Research Article

Journal of Environmental Nanotechnology

# Nanosensors for Monitoring and Detecting Nanoparticle Effects on Crops

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Received: 20.01.2025 Accepted: 16.03.2025 Published: 30.03.2025
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## ABSTRACT

Nanotechnology has revolutionized biosensing in agriculture, offering unprecedented capabilities to monitor and enhance crop growth, detect contaminants, and ensure food safety. This review explores the applications of nanosensors in numerous aspects of agriculture, ranging from crop management to environmental monitoring. The paper begins with an exploration of biosensors and nanosensors, elucidating their essential characteristics and diverse applications in detecting biomolecules, toxic materials, and disease markers. Catalytic electrochemical biosensors, carbon nanotubes (CNTs), graphene nanosensors, and molecular nanosensors emerge as pivotal tools, showcasing remarkable sensitivity and specificity in diverse agricultural settings. This emphasizes the importance of studying nanoparticle impacts on crops, noting the potential of nanotechnology to improve plant growth, nutrient uptake, and pest control. It addresses concerns such as nanoparticle toxicity and environmental effects, stressing the need for responsible implementation and regulatory oversight. The passage also discusses recent progress in detection methods, including colorimetric optical nanosensors and microcavity sensors, which show promise for identifying trace explosives and monitoring environmental conditions. In summary, this paper highlights nanotechnology's transformative role in agriculture, providing insights into its opportunities, obstacles, and future prospects. Nanotechnology has the potential to revolutionize crop management practices and ensure food safety, playing a crucial role in developing sustainable and resilient food systems for the future.

**Keywords:** Nanosensors; Biosensors; Crop management; Environmental monitoring; Nanoparticle effect; Sustainable agriculture.

## 1. INTRODUCTION

Biosensors, coined by Cammann and defined by IUPAC, are analytical tools that convert biological responses into electrical signals. Essential characteristics include high specificity, independence from pH and temperature, and reusability. In tandem, nanosensors, compact devices measuring 100 nm or more, are pivotal in nanotechnology. They detect and analyze nanoscale information, monitor biomolecules, and measure toxic materials in industrial and environmental contexts. Together, biosensors and nanosensors contribute significantly to advancing our understanding of the nanoscale world and its implications (Abdel *et al.* 2020; Adam *et al*. 2022; Mahbub *et al.* 2020).

In India, the Soil Health Card (SHC) 2015 program promotes the examination of 12 soil characteristics. These include the primary nutrients (N, P, K), pH level, Soil Organic Carbon (SOC), micronutrients (Zn, Fe, Cu, Mn, B), electrical conductivity (EC) for measuring soil ion content, and available sulfur (Ridhi *et al.* 2024).

The integration of nanotechnology in agriculture has been increasingly driven by the need for enhanced food production and sustainability. Nanotechnology is being used to address the limitations of conventional farming, with key advancements including the use of nanoparticles such as silver, zinc oxide, and titanium dioxide, which are engineered for optimal size, surface charge, and functionalization to improve their uptake and bioavailability in plants (Mittal *et al*. 2020). These nanoparticles serve various purposes, including as nano-fertilizers and nano-pesticides, promoting seed germination and nutrient absorption while minimizing environmental impacts. Characterization techniques like dynamic light scattering (DLS) and electron microscopy are essential for assessing nanoparticle properties, which influence their efficacy. However, potential hazards such as toxicity to non-target organisms and environmental persistence require thorough risk assessments. Sustainable nanotechnology focuses on using biodegradable materials to ensure long-term ecological health. Chitosan nanoparticles, derived from chitin, exemplify this approach by enhancing plant growth and resistance while supporting sustainable agricultural practices.

Nanobiosensors and nanosensors are transforming precision farming and crop management by enabling real-time monitoring and early detection of stress, disease, and toxicity in crops. Their high sensitivity and specificity surpass conventional methods, which often struggle with sample handling and long processing times. These advanced tools are essential for sustainable agriculture, detecting crucial factors like soil quality, plant health, and pesticide levels with precision. In particular, nano biosensors are invaluable for phytopathogen detection and pesticide management, using metal nanoparticles (e.g., gold) to identify fungi, viruses, and bacteria early, helping prevent crop losses. They also manage pesticide usage, promoting food safety and environmental sustainability (Thakur *et al*. 2022).

In addition, Nanosensors enhance precision farming by monitoring soil quality and environmental factors, optimizing soil management strategies through the detection of pH, nutrients, and moisture levels. Advanced materials like carbon nanotubes and quantum dots enhance these sensors' ability to identify soil contaminants, supporting sustainable farming practices. Furthermore, nanosensors enable non-invasive, real-time monitoring of essential biological molecules and plant conditions in living organisms. This technology provides valuable insights into crucial cellular processes, including levels of oxygen, ATP, calcium ions, and plant hormones. Such capabilities contribute to more precise agricultural practices by facilitating the monitoring of fruit ripening and enhancing the detection of plant pathogens and mycotoxins with greater efficiency compared to conventional methods (Javaid *et al*. 2021).

The integration of bionanosensors into agriculture enables the real-time monitoring of soil health, crop conditions, and environmental factors, leading to the generation of substantial data volumes. Effectively collecting, processing, and interpreting this data is essential for informed decision-making, as it allows for timely interventions, improved yields, and sustainable resource management. However, this process presents challenges, including the need for robust data management systems, advanced analytical tools, and user-friendly interfaces to ensure that actionable insights are accessible to farmers and agronomists. Addressing these challenges is crucial for the successful implementation of precision agriculture practices (Issad *et al.* 2019).

Beyond agriculture, nanosensors have broad industrial applications, including medical diagnostics, environmental monitoring, and IoNT (Internet of Nano Things) communication. Their high sensitivity, cost-efficiency, and real-time monitoring capabilities make them essential in various sectors, from healthcare to environmental safety. As the market grows, nanosensors are poised to revolutionize industries that demand precise and efficient diagnostics (Shaw *et al.* 2022).

