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Nano Biosensors and Its Applications in Sustainable Agriculture

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Abstract

Sustainable agriculture has become a global priority due to increasing food demand, climate change, environmental degradation, and the need for efficient resource utilization. Conventional agricultural practices often rely on excessive use of fertilizers, pesticides, and water, resulting in reduced soil health and environmental pollution. Nanotechnology has emerged as a transformative tool to address these challenges, with nano biosensors representing one of its most promising applications.

Nano biosensors combine biological recognition elements with nanomaterial's to detect specific biological and chemical substances with exceptional sensitivity, accuracy, and speed. These advanced sensors enable real-time monitoring of soil nutrients, plant health, pathogens, pesticide residues, and environmental conditions. Their application supports precision agriculture by optimizing input use, minimizing crop losses, improving productivity, and reducing environmental impacts. This article highlights the principles, types, applications, advantages, challenges, and future prospects of nano biosensors in sustainable agriculture.

Keywords: Nanotechnology, Nano biosensors, Sustainable agriculture, Precision agriculture, Soil health, Plant disease detection, Smart farming.

Introduction

Agriculture is facing unprecedented challenges due to rapid population growth, climate change, declining soil fertility, water scarcity, and increasing pest and disease pressure. To ensure food security while protecting natural resources, sustainable agricultural practices have become essential. Modern technologies such as nanotechnology, artificial intelligence, precision agriculture, and biosensors are transforming conventional farming into a more efficient and environmentally friendly system. Among these innovations, nano biosensors have emerged as one of the most promising tools for real-time monitoring of crops, soil, water, and environmental conditions.

Nano biosensors combine the principles of nanotechnology and biotechnology to detect biological, chemical, or physical changes with exceptional sensitivity and accuracy. Their ability to provide rapid, precise, and on-site information enables farmers to make timely decisions, thereby improving crop productivity while reducing unnecessary use of fertilizers, pesticides, and irrigation water. These advanced sensing devices are playing a crucial role in promoting sustainable agriculture by enhancing resource-use efficiency and minimizing environmental pollution.

Characteristics of Nano biosensors

- **High Sensitivity:** Detects very low concentrations of target substances.
- **High Specificity:** Accurately identifies specific analytes.
- **Rapid Response:** Provides quick and real-time results.
- **Miniaturized:** Small, compact, and portable devices.
- **High Accuracy:** Produces precise and reliable measurements.
- **Low Sample Requirement:** Requires only a small amount of sample.
- **Real-Time Monitoring:** Continuously monitors biological and environmental changes.
- **Multiplex Detection:** Can detect multiple targets simultaneously.
- **Eco-Friendly:** Supports sustainable agriculture by reducing excessive chemical use.
- **Easy Integration:** Compatible with IoT, AI, and smart farming technologies.

Parts of a Nano biosensor

1. Probe

It is a bio sensitized element including the receptors, antibodies, enzymes, nucleic acid, tissues, microorganisms, those are either bio-components or biologically derived materials that receives the signals emitting from analytes and transmit it to transducer.

2. Transducer

It serves as an interface between probe and detector. It transforms the any changes like physical changes that happen due to interaction of probe and detector into electrical energy.

3. Detector

The microprocessor present in detector receives the energy signal from transducer then amplifies it and gives the processed output. (Hassani 2016).

Types of Nano biosensors

1.Mechanical NanoBiosensor

Nanoscale mechanical forces help in detection of response from analytes and give readings. Cantilever beams are used to identify biomolecules by measuring the deflection upon interaction with specific biomolecules. Loading of materials, changes in temperature etc controls the detection of responses from analytes.

2. Optical NanoBiosensor

This biosenors can detect the analytes by using the potential light source, optical transducer system, detector and sensing element. Optical transducer emits the light and also helps in detection of interaction; thus, the interaction creates some physico-chemical changes and detector measures the output as transduced light.

3. Viral Nanobiosensor

These are bio nanoparticles use the Herpes Simplex Virus (HSV) and adenovirus to set off the aggregation of magnetic nanobeads as sensor for those particular viruses.

