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Farmers best assistant: Nano biosensors

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INTRODUCTION

Today's world is data driven and agriculture is no such exception, as precision farming is at its peak and nanotechnology is transforming the sector with nano-enabled biosensors, that can detect pathogens, toxins, pollutants, soil nutrients, pesticide residues, or stress markers in plants before visible symptoms appear. This revolution is needed as traditional agricultural monitoring techniques are becoming inadequate for the unprecedented threats from climate change, evolving plant pathogens and environmental degradation. Nano biosensors have biological material as receptors coupled with a nanomaterial-based transducer that converts a biological interaction into a measurable signal and the raw signal is amplified and processed by microelectronics (Naresh and Lee, 2021). Nanomaterials amplify the signal due to their high surface area and unique optical/electrical properties. Some examples of nanomaterials are- gold nanoparticles (AuNPs), carbon nanotubes (CNTs), graphene oxide, etc. for agriculture the sensors are made portable, sturdy and miniature sized. They are field tested to evaluate their performance under real agricultural conditions like temperature fluctuation, humidity, rain, dust, different soil types and other biological substances. They are made wireless for real-time data transfer to farm management systems. Integration of sensors with IoT and AI has aided to do "Smart Agriculture" (Miguel-Rojas and Pérez-de-Luque, 2023). These devices work as assistants to farmers making their work a lot easier as they can monitor their field from afar and know about the field conditions and decide what to do. In the world where agriculture is becoming data driven and all decisions are predicted based on it, biosensors particularly nano biosensors are the need of hour. They can detect the soil moisture content, nutrient requirement in specific areas, pH of soil, pests, metabolic production inside plant, stress and diseases (Chen, 2022). The biosensors are thus emerging as the most suitable aid to the farmers.

What is a biosensor and nano biosensor?

Biosensors are device used to detect the presence or concentration of a biological analyte such as a biomolecule, a biological structure or a microorganism. It consists of a biological analyte as recognition element with an electronic component to generate signal. The electronic component senses the physio-biochemical change in the sample and records and transfer the information. Biosensors are very sensitive devices and can detect and measure very low amount of the analytes such as pathogens, chemicals, pH levels and moisture (Singh et al., 2024). They are of varied shape and size. Different biomaterials and sensor elements have been used for the manufacturing of biosensors for various applications. However, traditionally used material in manufacturing of biosensors have broad spectrum but limited range, which limits its application. This limitation can be solved by nanotechnology which enables the development of devices at the nanoscale level using various nanomaterials, which directly interacts with the biomolecules or analytes (Rai et al., 2012). Such biosensors have enhanced properties including magnetic, electrical, and optical properties, high sensitivity, and a low response time and are called nano biosensors. Like a biosensor, nano biosensor also contains bioreceptor, transducer, processor/amplifier, and display and works on the principle of signal transduction (Fig. 1). Silver nanoparticles, nanowires and other nanomaterials are mostly used in these nano biosensors for the immobilization of the bioreceptor. By incorporating nanomaterials, which also act as a transducer to convert the biological interaction into measurable signal, these sensors significantly enhance performance in terms of detection limits, response time.

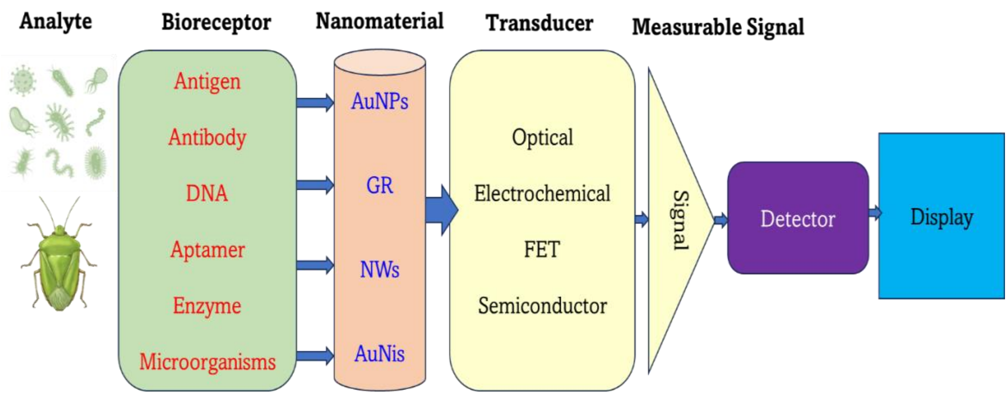

Fig. 1 Schematic diagram of different components of a nano biosensor

How nano biosensor works?

Biosensors are operated based on the principle of signal transduction. Bioreceptor is allowed to interact with a specific analyte. The transducer measures this interaction and outputs a signal. The intensity of the signal output is proportional to the concentration of the analytes. The mechanism involves four main steps:

1. Recognition

The target analyte (e.g., pesticide, pathogen DNA) binds specifically to the bioreceptor immobilized on the nanomaterial surface. The sensors use biological elements like enzymes, antibodies, nucleic acids, or microorganisms to specifically interact with the target substance (called the analyte). This interaction is highly selective, ensuring precise detection even in complex mixtures.

