



Smart Nanosensors for Assessing Nanoparticle Interactions in Crops: A Review

K. Parimalagandhi^{1*}, Subha Rajendran², M. Esakkiammal³, P. Sudha⁴ and A. Simi⁵

¹Department of Science and Humanities, Nehru Institute of Technology, Coimbatore, TN, India

²Department of Chemistry, Cauvery College for Women, Trichy, TN, India

³Department of Chemistry, National College, Trichy, TN, India

⁴Department of Mathematics, Cauvery College for Women, Trichy, TN, India

⁵Department of Chemistry, St. Joseph College, Trichy, TN, India

Received: 08.09.2025 Accepted: 01.12.2025 Published: 30.12.2025

*nitparimala@nehrucolleges.com



ABSTRACT

Growing use of nanotechnology in agriculture has sparked concerns about the intricate relationships between crop systems and nanoparticles (NPs). Engineered nanoparticles such as carbon-based compounds, silver, zinc oxide, and titanium dioxide can enhance stress tolerance, insect resistance, and nutrient delivery. However, little is known about their unforeseen consequences for plant physiology and food safety. Conventional techniques for monitoring NP behavior are frequently damaging, time-consuming, and inappropriate for real-time observation. Cutting-edge nanosensors offer a revolutionary alternative. They enable precise measurement of NP uptake, transport, accumulation, and associated metabolic reactions in plants by integrating advanced sensing mechanisms with wireless and data-driven technologies. These sensors employ highly sensitive and selective optical, electrochemical, and biosensing platforms. For example, electrochemical nanosensors have been employed to identify the advantages and disadvantages of silver NP accumulation in spinach leaves. Their versatility across wearable, IoT-enabled, and field-deployable formats makes them useful for tracking and monitoring the health of plants exposed to NP. This paper examines the fundamentals, applications, and most recent developments in agricultural nanosensors, emphasizing their use in assessing the risks and advantages of nanoparticles. Environmental safety, cost-effectiveness, and sensor stability are currently the key challenges. Future developments will be guided by sustainability, AI integration, and multifunctional sensing. Nanosensors are a significant advancement in precision agriculture and well-informed risk assessment in the age of nano-enabled food production.

Keywords: Smart nanosensors; Nanoparticle–crop interactions; Biosensing technologies; Plant health monitoring; Nanotoxicology; Food safety assessment.

1. INTRODUCTION

With the ever-advancing nanotechnology, agriculture is undergoing ground-breaking change. The use of nanoscale materials and sensors permits accurate input distribution and ongoing crop health monitoring. Carbon-based materials, ZnO, Ag, TiO₂, and other engineered nanoparticles (NPs) are being investigated as nanopesticides, nanofertilizers, and stress-modulators. Concerns regarding absorption, translocation, phytotoxicity, and food safety are raised by their activity in soil–plant systems. Oxidative stress, nutritional imbalance, and bioaccumulation are among the effects that have been documented. These hazards emphasize the necessity of *in situ*, real-time monitoring under various field circumstances and growth stages (Chaturvedi *et al.* 2025).

Plant NP fate can be mapped using standard techniques such as spectroscopy, chromatography, and microscopy. However, they are sluggish, damaging, and unsuitable for ongoing field monitoring. To fill this gap,

smart nanosensors are used. They monitor NP interactions with great sensitivity and selectivity using optical, electrochemical, and biosensing systems. For instance, in real-time, nanosensors can identify ambient pollutants, pathogens, nutrients, phytohormones, and redox signals, such as H₂O₂ (Ur *et al.* 2021).

As wireless communication, Internet of Things (IoT) architectures, and machine-learning analytics converge, deployment from the lab to the field is speeding up. Wearable and implantable plant sensors, such as flexible patches, leaf tattoos, and stem wraps, now capture strain, transpiration, electrophysiological, and chemical signaling. This allows for the early diagnosis of stress before symptoms become apparent (Gupta *et al.* 2023). Plant surface coupling, durability, and data quality issues are being addressed by these systems more and more, leading to reliable, field-ready platforms that can map NP-induced responses over time and space. However, the larger body of research in nanobionics shows how nano-enabled interfaces can give plants sensing capabilities for a variety of analytes,

confirming the viability of on-plant chemical surveillance pertinent to NP exposure situations (Rowe *et al.* 2022). While critically analyzing limitations (such as selectivity in complex matrices, long-term stability, and biocompatibility), regulatory considerations, and opportunities for AI-assisted, climate-smart agriculture, this body of work collectively calls for a specialized synthesis on innovative nanosensors for evaluating nanoparticle interactions in crops—from fundamental principles and device architectures to case studies and field deployment.

