into detectable signals.

Agricultural applications: Research into detecting selected pesticide residues, toxins, pathogen-associated targets and other agricultural contaminants. Aptamers can be synthesised and modified for different sensor designs, but each aptamer must be tested for binding specificity and performance in the actual sample. Not every aptamer works reliably in complex soil extracts or plant fluids.

6.3 Electrochemical nano biosensors

Electrochemical nano biosensors measure changes in electrical properties produced by a recognition event (Mondal *et al*., 2022). Based on the design, They may be used to detect current, voltage, resistance or impedance depending on the system design. Using nanomaterials means that the surface area of the electrodes can be increased so that small devices can be made for fast detection.

Applications in Agricultural: Certain pesticide residues, heavy metals, pathogen related molecules and nutrients can be detected using electrochemical sensors. The analyte and detection method will determine what can be detected. Electrochemical sensors are attractive due to their portability and potential for low cost electronics. Fouling on the electrode, interference from other molecules, calibration issues and variability in the environment must be overcome.

6.4 Optical nano biosensors

Optical nano biosensors detect changes in fluorescence, colour changes, absorbance or surface plasmon resonance (Versiani *et al*., 2016). Some will utilise fluorescent quantum dots, gold nanoparticles or other optical nanomaterials. Interaction with the target can cause an increase or decrease in fluorescence, change in colour of sensing system or change in optical properties.

Agricultural applications: Can be used to detect specific plant pathogens, pesticide residues, toxins and other contaminants. Optical methods can be used for quick visual screening as they can change colour. They can be sensitive but some may require specialist light sources, detectors or controlled conditions. Simple colour changes could be a better option for on-site screening.

7. APPLICATIONS OF NANOBIOSENSORS IN AGRICULTURE

Nano biosensors have the potential to bring diagnostics to the field meaning targeted information can be gained without lengthy lab testing. There are many important areas of interest.

7.1 Early detection of crop disease

Nano biosensors can be designed to detect pathogen specific genetic material, proteins or biomarkers. This will help monitor any diseases and take necessary measures. The success of this will depend upon the pathogen and the type of crop.

7.2 Soil and nutrient levels

There is research looking into using nanomaterials to create sensing platforms for specific nutrient related compounds, soil contaminants and biological activity. This could be used to supplement traditional soil testing and give more regular information. Not all plant available nutrients will be directly measured.

7.3 Stress monitoring in plants

By using sensors we can detect specific plant signalling molecules or biomarkers related to stress. This can help researchers understand how plants are reacting to drought, salinity, heat and nutrient imbalance. Wearable or non-invasive systems can be used to collect regular data.

7.4 Detection of Pesticide/contaminants

Nano biosensors can be used to quickly screen for specific pesticide residues, toxic compounds and heavy metals. Portable systems can be very useful if the lab is a long way away. However positive or borderline results may need validating using validated methods.
Smart farming and real-time crop intelligence

When integrated with wireless communication, the Internet of Things (IoT) and data-analysis platforms, nano biosensors can contribute to continuous or repeated monitoring. If combined with weather data, remote sensing and field observations this can help better interpret crop conditions.

8. CHALLENGES AND FUTURE PROSPECTS

Despite their potential, nano biosensors are not yet a complete replacement for traditional testing in agriculture. There are several issues to consider.

- Accuracy in the field: Temperature, humidity, dust, pH changes and complex sample can effect results.
- Interference: Interferences may be caused by simultaneous existence of other chemicals in the tested medium (e.g., soil, water, plant tissue).
- Calibration and standardisation: Reproducibility and consistency of results in different types of devices should be achieved to make the use of such tools possible.
- Accessibility: Manufacturing, maintenance, replacement of exchangeable sensing elements and electronic measuring system have to be affordable for agriculture use.
- Environmental issues: Impact on the environment should be estimated, including stability of nanoparticles used, their potential release in the environment and associated risks.
- Validation: Sensors manufactured in laboratories must be tested on relevant crops, soils, locations and seasons before their results provide effective guidance for agricultural practices.

Future developments can include the combination of nano biosensors with wearable devices of plants, wireless communication, artificial intelligence, and decision-making systems. This combination has the capability of turning isolated measurement results into information about crop responses to the environment. However, its effectiveness would greatly depend on sensor reliability, economic efficiency, longevity, and usefulness of management decisions generated by data.

9. CONCLUSION

Biological sensors are a significant advancement in terms of monitoring in agriculture due to the connection between the biological sensing and measuring signals. Nano biosensors, being the combination of nanomaterials with certain sensor characteristics, can provide improvements in such areas as signal performance, sensitivity, signal transduction, and sensor miniaturization. Disease diagnosis, detection of contaminants, monitoring of plant stress and precision agriculture are examples where nano sensors can be successfully used and provide fast and selective solutions. What is important about this technological approach is that apart from detecting some material presence, this technology gives us the ability to convert the result into useful information for agricultural decisions. With further improvement of these nano sensors in terms of reliability, cost-effectiveness and operability in the field, their implementation along with digital agriculture may provide the opportunity to move from monitoring the existing problems with crops to selective monitoring and response to the certain changes in advance.

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