

Nanosensor Deployment in Precision Nutrient & Moisture Monitoring

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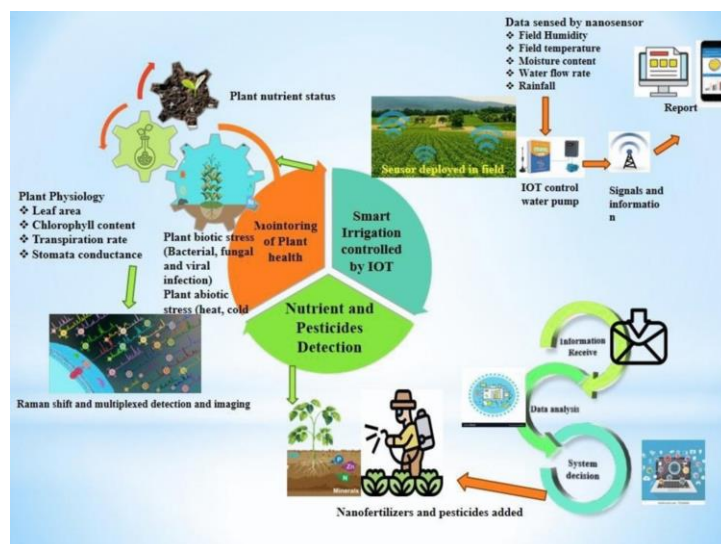
INTRODUCTION

Precision agriculture leverages data-driven tools to optimize resource use, improve crop yield, and reduce environmental impact. Fundamental to this is monitoring soil nutrients (N, P, K, micronutrients) and moisture—key indicators of plant health. Traditional laboratory-based testing, while accurate, is costly, slow, and low-resolution in time and space. With the advent of nanosensors—miniaturized sensors utilizing nanomaterials—farmers can now achieve in-situ, real-time, high-resolution measurements directly in the field, transforming nutrient and moisture management.

2. What Makes Nanosensors Ideal for Field Use?

2.1. High Selectivity & Sensitivity

Nanomaterials such as CNTs, graphene, metal oxides, and quantum dots have great surface-to-volume ratios and functionalizability, which allow detection of infinitesimal changes in soil water and nutrient.



Source: <https://link.springer.com>

2.2. High-Speed Response with Low Power Demand

With fast adsorption–desorption kinetics at the nanoscale and high-performance electrochemical transduction, sensors such as graphene oxide-based humidity sensors respond in seconds, detecting soil moisture over 0.1–90% RH.

2.3. Miniaturized & In Situ Deployment

Made with micro/nano methods and flexible electronics, sensors may be integrated into soil or placed on the leaves of plants (e.g. leaf/plant wearables), providing real-time, spatially resolved data.

2.4. Connectivity & Intelligence

Low power wireless communication (LoRa, NB IoT) facilitates deployment in sensor networks. Data is input to cloud/AI platforms to analyze trends, detect anomalies, and support decisions.

3. Nutrient Monitoring with Nanosensors

3.1. Nitrogen (N)

Point-of-use ammonium (NH_4^+) sensors— $< \$0.10$ —sense NH_4^+ at $\sim 3 \pm 1$ ppm. Combined with pH and conductivity, they calculate nitrate (NO_3^-) concentrations, allowing for optimal fertilization.

Graphene/CNT-based sensors functionalized to measure nitrate, phosphate, and micronutrients provide real-time soil nutrient profiling.

3.2. Phosphorus (P) & Potassium (K)

Although less developed than nitrogen sensors, new electrochemical sensors hold promise for sensing multiple macro-nutrients.

3.3. Micro- and Secondary Nutrients

Metal-oxide quantum dots monitor Fe, Zn, Cu, supplementing macro-nutrient sensing in precision nutrient management.

3.4. Nano-biosensors & Plant Wearables

Biosensors analyze phytohormones, chlorophyll fluxes, sap nutrient concentrations—offering direct insight into plant nutritional stress.

4. Moisture Monitoring with Nanosensors

4.1. Soil Moisture Sensors

- CNT or graphene sensors quantify dielectric constant or impedance changes with water content.

