Nano sensors: A Smart Technology for Improving Nutrient Use Efficiency

Barsha Mansingh[1]*, G.D. Sharma[2] Sandeep Manuja[3], Shivalika[4], Sabhya Sharma[5] and Shagun Thakur[6]

[1,4,5,6]Ph. D. Scholar, [2]Principal Scientist, [3]Professor Agronomy, Department of Agronomy, CSK HPKV, Palampur, HP, India-176062

Corresponding Author
Barsha Mansingh
Email: barshamansingh5480@gmail.com

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ABSTRACT

Nutrient use efficiency (NUE) plays an important role in improving crop productivity while reducing excessive fertilizer use in agriculture. However, a significant portion of applied nutrients is lost through leaching, runoff, and volatilization, resulting in economic losses and environmental pollution. Nano sensor technology has emerged as a promising tool to address this challenge by enabling precise monitoring of soil nutrients and plant conditions. These sensors can detect small changes in nutrient levels and provide real-time information for better nutrient management. By supporting precise fertilizer application, nano sensors have the potential to enhance NUE and promote sustainable agricultural practices.

INTRODUCTION

Plant nutrients are essential for crop growth and productivity. Nutrients such as nitrogen, phosphorus, and potassium play key roles in processes like photosynthesis, root development and grain formation. To achieve higher yields farmers depends on fertilizers. However, crops often utilize only a portion of the applied nutrients. A significant amount is lost through leaching, runoff, volatilization and fixation in the soil. These losses increase production costs and contribute to environmental problems such as soil degradation and water pollution. India is one of the largest consumers of fertilizers and spends heavily on subsidies while also depending on imports, particularly for

phosphatic and potassic fertilizers. Yet, the efficiency with which crops use these nutrients remains relatively low, highlighting the need for more precise and efficient nutrient management strategies (Zhang *et al.,* 2023).

Now a days nanotechnology has emerged as a promising field offering new solutions for improving nutrient efficiency. Among these innovations, nano sensors are gaining considerable attention. Nanosensors are extremely small sensing devices capable of detecting minute changes in soil nutrients, plant root zone and environmental conditions with high sensitivity and accuracy. By providing real-time information about nutrient availability and plant requirements, nanosensors enable farmers to apply fertilizers more precisely and only when needed. This targeted approach helps minimize nutrient losses, optimize fertilizer use and improve crop productivity. Therefore, nanosensor technology holds significant promise for improving nutrient use efficiency and promoting more sustainable agricultural practices (Mobeen *et al.,* 2025).

Nano sensors:

Nanosensors are extremely small sensing devices developed with the help of nanotechnology. Due to their tiny size and high sensitivity, they can detect very small changes in their surroundings, such as variations in nutrient levels, changes in root zone nutrient concentration, plant responses and environmental conditions. Nano sensors act like miniaturized monitoring tool that help scientists and farmers understand what is happening in the soil and inside plants. Nanotechnology in agriculture involves the use of materials at a very small scale (about 1–100 nano meters) to improve farming practices. At this scale, materials show unique properties that is very different from macro materials. By using these properties, nano sensors can monitor soil nutrients, plant health and environmental conditions more precisely than conventional methods (Ibrahim *et al.,* 2024). The working principle of nano sensors is quite simple. These sensors contain special sensing materials that react when they come in contact with a specific nutrient or chemical compound. This interaction causes a small change in properties such as electrical signals, light signals or magnetic responses. The sensor detects this change and converts it into a measurable signal that can be analyzed. By providing timely and accurate information, nano sensors can support more efficient nutrient management and help improve crop productivity. This information can help farmers make better decisions about fertilizer application and crop management.

Types of Nano sensors Used in Agriculture:

Different types of nano sensors have been developed to monitor soil nutrients and plant conditions. Each type works in a different way depending on the property it measures.

- Electrochemical nano sensors are commonly used to detect nutrient ions present in the soil solution. These sensors work by measuring small changes in electrical signals that occur when specific nutrients such as nitrate, ammonium, phosphorus or potassium interact with the sensing surface (Narang *et al.,* 2024).