## 1.1 Types of Sensors

### 1.1.1 Catalytic Electrochemical

Biosensors employ enzymes, cells, or tissues to detect specific substances, often using oxide reductase enzymes. These biosensors are created by fixing enzyme coatings onto electrodes through techniques like surface adsorption or covalent bonding. The enzyme catalyzes chemical reactions, generating measurable electrical signals for efficient and specific measurement of substrate or inhibitor concentrations. Despite challenges such as enzyme stability and cost, catalytic biosensors, exemplified by glucose oxidase-based glucose sensors and alcohol dehydrogenase-based ethanol sensors, play a vital role in various fields. The use of cells and tissues as alternative enzyme sources addresses challenges and enhances the versatility of catalytic electrochemical biosensors (Huang *et al.* 2021).

### 1.1.2 Carbon Nanotubes

Nanotechnology advancements usher in new prospects for disease analysis through biosensors, prominently featuring carbon-based materials like carbon nanotubes (CNTs). CNTs boast exceptional mechanical, electrical, and chemical properties, rendering them ideal for diverse biosensing applications, particularly in medicine. CNT-based biosensors exhibit promise in detecting various biomolecules across fields such as glucose, DNA, proteins, amino acids, and neurotransmitters. Their versatile applications extend to environments, agriculture, food, and energy. Despite their advantages, ongoing research identifies limitations, emphasizing the need to address these shortcomings for heightened efficacy. The crucial role of biomolecule detection spans healthcare, clinical medicine, food safety, environmental monitoring, and homeland security, necessitating the development of reliable, cost-effective devices for direct, highly sensitive/selective, and rapid analysis. Biosensors, amalgamating biological recognition with chemical or physical transduction, hold significant advantages and commercialization potential, offering a pivotal avenue for advancing human life (Dai *et al.* 2022; Yang *et al*. 2015). Carbon nanotubes (CNTs) are promising biosensor materials due to their electrical properties and surface characteristics, offering high sensitivity and robustness. Integrating CNTs into biosensors enhances performance for improved detection and analysis in various applications (Lee, 2023).

### 1.1.3 Graphene Nanosensors

Graphene nanosensors have emerged as promising tools to address environmental and health concerns related to harmful metal ions, including mercury, lead, cadmium, silver, and copper found in water and food due to industrial and agricultural activities. The conventional detection methods for these ions are both expensive and time-consuming, prompting scientists to explore more accessible techniques like electrochemical and optical approaches (Zhang *et al.* 2018).

Biosensors, essential tools in medicine and environmental monitoring, are gaining significance, with graphene-based biosensors standing out due to graphene's unique properties. These sensors utilize graphene in diverse applications, from enzymes and immune systems to DNA and wearable sensors, benefitting from graphene's compatibility with living organisms and its ability to form new materials when combined with metals. In the realm of food safety, biosensors, particularly those incorporating graphene, play a pivotal role in our globally interconnected food supply chain. Leveraging nanomaterials like graphene offers high conductivity and biocompatibility, enhancing biosensor performance. Additionally, it underscores the significance of smart food packaging systems, including time-temperature indicators and radio frequency identification, in ensuring food safety. Despite these strides, challenges persist in graphene-based nanosensors and smart packaging solutions, urging further exploration and refinement" (Cheng *et al.* 2020; Madan *et al*. 2022; Sundramoorthy *et al.* 2018).

#### 1.1.4 Nanowire Nanosensors

Precisely deliver drugs to injury sites, revolutionizing treatments for conditions like lung cancer. They can also target tumor sites with minimal side effects. Moreover, research into zinc oxide nanosensors doped with rare earth elements like europium shows promise for detecting hydrogen gas safely and effectively. Incorporating ZnO: Eu nanowire arrays into nanosensors showcases advanced sensing capabilities for UV light and hydrogen gas detection. Utilizing density functional theory-based simulations, the fundamental gas sensing mechanisms are illuminated, underscoring the potential of nanosensors for safer and more efficient gas detection across diverse domains(Chanu *et al.* 2021; Lupan *et al*. 2022).

#### 1.1.5 Molecular Nanosensors

Molecular nanosensors are highly advanced devices that can detect specific molecules or ions using nano-sized structures with specific molecules or ligands. They deploy surface-enhanced Raman spectroscopy (SERS) with metallic nanoparticles coated with Raman-active molecules to detect target molecules, making them highly sensitive and specific in detecting analytes within complex matrices. Molecular SERS nanosensors are capable of detecting specific targets like intracellular pH values or metal ion concentrations, providing insight into cellular microenvironments and environmental monitoring. These nanosensors are indispensable in environmental monitoring, medical diagnostics, and biochemical analysis, making them an essential tool in the field (Izabella *et al*. 2020).

#### 1.1.6 Quantum dots (QDs)

Single-molecule detection is an incredibly sensitive approach to quantifying target molecules. Quantum dots (QDs) have exceptional properties that make them ideal for nanosensor development. By combining single-molecule detection with QDs, single QD-based nanosensors achieve remarkable sensitivity. These nanosensors are divided into two types: burst coincidence and fluorescence resonance energy transfer (FRET) detection. They can directly detect low-abundance species like DNAs, microRNAs, proteins, and viruses without the need for nucleic acid amplification. This enables real-time elucidation of biological phenomena.

Moreover, ultrasensitive nanosensors based on QDs linked to DNA probes facilitate rapid, separation-free detection of low concentrations of DNA. This is crucial for diagnosing genetic diseases. Similarly, QD-based nanosensors for enzyme detection leverage superior optical properties to probe enzymatic activities. They offer improved sensitivity for early disease diagnosis. Carbon quantum dots (CQDs) are emerging as promising alternatives to metal nanoparticles. They offer cost-effectiveness and scalability for sensor development, thereby advancing the field of nanosensors (Chun *et al.* 2005; Hu *et al*. 2017; Knudsen *et al*. 2013; Saha *et al*. 2023).