- A graphenic humidity sensor provides real-time RH detection from 0.1–90%.
- Advances in dispersive phase shifter sensors provide $\sim \pm 1.2\%$ VWC accuracy at 30% moisture—small and IoT compliant.

4.2. Leaf/Plant Moisture Monitoring

Leaf sensor products (e.g. AgriHouse SG 1000) detect water potential or leaf thickness to indicate plant water stress, supporting irrigation.

4.3. Hydrogel Embedded & Nano functionalized Materials

Nanoclay/hydrogel sensors are able to sense both moisture and release water/nutrients gradually—dual-purpose for soil conditioning.

5. Sensing Platforms & Integration

5.1. Wireless Sensor Networks (WSNs)

Wireless protocols of distributed sensor arrays (nutrient + water) input data into field-scale monitoring and management systems.

5.2. Micro-nano-Systems & Flexible Electronics

Microfluidics and flexible CNT or graphene electronics integrated into sensors bend around soils/plants for non-invasive application and resilient performance.

5.3. AI & Cloud Based Analytics

Biological sensor data (nutrient, moisture, stress, VOCs) is combined with AI to forecast disease onset, irrigation planning, nutrient requirements; cloud platforms provide visualization & decision support.

6. Case Studies & Impact

- **Japan (rice paddies):** real-time nanosensing enabled a 20% yield increase and 30% reduction in water/fertilizer use.
- **India (Punjab, nano-fertilizers):** sensor-guided use of nano-fertilizers yielded 25% more wheat and cut fertilizer use by 40%.
- **Brazil (soy plantations):** nano-pesticide targeting, paired with nutrient/moisture sensors, cut chemical use by 50% and contamination by 70%.
- **Australian vineyards:** nanosensor deployment improved monitoring of soil pH/nutrient/moisture, slicing inputs by $\sim 35\%$.

These demonstrate improved input efficiency, yield boost, cost reduction, and environmental gains.

7. Challenges and Limitations

Challenge	Description
Manufacturing & Scalability	Producing robust, low-cost nanosensors at field scale remains difficult .
Durability	Soil environments—moisture, pH, biofouling—demand chemically stable designs with long-term accuracy.
Calibration & Standardization	Sensor drift and environmental variability require frequent calibration and universal protocols.
Data Overload	WSNs generate massive data streams; AI/ML integration and infrastructure for storage and processing pose big challenges .
Regulatory & Environmental Concerns	Safety of nanomaterials in soil/water needs regulation; standard guidelines are lacking .
Farmer Training & Cost	Adoption depends on farmer education and lower upfront costs .

8. Future Outlook & Research Directions

The future of nanosensor deployment in agriculture lies in advancing sustainable, intelligent, and accessible technologies. **Biodegradable and eco-safe nanomaterials**, like cellulose-based sensors, will reduce environmental impact post-use. **Multiplexed, multi-modal sensors** will provide comprehensive soil data by tracking nutrients, moisture, pH, and pathogens simultaneously. **Energy-harvesting systems**, using solar or RF technologies, will power sensors autonomously, eliminating battery dependency.

The rise of **edge AI and federated learning** will enable real-time data analysis on-device while preserving farm data privacy. **Open-source sensor platforms** combined with farmer training programs will empower smallholders through DIY solutions. Finally, the implementation of **global governance standards and certifications** will ensure sensor accuracy, safety, and interoperability—crucial for scalable, responsible agricultural technology adoption worldwide.

9. CONCLUSION

Nanosensor deployment is revolutionizing precision agriculture by enabling real-time, high-resolution, wirelessly-connected monitoring of critical soil parameters—nutrients and moisture. These innovations support optimized irrigation, fertilizer use, early stress detection, and

environmentally sustainable practices. Real-world cases show up to 30–50% resource savings and yield gains. However, large-scale implementation hinges on addressing durability, cost, regulatory, and data challenges. With multidisciplinary cooperation across nanotech, agronomy, engineering, AI, and policy, nanosensor systems promise to underpin next-generation smart farming—boosting productivity sustainably to feed humanity’s future.

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