- Optical nanosensors detect nutrients through changes in light signals. When certain nutrients interact with the sensing material, they can alter the way light is absorbed, emitted, or reflected. These changes are then measured by the sensor to determine the presence or concentration of nutrients. Optical nanosensors are useful for monitoring plant health and detecting nutrient deficiencies at an early stage.

- Magnetic nanosensors use magnetic nanoparticles to identify specific molecules or substances. When these particles interact

with targeted nutrients or biological molecules, they produce measurable magnetic signals. This type of sensor is particularly helpful for detecting small quantities of substances with high accuracy.

- Biosensors combine biological components such as enzymes, proteins or microorganisms with nanomaterials. These biological elements react with specific nutrients and the nanoscale materials help convert that reaction into a detectable signal. Biosensors are widely used for monitoring soil nutrients and assessing plant physiological conditions.

Applications of Nano sensors in Agriculture:

- Monitoring soil nutrient status: Detect real-time levels of nutrients such as nitrogen, phosphorus, and potassium in the soil.
- Early detection of nutrient deficiencies: Identify nutrient shortages in crops before visible symptoms appear.
- Monitoring plant health and stress: Detect stress caused by nutrient deficiency, drought, pests, or diseases.
- Precision fertilizer management: Guide accurate and timely fertilizer application based on crop requirements.
- Soil moisture monitoring: Measure soil water content to support efficient irrigation management.
- Detection of pathogens and pests: Identify harmful microorganisms or pests affecting crops.
- Environmental monitoring: Track factors such as temperature, humidity, and soil conditions affecting crop growth.
- Integration with precision agriculture: Work with technologies like drones, GPS, and digital farming systems for site-specific crop management.

Advantages of Nanosensors:

- High sensitivity and accuracy: They are extremely sensitive and can detect even very small changes in nutrient levels or plant signals.
- Rapid detection: These sensors can quickly identify changes in nutrient concentrations or plant conditions.
- Real-time monitoring: Nanosensors can continuously monitor soil and plant conditions and provide real-time data.
- Reduced fertilizer wastage: By providing precise information about nutrient availability, nanosensors help farmers apply fertilizers only when needed and in appropriate amounts, reducing unnecessary fertilizer use.
- Environment-friendly farming: Efficient nutrient management through nano sensors helps minimize nutrient losses to the environment so helps in reducing soil degradation and water pollution.

Limitations of Nanosensors:

- High initial cost: The development and installation of nanosensor-based systems can be costly, which may limit their use by many farmers.
- Limited availability: Most nanosensor technologies are still in the research or experimental stage and are not yet widely available in the market.
- Need for technical expertise: Farmers may require training to properly use nano sensors and understand the data generated by these systems.

- Limited field validation: Many nano sensors have been tested mainly under controlled conditions.
- Environmental and safety concerns: The long-term impact of nanomaterials on soil health, ecosystems and human safety still needs further investigation.

Future Prospects:

- Integration with precision agriculture: Nano sensors can be combined with modern tools such as drones, satellite monitoring, and digital farming platforms to support data-driven nutrient management.
- Development of low-cost nanosensors: Ongoing research aims to design affordable nanosensor technologies that can be easily adopted by farmers.
- Smart nutrient management systems: In the future, nano sensors may help guide fertilizer application based on real-time information about soil and crop nutrient status.
- Promoting sustainable agriculture: By improving nutrient monitoring and reducing fertilizer losses, nanosensors can support environmentally friendly farming practices.

CONCLUSION:

Nanosensor technology offers a promising approach for improving nutrient management in modern agriculture. By providing accurate and real-time information about soil nutrients and plant health, these sensors can help farmers apply fertilizers more efficiently and reduce nutrient losses. Although challenges such as cost, technical requirements, and limited field validation still exist, ongoing research and technological advancements are expected to overcome these barriers. In the coming years, nanosensors could play an important role in enhancing nutrient use efficiency, promoting sustainable farming practices, and ensuring long-term food security (Karuvelan *et al*., 2025).

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