### 1.2 Nanosensor Structure

Nanosensors are engineered to identify and react to chemical and physical changes at the nanoscale level. These sensors typically comprise three key components: a sensing element, a transducer, and a readout system, each essential for the device's operation. The sensing component is frequently constructed from nanomaterials like carbon nanotubes, nanoparticles, or nanowires. These materials offer a large surface area and exhibit unique nanoscale properties, which enhance the sensor's sensitivity and specificity. When these nanomaterials interact with target analytes, such as gases, chemicals, or biomolecules, they produce detectable changes in electrical, optical, or thermal characteristics.

The transducer transforms these alterations into a discernible signal, which may be electrical, optical, or mechanical, based on the specific application. For example, chemical nanosensors might experience a change in resistance when a target molecule attaches to the sensing component, while optical nanosensors may detect the presence of a specific substance through shifts in light absorption or emission. By combining nanomaterials with microfabrication techniques, researchers can miniaturize the entire sensor structure, enabling the creation of compact, portable devices. This reduction in size not only facilitates real-time monitoring of environmental conditions, biological systems, or chemical processes but also enhances the potential for incorporation into various applications, ranging from healthcare diagnostics to environmental monitoring.

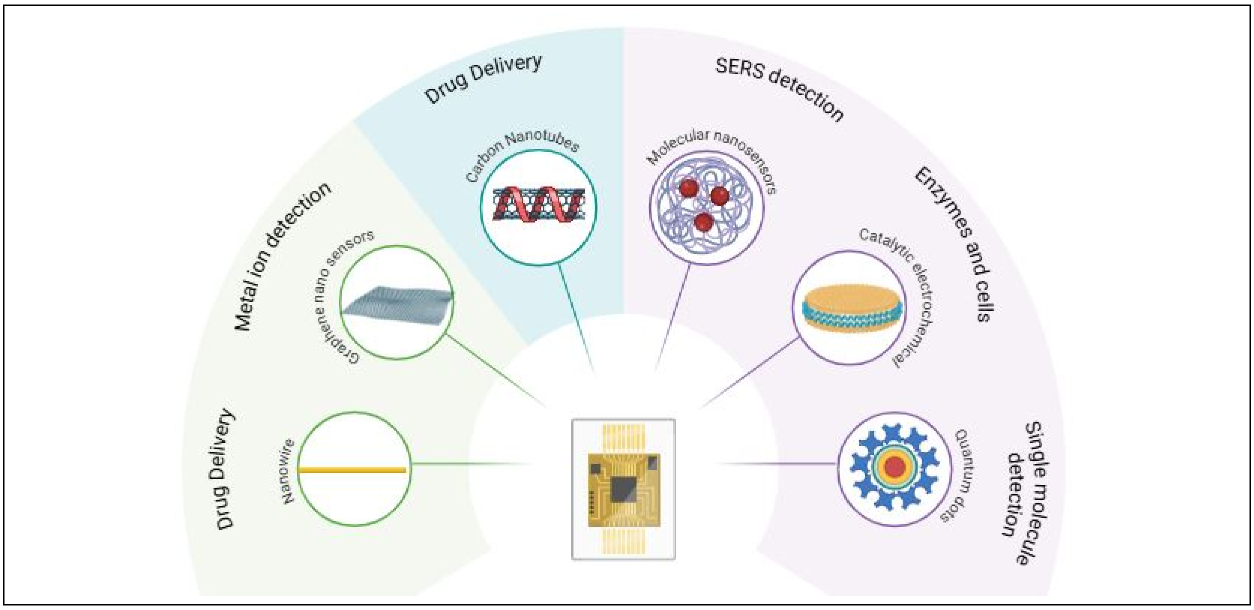


**Fig. 1: Types of advanced nanosensors and their applications**

**Table 1: Various biosensors and their applications**

| Nanosensors | Applications | References |
|---|---|---|
| Catalytic Electrochemical Biosensors | Health monitoring and neurological research: Detecting dopamine in biological fluids. | (DeVoe *et al*. 2024) |
| | Wearable fabric for lactate measurement: Incorporating the MXCeO2 biosensor into the wearable fabric for highly sensitive lactate measurement in sweat. | (Khan *et al*. 2024) |
| | Early cancer diagnostics | (Sheng *et al*. 2021) |
| | Selective and sensitive RNA detection | |
| | Reduction of hydrogen peroxide (H2O2) | (Khan *et al*. 2024) |
| Graphene Nanosensors | Nanocomposite-based Graphene Oxide as Fluorescence Sensors-<br>Detection of Amino Acids<br>• Detection of lysine<br>• Detection of tyramine<br>• Detection of l-arginine | (Cheng *et al*. 2020) |
| | Detection of Drug Molecules<br>• Detection of doxorubicin (DOX)<br>• Detection of virginiamycin<br>• Detection of dopamine | |
| | Specific DNA detection | (Atta *et al*. 2015) |
| | Acts as Immunosensor | |
| Nanowire based Biosensor | Detection of GABA molecules | (Tran *et al*. 2023) |
| | • Simultaneous detection of penicillin and tetracycline<br>• RNA capture and detection<br>• Detection of microRNAs (miRNAs) | |
| Quantum Dots based nanosensors | Detection of various toxic chemicals in analytical toxicology, including gaseous, anionic, phenolic, metallic, drug overdose, and pesticide poison. Detection of antibiotics in medical and food safety applications, addressing complex factors beyond simple aqueous solutions. | (Ganesan *et al*. 2020;Sabzehmeidani *et al*. 2022) |

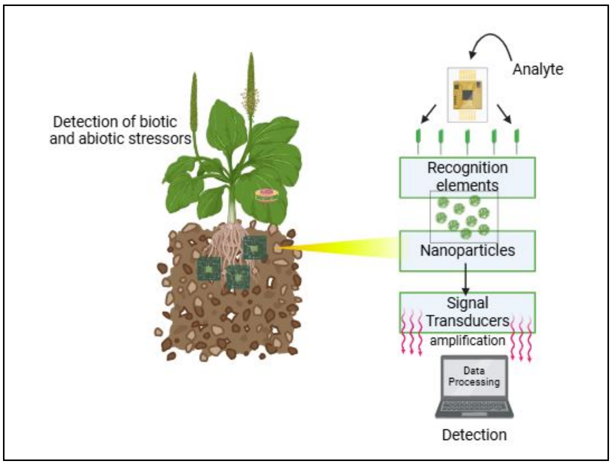


**Fig. 2: Mechanism of nanosensor**

Nanosensors are versatile and can be customized for individual applications. Researchers aim to optimize performance by experimenting with different material arrangements. Hybrid nanosensors combine different nanomaterials to improve detection capabilities. Nanosensors have the potential to improve sensitivity, selectivity, and reaction time, making them useful in domains including health, environmental science, and food safety. Nanosensors have the potential to revolutionize environmental monitoring and understanding by providing unprecedented information at the molecular level (Kazi *et al.* 2024).