2. PRINCIPLES OF SMART NANOSENSORS

Innovative nanosensors are cutting-edge instruments with great sensitivity, selectivity, and quick reaction times that are intended to identify and measure specific chemical or biological signals at the nanoscale. These sensors fall into three general categories: optical, electrochemical, and biosensing platforms (Singh *et al.* 2021). Each of these uses a different transduction mechanism to monitor target analytes in agricultural systems and plants. Optical nanosensors use surface plasmon resonance, quantum dot emission, or variations in fluorescence to identify particular chemicals or environmental stimuli. Owing to their high sensitivity and non-invasiveness, they can monitor physiological and biochemical activities in plants in real time (Parimala *et al.* 2024). By detecting analytes by electrical property changes, such as voltammetry, impedance, or conductometry, electrochemical nanosensors can provide quick and accurate readouts of pollutants, stress markers, or nutritional levels (Lew *et al.* 2020). Enzymes, DNA, antibodies, aptamers, and other biological recognition components are combined with transducers in biosensors to selectively detect biomolecules, pathogens, or signaling molecules in plant tissues.

Wearable and implantable nanosensors for plants, such as flexible leaf patches or stem-integrated devices, have been made possible by recent advancements. These devices allow for continuous monitoring without interfering with plant growth. These nanosensors offer a dynamic platform for precision agriculture when combined with smart features such as wireless transmission, real-time data capture, IoT connectivity, and AI-based data analysis. Innovative nanosensors provide an unparalleled toolkit to track crop health, identify the effects of nanoparticles, and direct sustainable agricultural treatments by fusing digital intelligence with nanoscale sensitivity.

3. EXPOSURE TO NANOPARTICLES IN AGRICULTURAL SYSTEMS

The need for agriculture to sustainably feed the world's expanding population is growing, despite obstacles including diminishing soil fertility, water scarcity, and stress brought on by climate change. Since

nanotechnology enables precise agrochemical administration, enhances nutrient efficiency, and improves plant stress tolerance, it has emerged as a promising avenue for addressing these global challenges. The manufactured materials known as nanoparticles, which have at least one dimension smaller than 100 nm, have special physicochemical characteristics such as a high surface-area-to-volume ratio, increased reactivity, adjustable surface functionalization, and controlled release capabilities. These characteristics render them appealing for a variety of agricultural uses, encompassing soil remediation, crop protection, fertilizers, and insecticides.

NPs can, however, interact with plants in intricate and frequently unforeseen ways due to their small size and strong reactivity. NPs can either cause toxicity, oxidative stress, and nutritional imbalances or they can promote plant growth and productivity, depending on their composition, concentration, size, shape, and surface chemistry. For the safe and efficient use of nanotechnology in agriculture, it is crucial to comprehend how NPs enter agricultural systems, how they interact with various plant structures, and how they ultimately affect crop performance and food safety (Mamatha *et al.* 2023). A thorough examination of nanoparticle exposure in agricultural systems is given in this section, with particular attention paid to: (i) common nanoparticles used in agriculture, (ii) pathways of entry into crop systems, (iii) mechanisms of interaction at the cellular, root, and leaf levels, and (iv) striking a balance between positive and negative effects.

3.1 Common Nanoparticles Used in Agriculture

The distinct physicochemical characteristics of NPs, such as their high surface area-to-volume ratio, adjustable reactivity, and improved solubility, have made nanotechnology a promising instrument in agriculture. In agriculture, zinc oxide (ZnO), titanium dioxide (TiO₂), silver (Ag), and carbon-based nanoparticles like graphene and carbon nanotubes are some of the most often used NPs (Kaliyaperumal *et al.* 2025). Numerous applications for zinc oxide nanoparticles as nano-fertilizers provide plants with vital micronutrients, especially zinc, which is essential for enzyme activity, protein synthesis, and general growth. Because of their photocatalytic qualities, TiO₂ nanoparticles are widely used to increase photosynthetic efficiency and shield plants from UV light (Haase *et al.* 2020). Ag nanoparticles are used in formulations to reduce plant diseases caused by bacteria and fungi, owing to their well-known antibacterial properties. The potential of carbon-based nanomaterials, like graphene oxide and carbon nanotubes, to improve soil structure, facilitate nutrient delivery, and increase water retention has been investigated. The various NP classes demonstrate their revolutionary potential in contemporary agriculture by offering a variety of uses, ranging from stress tolerance

to disease management and growth stimulation (Chanu and Singh, 2022). The extensive use of these materials, however, calls for a thorough evaluation of their effects on the environment and biology because of the unpredictable ways in which their special qualities may interact with crop systems.