2. Signal Transduction

This binding causes a measurable change such as electrical current variation, fluorescence intensity change, colour change and impedance variation. Nanomaterials significantly amplify these.

3. Signal Amplification

The weak signal generated is enhanced using nanostructures.

4. Signal Output

The processed signal is displayed as a numerical value, graph, or visible colour change.

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Types of Nano biosensors

A. Electrochemical nano biosensors

Electrochemical nano biosensors detect changes in current, voltage, or resistance. They are highly sensitive and widely used in point-of-care diagnostics.

Example: Carbon nanotube (CNT)-based acetylcholinesterase biosensor for pesticide detection Organophosphate pesticides inhibits acetylcholinesterase, resulting in decreased enzyme activity and altered electrical signal.

B. Optical Nano biosensors

These sensors rely on changes in light absorption, fluorescence, colour, surface plasmon resonance (SPR), and Raman scattering to detect the presence of specific biomolecules. They are often used in medical diagnostics and environmental monitoring. Quantum dot-based and SPR sensors are some examples.

Example: Gold nanoparticle-based colorimetric sensor for plant pathogen detection Aggregation of gold nanoparticles occurs when pathogen DNA hybridizes with probe DNA, causing a visible red-to-blue colour change.

C. Immuno-nano biosensors

They are based on antigen–antibody interactions.

Example: Graphene-based immunosensor for aflatoxin B1 detection

Antibodies immobilized on graphene detect aflatoxin contamination in grains through changes in electrical conductivity.

D. DNA/Aptamer-based Nano biosensors

These sensors detect specific DNA sequences or molecules.

Example: Quantum dot-based DNA biosensor for GMO detection.

Hybridization between target DNA and probe DNA leads to fluorescence changes.

How are Nano biosensors used in agriculture?

The nano biosensors find multiple uses in agriculture most notable being precision farming (e.g., plant health, nutrient monitoring) and pest and disease detection (e.g., plant diseases, pests) (Arduini et al., 2016; Singh et al., 2024). Some of the nano biosensors used in precision farming are as follows:

1. Soil Nutrient Monitoring

(a) Nitrogen (Nitrate and Ammonium) Sensors

Nanomaterials used: ZnO nanoparticles, carbon nanotubes.

Working: Nitrate or ammonium ions interact with ion-selective membranes or enzymes that are immobilized on nanomaterial-coated electrodes, producing an electrochemical signal that is proportional to nutrient concentration (Saini and Lone, 2025).

(b) Phosphorus and Potassium Sensors

Nanomaterials used: Graphene oxide, gold nanoparticles.

Working: Binding of phosphate or potassium ions alters electrical conductivity or optical signals.

2. Soil Moisture Monitoring

Nanomaterials used: Nanocomposites, metal oxide nanoparticles.

Working: Moisture content changes dielectric properties of soil, which is detected by the sensors.

3. Detection of Soil Contaminants

Targets: Heavy metals (Cd, Pb, Hg), pesticide residues (Parmeswari et al., 2024).

Nanomaterials used: Carbon nanotubes, gold nanoparticles, magnetic nanoparticles.

Working: Binding of contaminants to nanomaterial-immobilized receptors generates electrochemical or optical signals.

1. Plant Disease Detection

Targets: Bacteria, fungi, viruses.

Nanomaterials used: Gold nanoparticles, quantum dots, CNTs.

Working: Detection of pathogen DNA, RNA, or proteins via DNA probes or antibodies causes fluorescence or colour change.

2. Monitoring Plant Stress and Growth

Targets: Plant hormones (auxin, ethylene), reactive oxygen species (ROS).

Nanomaterials used: Graphene, CNTs, nanosensors embedded in leaves

Working: Hormone or stress molecule binding changes electrical or optical signals.

3. Monitoring Photosynthesis and Metabolism

Nanomaterials used: Carbon nanotubes, quantum dots

Working: Nanosensors monitor chlorophyll fluorescence and metabolic activity.

Recent advances include wearable nanosensors and implantable sensors that are attached to leaves or stems and monitor sap flow, nutrient uptake, and stress signals and transmit data wirelessly (IoT-based systems).

CONCLUSION

Nano biosensors are great tool of advancement in the agriculture sector, as it has boosted the farm production. It also takes away farmers' workload

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as everything is being monitored from moisture content to nutrient requirement and their constant presence in the field is not required. It lowers the cost of production, prevents soil toxicity with overdosed fertilizers. Al these benefits seems to really change the face of traditional agriculture, but traditional farmers are still the ones who are not able to afford buying it, or learn how to use it. So, digital literacy and infrastructure is still required for all farmers whether small land holders or large land holders can reap the benefits of nano biosensors and its associated IoT devices.

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