#### 1.2.1. Mechanisms of Nanosensor

Nanosensors use the unique features of nanomaterials to detect and measure physical, chemical, or biological changes on a very small scale. These sensors frequently rely on nanomaterials' high surface area-to-volume ratios, which improves their sensitivity and responsiveness. Carbon nanotubes, graphene, and nanoparticles, for example, are widely employed in nanosensors due to their superior electrical, thermal, and optical capabilities. When exposed to a specific analyte, these nanomaterials exhibit detectable changes in attributes such as electrical resistance, fluorescence, and magnetic properties. These changes are subsequently converted into readable signals, allowing for the accurate identification and measurement of the analyte. Nanosensors are employed in different industries such as medical diagnostics, environmental monitoring, and food safety, offering great sensitivity, rapid response, and the capacity to detect low levels (Kazi *et al*. 2024).

#### 1.2.2 Nanosensors

Nanosensors, made possible by advances in manufacturing technology and quantum physics, can detect even the smallest materials or phenomena. They have proven their potential in fields such as security, medicine, food, and environmental protection. Nanosensors provide valuable insights into nanomaterials and recognition molecules and have the ability to detect toxins and pollutants at the molecular level. They have substantial potential in areas such as healthcare, military, security, and environmental monitoring. During the COVID-19 pandemic, nanosensors were used to develop rapid tests for actively infected individuals. Researchers have created generic sensors for lab-on-chip nanoplatforms, providing an adaptive approach to detecting viral infections with different mutations. (Adam *et al.* 2022; Mahbub *et al.* 2020).

## 2. IMPORTANCE OF MONITORING AND DETECTING NANOPARTICLE EFFECTS ON CROPS

Nanotechnology can help protect plants against environmental stressors such as extreme temperatures, water deficiency, and pollution. Nanosensors can be used to monitor crop growth, soil conditions, and environmental factors, which can contribute to improved management practices and sustainability in agriculture. The concept of nano-farming involves the use of tiny particles known as nanoparticles that can be made from different materials like plants or metals. These particles are smaller than a strand of hair and are used by farmers to help crops grow better. The nanoparticles deliver nutrients to plants in a more precise manner, ensuring that plants receive exactly what they need to thrive. They can also protect plants from diseases and pests. Nanoparticles are so small that they can enter tiny openings in plants and deliver their cargo directly, which can help plants grow faster and healthier. The use of nanoparticles also reduces waste of things like fertilizers and pesticides, making it an environmentally friendly solution (Shang *et al*. 2019).

Plants can grow faster and stronger with the right nutrients, resulting in better yields and less waste from fertilizers and pesticides. This can lead to less pollution in the environment and even enhance the nutritional value of crops. It's particularly significant as the world's population grows. Nanoparticles can be used as pesticides to fight crop diseases, stimulate plant growth for better yields, and help us identify plant diseases more quickly. They can also monitor soil and water health and even help clean up polluted soil and water. Scientists need to carefully study these nanoparticles to ensure their safety for plants, people, and the environment, including their size, shape, and composition. Although nano-farming is a relatively new field of study, it has the potential to revolutionize agriculture. It could help us grow more food with fewer resources, which is critical as the world's population continues to grow. As research continues, nanoparticles have the potential to revolutionize agriculture, helping us grow more food and sustainably improve its quality (Jahan *et al.* 2022; Juliana *et al.* 2023).

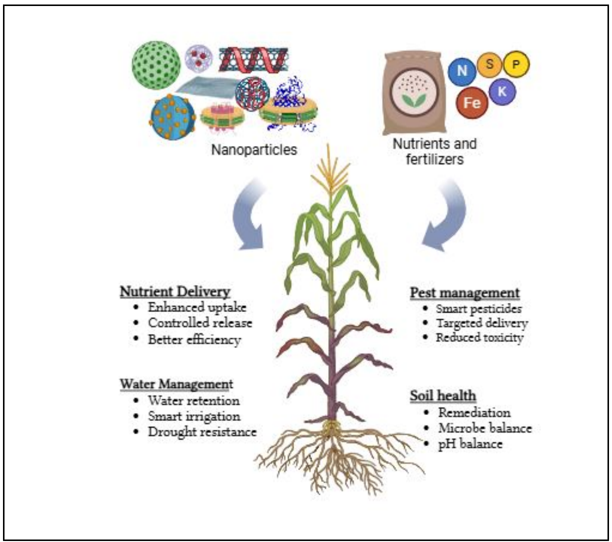


**Fig. 3: Main applications of nanoparticles in sustainable agriculture**

## 3. SIGNIFICANCE IN SUSTAINABLE AGRICULTURE AND CROP MANAGEMENT

Nanoparticles (NPs) have the potential to revolutionize sustainable agriculture and crop management by offering a range of benefits. Firstly, they can enhance efficiency and reduce waste by delivering nutrients, pesticides, and other inputs directly to plants, thus minimizing environmental pollution. Additionally, some NPs can slowly release nutrients to plants, ensuring a steady supply of essentials while minimizing excess. Furthermore, NPs can improve plant health and productivity by facilitating more efficient nutrient absorption, providing targeted pest and disease control, and enhancing stress tolerance against environmental factors such as drought.