3.2 Pathways of Entry into Crop Systems

There are several routes for nanoparticles to enter crop systems, reflecting their diverse applications in contemporary agriculture. One primary method is soil amendment, in which NPs are mixed into the soil as soil conditioners or nano-fertilizers. Once in the soil, these particles may interact with minerals, microbes, and soil organic matter, changing their toxicity, mobility, and bioavailability. Another critical method is foliar treatment, which involves directly applying NP-based sprays to leaves to improve nitrogen uptake or offer disease protection. By acting as a conduit for particle transport to roots, irrigation water contaminated or enriched with NPs may facilitate their absorption through the rhizosphere (Alam *et al.* 2024). Furthermore, nanoparticles are being increasingly used in the formulation of traditional agrochemicals, like pesticides and fertilizers, to increase their solubility, stability, and effectiveness of delivery. Since these entrance pathways interact uniquely with the plant's anatomy, physiology, and surrounding microenvironment, they highlight the intricate dynamics of nanoparticle exposure in agricultural systems. Environmental elements that influence the transport and alteration of nanoparticles and ultimately determine their fate within plant tissues include soil pH, moisture content, and microbial activity (Bharti *et al.* 2024).

3.3 Mechanisms of Interaction at the Cellular, Root and Leaf Levels

Crops and NPs interact in a variety of ways at the cellular, root, and leaf levels. NPs can either adsorb onto the root surface or pass through apoplastic and symplastic channels at the root interface. As the first barrier, the cell wall and root epidermis prevent bigger NP aggregates from passing through while permitting smaller NPs to enter the cell. NPs may move along the xylem after entering the root tissues, arriving at the aerial plant parts where they can affect nutrient transport and signaling cascades (Elsheery *et al.* 2020). NPs can also flow through root barriers by foliar absorption, which mostly takes place through stomatal apertures and cuticular routes, in addition to root uptake. Leaves are especially vulnerable to NP exposure since they are the main locations for photosynthesis. Overall, photosynthetic efficiency and stress responses can be

impacted by nanoparticles' ability to modify chlorophyll concentration, change stomatal conductance, and trigger the generation of reactive oxygen species (ROS). Nanoparticles may interact with membranes, organelles, and biomolecules at the cellular and subcellular levels. For example, carbon-based NPs can change membrane permeability or promote nutrient transport, whereas metallic NPs can catalyze the production of ROS, impacting redox equilibrium. Furthermore, several NPs can attach to proteins, DNA, or enzymes, changing signaling pathways and enzymatic activity. The intricate, context-dependent nature of nanoparticle-plant interactions is highlighted by the fact that they are impacted by NP properties such as size, shape, surface charge, and coating in addition to plant species and developmental stage (El-Saadony *et al.* 2022).

3.4 Striking a Balance Between Positive and Negative Effects

NPs offer a number of benefits for managing stress and increasing crop yield. The nutrient uptake, photosynthetic efficiency, root and shoot biomass, and germination rates have all been found to be improved by ZnO and TiO₂ NPs. Ag nanoparticles' antibacterial qualities can lower the prevalence of illness and encourage more robust crop growth. Carbon-based NPs increase the availability of nutrients in the soil and the efficiency of water consumption, particularly in nutrient-deficient and arid soils. Furthermore, tolerance to abiotic stressors, including drought, salt, and severe temperatures, can be conferred by specific nanoparticles that increase the expression of genes that respond to stress (Singh *et al.* 2022). All of these advantages work together to increase agricultural yields, enhance resource efficiency, and correlate with sustainable and precision farming concepts.

Despite these benefits, using NPs carries certain significant risks that should be carefully considered. By excessive ROS generation, metallic nanoparticles can cause oxidative stress and harm DNA, lipids, and proteins. Nutritional abnormalities could result from an overabundance of NPs interfering with the absorption and movement of vital minerals. Although antibacterial, silver and copper nanoparticles may potentially damage beneficial soil microbes and alter the dynamics of the rhizosphere. High quantities of nanoparticles can cause cytotoxicity, which hinders root growth, photosynthesis, and seed germination (Gulati *et al.* 2025). Additionally, the buildup of nanoparticles in edible plant tissues raises questions about food safety and possible health hazards for consumers. In order to maximize agronomic benefits and minimize negative effects, precise dose, targeted application, and ongoing monitoring are essential (Sampedro-Guerrero *et al.* 2023).