4. PEBBLE Nanobiosensors

This PEBBLE stands for Probes Encapsulated by Biologically Localized Embedding nanobiosensors contains sensing molecules fitted inside inert matrix by the process of emulsion polymerization producing sensors in size range of 20-200nm. The sensing molecules influence the optical change, changes in pH and other ions such as Calcium or detect the fluorescence (J.P Sumner et al., 2006). The nanosensors present can monitor real-time cellular images like inter and intra molecular structures as well as showing reversibility and stability to leaching along with photo bleaching.

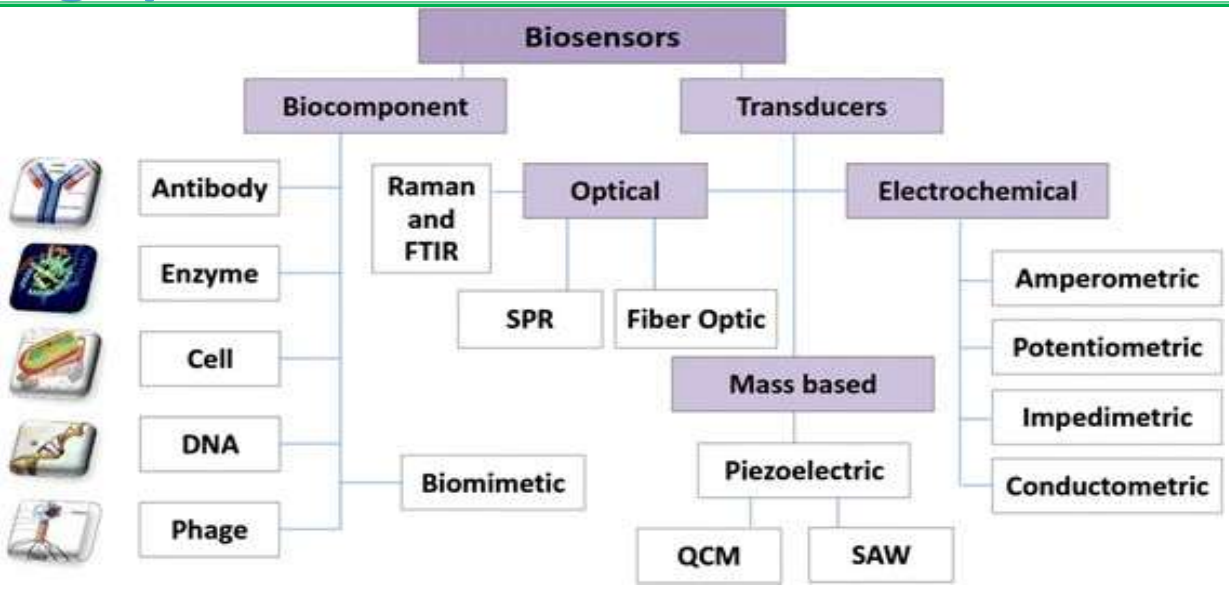

Fig.1- Parts of Nano biosensors (Hassani 2016)

5. Nanowire Biosensors

It is a hybrid of two molecules those are sensitive to outside signals such as Single Stranded DNA and Carbon nanotubes among which DNA act as detector and nanotubes as transmitter. The surface properties can be modified to observe the changes in any physico-chemical changes made by interaction with analytes.

Applications of Nano Biosensors in Sustainable Agriculture

1. Soil Nutrient Monitoring

Nano biosensors enable rapid measurement of essential nutrients such as nitrogen, phosphorus, potassium, and micronutrients directly in the field. Farmers can apply fertilizers based on actual crop requirements, reducing nutrient losses and improving fertilizer-use efficiency.

2. Precision Irrigation Management

Soil moisture sensors integrated with nanotechnology provide real-time information about water availability. This helps optimize irrigation scheduling, conserve water resources, and improve water-use efficiency, particularly in drought-prone regions.

3. Early Detection of Plant Diseases

Nano biosensors can identify plant pathogens, including bacteria, fungi, and viruses, before visible symptoms appear. Early diagnosis allows timely intervention, preventing disease spread and minimizing crop losses.