**Table 2. Depicts the tools and technologies used in agriculture for monitoring and analyzing crops and soil properties**

| Tool/Technology | Description | Applications | Benefits | Challenges | References |
|---|---|---|---|---|---|
| Mapping | Creation of maps for crops and soil properties | Monitoring crop health, soil moisture | Detailed spatial information, improved decision-making | Data collection complexity, integration with other technologies | (Garg *et al.* 2024) |
| Remote Sensing (RS) | Collecting data from a distance using satellites and UAVs | Monitoring plant and soil conditions, aerial photography | High spatial, temporal, and spectral resolution, dynamic monitoring | High initial cost, data processing requirements | (Garg *et al.* 2024) |
| Geographic Information System (GIS) | Integrating spatial data from various sources | Detailed maps of vegetation, productivity, and crop information | Efficient data analysis, large data handling, and decision support | High initial cost, need for specialized software and training | (Garg *et al.* 2024) |
| Wireless Sensor Networks (WSNs) | Networks of sensors communicating data wirelessly | Data collection, monitoring, and analysis in agricultural fields | Precise field information, reduced manpower, real-time monitoring | Signal loss due to topography, battery life limitations | (Garg *et al.* 2024) |
| Manual Mapping During Field Operations | Measuring soil characteristics and crop conditions manually | Pest infestations, crop problems, soil samples | Reliable data collection, specific measurements | Labor-intensive, time-consuming | (Garg *et al.* 2024) |
| Synthesis and Formulation | Nanomaterial synthesis and site-specific controlled release | Top-down, bottom-up approaches | Precise delivery, controlled release | Synthesis complexity, cost | (Arora *et al.* 2022) |
| Biosafety and Regulation | Risk assessment of agri-nanoproducts | Nano-safety protocols, Regulations | Safe use of nanomaterials, environmental protection | Regulatory hurdles, public perception | (Arora *et al.* 2022) |

Sustainable agriculture principles include preserving and restoring natural resources like soil, water, and biodiversity, integrating pest management techniques, managing soil health, promoting water conservation, incorporating agroforestry practices, implementing crop rotation and diversification, and fostering social and economic equity. Furthermore, using NPs in agriculture can yield environmental benefits such as reduced reliance on chemical fertilizers and pesticides, which results in decreased water pollution and soil contamination. Additionally, it has the potential to improve soil health and fertility (Rawat *et al.* 2023)

There are different farming techniques that improve agriculture production and sustainability.

- **Multi-layer farming** grows crops vertically to maximize space usage and resource efficiency. This is useful in urban areas with limited space.

- **Smart farming**, the latest agricultural revolution, utilizes information and communication technologies to connect smart machines and sensors on farms through the Internet of Things (IoT). It makes agricultural practices data-driven, optimizing each variable and input during production (Güven *et al*. 2023).

- **Agroforestry** combines trees and crops together. Trees improve soil health, provide habitat for wildlife, and reduce erosion.
- **Crop diversification** involves planting different crops together to reduce risks from pests, diseases, and weather.
- **Cover crops** are grown between cash crop seasons to protect the soil, suppress weeds, and improve soil fertility (Rawat *et al.* 2023).

Nonetheless, challenges such as the unknown long-term effects of NPs on plants, soil, and human health, the possibility of unintended consequences such as environmental accumulation, and the initial cost and availability of NP-based agricultural products must be carefully considered.

## 4. DETECTION OF POLLUTANTS THROUGH NANOSENSORS

A basic gas sensor can be described as a detection device comprising three key components: a sensing element or receptor probe, a transducer element, and an amplifier that converts the transducer's response into a measurable signal when a contaminant is present. The sensor operates by allowing air pollutants to interact with the receptor, generating a response. This response is then captured by the transducer component through various mechanisms, followed by signal amplification and conversion into a quantifiable form within the microelectronic signal processor. The fundamental components of sensors are units that respond to alterations in chemical or physical properties, which are then transformed into electrical signals by transducers. Gas detection occurs through the interaction between the sensing material and the target gases.

Improving the effectiveness of pollutant detection is crucial. Sensor development presents numerous obstacles, including:

a) Challenges in improving air pollution sensors for greater sensitivity, selectivity, and stability under ambient circumstances.

b) Additional problems include improving real-time control sensors.

c) Reducing maintenance involves reducing the use of chemicals and reagents, as well as on-site detection of pollutant composition before discharge into the environment. This also saves on battery changes and data analysis costs, which can sometimes exceed the cost of the sensor device. (Mohamed *et al*. 2022).

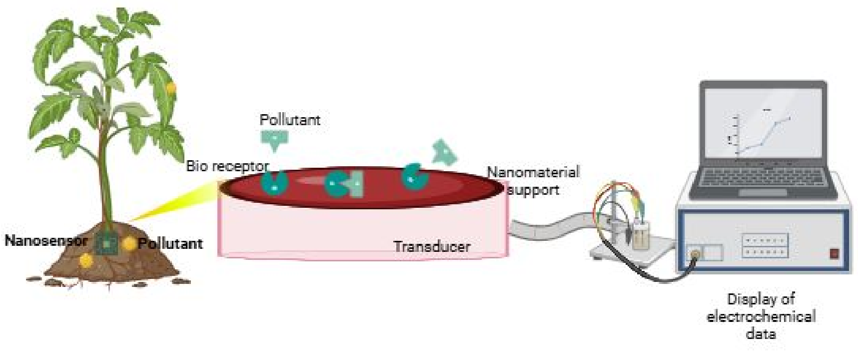


**Fig. 4: Detection of pollutants using nanosensors**

Because of their amazing intrinsic properties, some novel materials—such as carbon materials (such as graphene, carbon nanotubes, graphitic carbon nitride nanometals and their oxide materials), conductive polymer materials, and mesoporous materials—have found widespread application in pollutant monitoring sensors. Since there are numerous kinds of capture with various known and unknown action processes, it is more complicated for sensors based on the capture effect. Research based on related mechanisms is insufficiently comprehensive, which is a pressing issue that has to be resolved for the use of sensing techniques in environmental monitoring. The practicality of the sensing approach is now its biggest application hurdle. It is readily connected to the direct transition points for applying sensing technology to production, such as cost, manufacture, operability, portability, etc. Development of nanosensors with features like affordability, ease of use and manufacture, quick reaction, compact (micro) size, and real-time in situ detection, is a critical goal for environmental monitoring (Zhang *et al*. 2020).