4. APPLICATIONS OF NANOSENSORS IN MONITORING CROP NANOPARTICLE INTERACTIONS

4.1 Nutrient Uptake and Transport Monitoring

Precision monitoring of nutrient uptake and transport in crops is made possible by innovative nanosensors, mainly when nanoparticles like zinc and iron are employed as micronutrient carriers. The effectiveness of NP-assisted nutrient delivery is revealed by nanosensors, which identify the dynamic mobility of these vital components throughout roots, stems, and leaves (Fig. 1). This real-time tracking enables the optimization of nano-fertilizer compositions and application rates, ensuring that plants receive adequate nutrition while reducing waste and environmental runoff (Zhang *et al.* 2022).

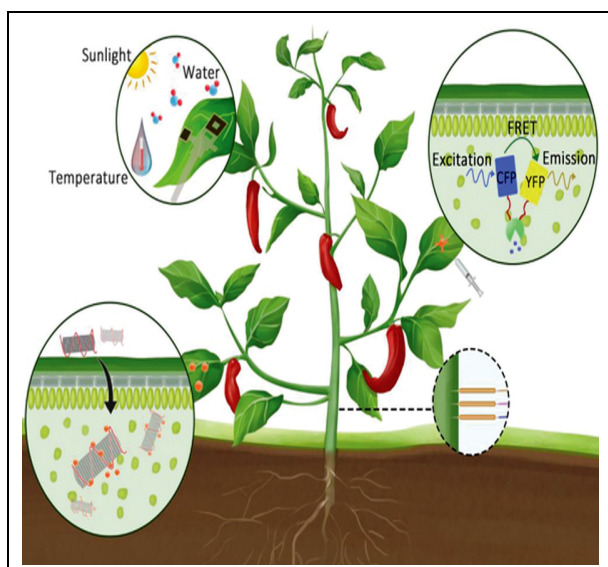


Fig. 1: Nanosensors for plant monitoring

4.2 Detection of Nanoparticle-induced Stress

At low concentrations, NPs are advantageous, but at greater quantities, they can cause oxidative stress and cellular damage. By detecting biomarkers, including ROS, hydrogen peroxide, and stress-related enzymes (Fig. 2), nanosensors allow for the early detection of physiological abnormalities brought on by NPs. Timely treatments to reduce toxicity, preserve plant health, and avoid yield losses are made possible by early detection of such stress responses (Zain *et al.* 2023).

4.3 Soil and Rhizosphere Monitoring

One of the most important elements influencing how nanoparticles affect crops is their mobility and bioavailability in the soil and rhizosphere. When placed in the soil, nanosensors can track the concentrations, changes, and interactions of NP with soil microbes (Shaw

and Honeychurch, 2022). To support sustainable agricultural operations, this information is crucial for understanding NP fate, improving soil application techniques, and reducing possible environmental pollution.

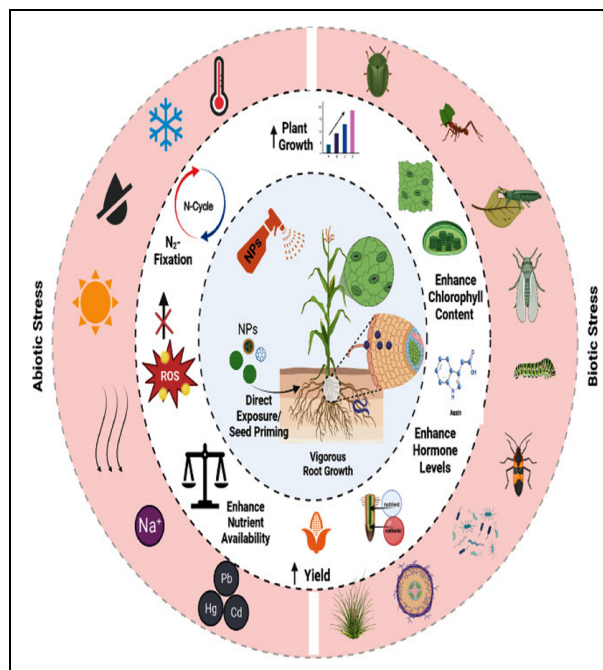


Fig. 2: Pictorial representation of plant–NP interactions under various biotic and abiotic stress conditions

4.4 Tracking Nanoparticle Accumulation in Edible Plant Parts

Food safety is a big concern when nanoparticles accumulate in edible plant tissues. Fruits, cereals, and vegetables can have NP deposition detected and measured using nanosensors, which provide vital information for risk assessment and regulatory compliance. These sensors guide the ethical use of nano-enabled agrochemicals and help guarantee that crops remain safe for human consumption by providing non-destructive, *in situ* monitoring (Subodh *et al.* 2023).