4. Pest Monitoring

These sensors detect insect pheromones, pest metabolites, or plant stress signals, enabling early pest surveillance. Farmers can adopt integrated pest management (IPM) strategies, reducing excessive pesticide applications.

5. Detection of Pesticide Residues

Nano biosensors rapidly detect pesticide residues in crops, soil, and water. This ensures food safety, supports regulatory compliance, and protects consumers from harmful chemical exposure.

6. Environmental Monitoring

Nano biosensors continuously monitor pollutants, heavy metals, toxic chemicals, greenhouse gases, and water quality, helping assess environmental health and promote sustainable land management.

7. Crop Health Monitoring

Stress biomarkers associated with nutrient deficiency, drought, salinity, and heat stress can be detected in real time. Early stress detection enables farmers to implement corrective measures before significant yield losses occur.

8. Food Quality and Safety

After harvest, nano biosensors monitor freshness, detect microbial contamination, identify adulterants, and assess storage conditions, thereby improving food quality throughout the supply chain.

9. Smart Farming and Internet of Things (IoT)

Nano biosensors integrated with wireless communication technologies and IoT platforms provide continuous monitoring of agricultural fields. Real-time data collected from sensors assist in automated decision-making, improving productivity and resource efficiency.

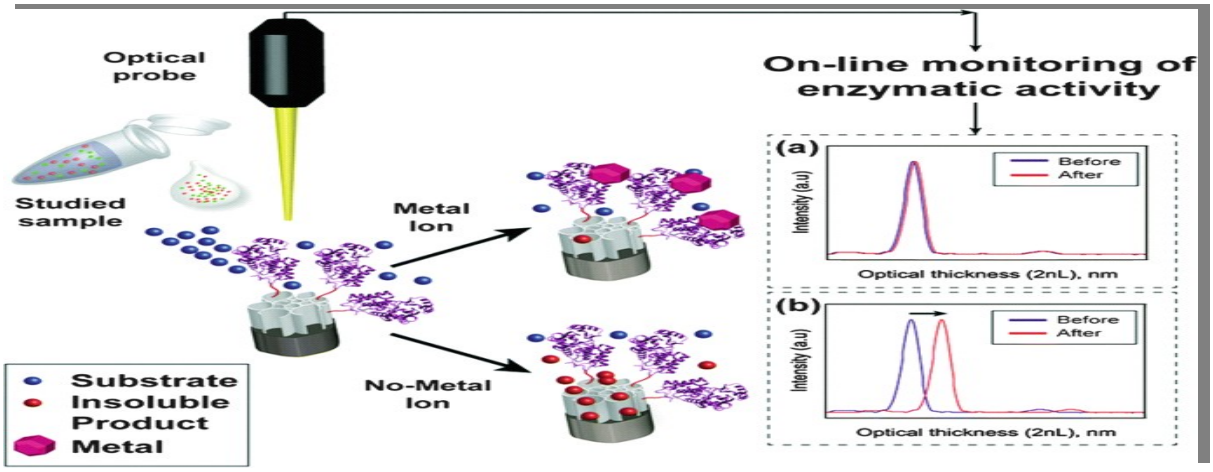

Fig-2: Detection of Heavy metals by Nanobiosensors (Zhylyak *et al*., 1995)

Advantages of Nano Biosensors

- High sensitivity and specificity
- Rapid and real-time detection
- Portable and field-deployable devices
- Low sample requirement
- Reduced labor and operational costs
- Early diagnosis of diseases and nutrient deficiencies
- Improved fertilizer and pesticide management
- Environmentally friendly agricultural practices
- Enhanced crop productivity and profitability

Conclusion

Nano biosensors represent a revolutionary advancement in agricultural technology by providing rapid, accurate, and real-time monitoring of soil health, crop nutrition, plant diseases, pests, environmental quality, and food safety. Their application enables precision management of agricultural inputs, enhances resource-use efficiency, reduces environmental pollution, and supports sustainable crop production.