## 5. APPLICATIONS IN MONITORING NANOPARTICLE EFFECTS ON CROPS

Nanotechnology is a promising field in agriculture, but it has also raised concerns due to its potential consequences. Nanoparticles can enter agroecosystems through the application of nano-based agricultural products and the release of waste from industries and households. Direct exposure of plants to nanoparticles can have both positive and negative effects on soil health, crop growth, and quality. Factors influencing nanoparticle effects include nanoparticle type and size, plant species, nanoparticle concentration, and duration of exposure. Studies suggest that the effects of nanoparticles on plants are mixed. Some studies have shown the positive effects of nanoparticles, such as boosting chlorophyll and enhancing seed germination and plant growth. However, other studies have shown negative impacts, such as reduced yield and biomass. Nanoparticles can also harm plants indirectly by damaging roots and affecting microbes (Mgadi *et al.* 2024).

The intensive agricultural practice has led to detrimental effects on soil health, including the destruction of microorganisms, soil humus, emergence of pathogen resistance, and loss of organic matter, posing a serious threat to sustainable agriculture. Nanotechnology offers promising solutions to address these challenges in agriculture.

Nanoparticles with sensors can assess soil health and microorganisms and even detoxify contaminants. Nano-biofertilizers with added nutrients can deliver precise nutrition to crops, and Nano-based tools can improve nutrient recycling and resource conservation. Nanosensors can provide early warnings of disease outbreaks (Zain *et al*. 2024).

Nanotechnology has a lot of potential to change the way we do agriculture. It has already been used in different forms, such as nanofertilizers, nanopesticides, and nano-biosensors. Nanoparticles (NPs) have the ability to affect the growth, yield, and quality of crops, but the outcome can vary depending on several factors, such as the type, concentration, size, treatment method, duration of exposure, and plant species involved. When plants are exposed to NPs, they may experience both positive and negative effects on their growth and development (Jahan *et al.* 2022).

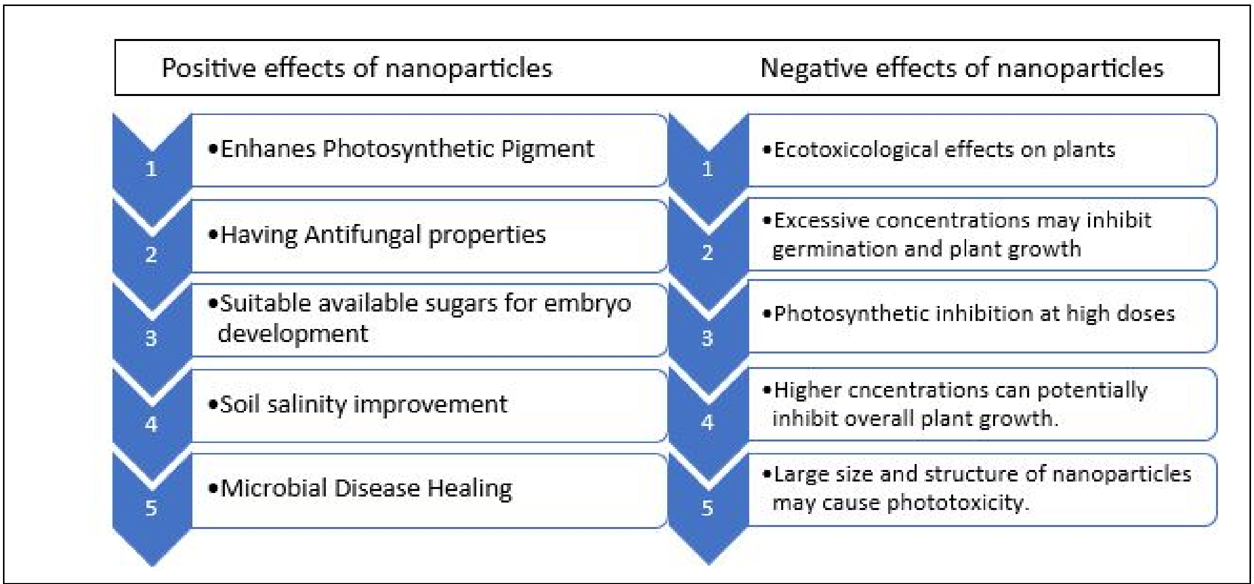


**Fig. 5: Pros and cons of nanoparticle effects on crops**

The impact of NPs on crop production and yield can be both positive and negative, depending on factors such as their characteristics, size, concentration, and category. For example, the effect of silver nanoparticles (AgNPs) on barley root length was found to be dose-dependent, with lower concentrations improving growth and higher concentrations inhibiting it. Similarly, titanium dioxide nanoparticles (TiO2NPs) have shown a dual nature, with some studies suggesting their role in increasing phosphorus availability for crop uptake and reducing heavy metal uptake by plants. Moreover, NPs may help improve plant CO2 fixation by interacting with RuBisCO, an important enzyme for photosynthesis. Nanotechnology can also enhance precision agriculture through variable rate technology (VRT) and automated machinery. VRT applies resources like fertilizers and pesticides precisely based on the specific needs of different soil types and crop health. Nanoparticles can be used as carriers for VRT, delivering resources exactly where they are required. This reduces waste, minimizes environmental pollution, and optimizes crop growth. Additionally, nano-biosensors can identify harmful heavy metals in soil, helping farmers take steps to protect crops and human health (Zain *et al.* 2024).

### 5.1 Nanosensors for Detecting Plant Pathogens

Pathogen detection and identification are critical to scientific understanding, environmental monitoring, and food safety. To detect bacteria, a variety of recognition components are utilized, including lectins, phages, aptamers, antibodies, bacterial imprints, and cell receptors, with bacterial receptors, antibodies, and lectins being the most prevalent due to their ease of integration into biosensors. While aptamers have advantages over antibody-based approaches in terms of cost and chemical stability, they also have drawbacks, such as batch fluctuations and complex production. "Chemical nose" technology, which mimics the human sense of smell, is a viable solution. This method uses a variety of receptors to generate distinct response patterns for various targets, which can then be identified by comparing them to a reference database. Nanoparticle-based "chemical nose" biosensors frequently involve altering nanoparticle surfaces with ligands for specific targets. Changes in nanoparticle aggregation are detected via colorimetric shifts and absorption spectrum alterations. This aggregation is controlled by bacterial cell wall components such as teichoic acids (Gram-positive) and lipopolysaccharides/phospholipids (Gram-negative), resulting in unique patterns for various bacteria. This method can even distinguish between polymicrobial and monomicrobial illnesses, facilitating tailored antibiotic therapy. Multichannel nanosensors, such as those based on gold nanoparticles, are capable of detecting bacterial species and biofilms quickly. Other nanosensor techniques are based on olfaction, which uses surface-functionalized nanoparticles, pro-smell fragments, and enzymes to achieve high sensitivity. Magnetic nanoparticles can also be used for pathogen separation and purification. Enzyme-based nanosensors provide another approach to detecting toxicologically relevant targets. Various optical, electrochemical, and immunosensors have also been created to detect plant-harmful bacteria, indicating nanotechnology's potential to transform pathogen detection (Sharma *et al.*, 2021).

## 6. ADVANCED DETECTION TECHNIQUES OF NANOPARTICLES

Nanosensors offer a promising solution for detecting heavy metal ions, which pose significant risks to human health and the environment. Optical chemical sensors that use nanohybrid CdSe quantum dots and noble nanoparticles hybridized with graphene can rapidly and sensitively detect heavy metals (Wang *et al*. 2016).

Colorimetric detection methods based on DNA conformation changes provide a simple and cost-effective way to detect heavy metals. Nanocomposites that have fluorescent and magnetic functionality can simultaneously detect and remove heavy metals, addressing concerns about secondary pollution. Multimodal nanosensors that encapsulate magnetic nanoparticles and fluorescent quantum dots provide efficient and eco-friendly detection and removal of heavy metals.

Nanoparticles, both naturally occurring and engineered, can pose environmental risks due to their widespread use and potential toxicity. Various nanomaterials, including metals, metal oxides, and carbon-based nanoparticles, can accumulate in the environment and harm cells by disrupting membrane permeability and protein transport pathways. Engineered nanoparticles that are released into soil systems can inhibit the growth of beneficial soil bacteria and affect soil nitrogen transformations. To address this, nanoparticles need to be monitored, especially in agroecosystems. Microcavity sensors, such as whispering gallery resonators, offer a promising technique for sensing nanoparticles by detecting changes in optical properties caused by particle binding. Optical sensing, particularly with single nanoscale entities, holds great potential for environmental monitoring and homeland security applications. These techniques enable real-time monitoring and evaluation of nanoparticle presence and size.

In agriculture, nanosensors can detect amino acids, metal ions, contaminants like fluoride ions, transgenic plants, aflatoxins, and plant wounds, enhancing productivity and safety across various fields (Sharma *et al.* 2021).

## 7. ROLE OF NANOPARTICLES AND NANOSTRUCTURES IN BIOLOGICAL DETECTION

Nanotechnology offers groundbreaking solutions by manipulating atoms and molecules to create nano- or microscale devices, revolutionizing fields like molecular diagnostics. Nanoparticles and nanostructures, with unique properties, are ideal for advanced biological detection, including lab-on-a-chip technology. Metal nanoparticles, like gold and magnetic varieties, show promise in bio-separation and diverse biological processes. Furthermore, quantum dots and nanowires enhance molecular detection, while nanopore technology identifies anomalies in nucleic acids. Transition Metal Dichalcogenides (TMDs) provide versatile materials with tunable properties that are beneficial for optoelectronics. However, the rising threat of warfare and terrorism necessitates efficient explosive detection methods. Metal nanoparticles show potential for trace explosive detection, but challenges remain in ensuring analytical parameters like sensitivity and selectivity, influenced by factors such as size, shape, and surface properties. Research into colorimetric explosive sensor systems utilizing metal nanoparticles as optical signal transducers aims to overcome these challenges, offering insights for developing reliable detection technologies (Adegoke *et al.* 2021; Hossain *et al.* 2023; Kirtana *et al.* 2022).

## 8. MONITORING NANOPARTICLE EFFECTS ON CROPS

Nanoparticles (NPs) exhibit diverse effects on plants, with silver (Ag) NPs enhancing root growth at lower concentrations but inhibiting growth at higher levels, while titanium dioxide (TiO2) NPs both increase phosphorus availability and reduce heavy metal uptake. Understanding NPs' environmental and health impacts is challenging due to their small size. They can influence key enzyme activity like RuBisCO, affecting photosynthesis. Studies show that nano-SiO2 and nano zeolite improve seed germination and growth under salinity stress, while nanofertilizers accelerate plant maturity in drought-prone areas. Nanomaterials also detoxify heavy metal pollutants and manage pests and diseases without harming the environment. Additionally, multi-walled carbon nanotubes and nano SiO2 enhance seed germination by improving water absorption and enzymatic systems. Despite benefits, NPs can induce genotoxicity, disrupt protein synthesis, and damage DNA, emphasizing the importance of careful application (Bakht *et al*. 2021; Shang *et al*. 2019). Gold exposure affects plant growth differently. Arabidopsis plants show stunted root growth and stress-related gene activation, while alfalfa plants prefer ionic gold uptake and adapt gene expression to cope with stress (Taylor *et al.* 2014). Silver nanoparticles can harm plants and human health. A study on tomato plants found that silver exposure changed water and nutrient absorption, posing significant implications for agriculture and human health (Noori *et al.* 2020). The potential of nanotechnology to create sustainable agricultural practices is explored, focusing on the use of nanosensors to monitor nanoparticle effects on crops, specifically highlighting the photocatalytic properties of Zn-doped NiO nanoparticles in eradicating toxins from aquatic environments. It proposes the use of photocatalytic nanoparticles in treating textile effluent for non-domestic applications, promoting sustainable agricultural practices. Additionally, the review examines the potential of hybrid nanoparticles as smart carriers for delivering agrochemicals, addressing climate change-induced water scarcity, and evaluating the use of Ag/SiO2 nanocomposites as an alternative to silver nanoparticles. Overall, the emphasis is on the promising role of nanotechnology in creating sustainable agriculture that can withstand environmental challenges (Boora *et al*. 2023; Kumari *et al*. 2024; Pavithra *et al*. 2023; Takeshita *et al*. 2023).

Nanoparticles were initially hailed for their potential to clean up the environment, but it turns out that they can unintentionally harm plants, posing risks to agricultural productivity and ecosystem health due to their toxicity, accumulation, and disruption of nutrient balance. Despite their potential benefits, concerns remain about nanoparticle safety and ecological impacts, which are hindering their widespread adoption in agriculture. The prevalence of engineered nanoparticles in everyday products is causing alarm about potential soil contamination and harmful effects on plant life. With advancements in nanotechnology, it is critical to understand how nanoparticles interact with plants to ensure their responsible use in sustainable agriculture and environmental management. As nanotechnology continues to advance, it becomes increasingly important to comprehend how nanoparticles interact with plants, given their significant influence on plant growth and health. Despite the promising agricultural potential of nanoparticles, concerns about their effectiveness and safety continue to impede widespread adoption, highlighting the need for ongoing research and monitoring efforts (Shrivastava *et al*. 2019; Xu *et al.* 2021).

## 9. FUTURE PERSPECTIVES AND LIMITATIONS

Nanobiosensors have created a breakthrough in plant pathogen detection by introducing innovative, cost-effective, and non-destructive solutions that use biomolecules as sensing receptors. This advancement is particularly vital in the food and agriculture industry, where strict quality control measures are necessary for both economic growth and public health. With the help of nanotechnology, electrochemical and optical sensors enable real-time monitoring, revolutionizing the industry by swiftly detecting contaminants and pathogens. This ensures food safety and enhances overall quality assurance measures (Kashyap *et al*. 2019; Srivastava *et al.* 2018).

However, there are some limitations to nanosensors in crops that need to be addressed. The environmental impact and toxicity associated with these sensors raise concerns, and it is crucial to ensure their long-term stability in harsh agricultural conditions. Additionally, the high initial costs hinder widespread adoption, making it challenging to implement them in resource-limited settings. Furthermore, nanosensors may face limitations in detecting a wide range of pathogens or contaminants, which can lead to false negatives or restricted applicability in certain crop diseases.

Therefore, it is necessary to address the safety concerns associated with nanomaterials. Developing robust regulatory frameworks will ensure the safe and effective deployment of nanosensors in agricultural settings. This approach will help ensure that the benefits of nanotechnology are fully realized, making our food systems safer, more efficient, and more sustainable (Li *et al.* 2020).

**Table 3. The effects of nanoparticles on different plant species**

| Study No. | Plant Species | Nanoparticle Type | Concentration (mg/L) | Uptake Mechanism | Physiological Responses | References |
|---|---|---|---|---|---|---|
| 1 | Lavandula angustifolia (Lavender) | Silver(Ag) NPs | 1-2 mg/L | In vitro solid cultivation medium | Stimulated root development and biomass growth | (Landa, 2021) |
| 2 | O. sativa, Z. mays | CuO NPs | 40 nm | Transported from roots to shoots, dissolved Cu(II) combined with ligands | Reduction of Cu(II) to Cu(I) inside plant tissues | (Rajput *et al*. 2020b) |
| 3 | Dicotyledon plants | Nanostructure s | - | Stomata, Cuticle, Trichomes, Hydathodes, Necrotic spots | Improved foliar uptake, increased bioavailability, reduced environmental impact | (Avellan *et al*. 2021) |
| 4 | Mung bean (Vigna mungo) | Carbon dots | 1 mg/mL | Transported through apo plastic pathways | Boosted nutrient consumption and utilization | (Ali *et al*. 2021) |
| 5 | Zea mays | Carbon Nanodots (CDs) | 1000-2000 | Effective absorption and translocation | Decreased root and shoot biomass, $H_2O_2$ accumulation, lipid peroxidation, and activation of antioxidant enzymes (CAT, APX, GPX, SOD). | (Szőllősi *et al*. 2020) |
| 6 | Zea mays | Si nanoparticles | - | Active, Passive | Increased microbial biomass, enhanced growth | (Rajput *et al*. 2021a) |

Future research will focus on development of nanomaterials and nanotechnology to enable IoNT vision and to provide widespread nanoproducts that are safe for humans as well as the environment (Omanović *et al.* 2016).

## 10. CONCLUSION

In conclusion, the exploration of nanotechnology's applications in agriculture, particularly in monitoring and detecting nanoparticle effects on crops, represents a pivotal step towards sustainable and efficient food production. Nanoparticles offer a multitude of benefits, from enhancing nutrient delivery and pest management to improving plant health and resilience against environmental stressors. However, alongside these promising advancements come important considerations regarding the long-term effects, safety, and environmental impact of nanoparticle use in agriculture. As we navigate this frontier, it becomes increasingly evident that careful research, monitoring, and regulation are paramount to ensure the responsible and effective deployment of nanotechnology in farming practices. Addressing concerns about nanoparticle toxicity, environmental accumulation, and unintended consequences is crucial for fostering trust and widespread adoption within the agricultural community. Moreover, the development of advanced detection techniques presents an invaluable opportunity to revolutionize crop monitoring and disease detection, thereby enhancing food safety and quality assurance measures. Despite challenges such as cost and environmental impact, continued innovation and collaboration in this field hold immense potential to transform our food systems for the better. In moving forward, it is imperative to prioritize sustainability, safety, and equity in agricultural practices, leveraging the power of nanotechnology to create resilient and environmentally conscious farming solutions. By embracing these principles and harnessing the potential of nanotechnology responsibly, we can pave the way for a brighter and more sustainable future for agriculture and food security worldwide.

## FUNDING

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

## CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.



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