4.5 Field-deployable Nanosensor Systems for Large-scale Monitoring

Nanosensors may now be used at the field scale for real-time crop monitoring thanks to recent developments (Dehghanian *et al.* 2021). These systems provide continuous monitoring of vast agricultural fields by integrating wireless data transmission, IoT connectivity, and AI-based analytics. By giving farmers useful information on nutritional status, stress levels, and nanoparticle dispersion, such deployment aids precision agriculture techniques and eventually increases production, efficiency, and sustainability.

5. OBSTACLES AND RESTRICTIONS

Several obstacles prevent nanosensors from being widely used in agriculture, despite their promising applications in tracking nanoparticle-crop interactions. Technological challenges include maintaining sensitivity and selectivity, which can be hindered by complex crop matrices such as soil organic matter, root exudates, and diverse microbial communities (Giraldo *et al.* 2019). Ensuring stability and durability under real-world field conditions, such as fluctuating temperatures, high humidity, UV radiation, and mechanical stress, remains a substantial hurdle. Furthermore, scalability and cost-effectiveness pose difficulties, particularly for deployment in resource-limited agricultural settings (Miguel and Perez, 2023). Environmental challenges arise from the potential impacts of metallic or carbon-based nanosensors on soil ecosystems, including disruptions to microbial communities and alterations in soil nutrient cycling. Ethical concerns relate to unintended ecological repercussions, such as bioaccumulation of nanomaterials in plants or their transfer across food webs, which could affect food safety and biodiversity. Finally, regulatory challenges stem from the absence of clear guidelines for nanosensor use in agriculture, making it difficult to standardize testing protocols, assess long-term risks, and achieve market approval. Addressing these issues will require not only scientific innovation but also interdisciplinary collaboration to establish robust governance and safety frameworks. Together, these steps are essential to responsibly harness nanosensors for sustainable agriculture (Pinki *et al.* 2025).

6. FUTURE DIRECTIONS AND CHALLENGES IN NANOPARTICLE INTERACTIONS IN CROPS

The creation of multipurpose, highly integrated systems that can concurrently monitor numerous physiological, biochemical, and environmental factors is the key to the future of nanosensors in agriculture (Wong *et al.* 2017). Technical advances are expected to include the integration of machine learning and artificial intelligence for improved data interpretation, enabling early warning systems for stress detection and predictive modeling of crop responses to nanoparticle exposure. Real-time decision-making will be supported by linking nanosensors with cloud platforms and IoT-enabled networks, which directly connect sensor outputs to precision agriculture interventions such as targeted watering or fertilization (Prasad *et al.* 2017). Emerging technologies like self-powered and biodegradable nanosensors provide sustainable options for continuous monitoring, while wearable and implantable plant nanosensors are anticipated to evolve into scalable platforms capable of delivering spatially resolved field

data to guide yield optimization, stress reduction, and nutrient management. On the other hand, responsible deployment will require aligning nanosensor design with safety standards, ethical norms, and regulatory frameworks to minimize environmental and societal risks. Together, these developments in technology and governance will drive climate-smart, resource-efficient, and sustainable agricultural systems capable of adapting to environmental changes and maximizing agronomic benefits by optimizing nanoparticle applications (Ahmed *et al.* 2025).

7. CONCLUSION

Innovative nanosensors, which offer high-resolution, real-time insights into nutrient intake, stress responses, and nanoparticle accumulation, have become essential instruments for evaluating the intricate relationships between NPs and crops. To optimize agronomic benefits and minimize dangers, nanoparticles must be carefully monitored and managed due to their dual roles as advantageous agents that improve growth, nutrient efficiency, and stress tolerance, as well as possible sources of toxicity and oxidative stress. Intelligent nanosensors are revolutionizing precision agriculture, promoting sustainable crop production, and guaranteeing food safety by enabling non-invasive, continuous, and field-deployable monitoring. Interdisciplinary research combining knowledge of nanotechnology, plant physiology, agronomy, and data science is necessary to realize their full potential. International cooperation is also needed to create safety standards, regulatory frameworks, and scalable implementation plans. Finally, in the age of nano-enabled technologies, innovative nanosensors provide a pathway to resilient, resource-efficient, and climate-smart agricultural systems, addressing global food security concerns.

Smart nanosensors offer real-time insights on uptake, translocation, and any dangers or advantages at the cellular and field level, making them a game-changing tool for evaluating how nanoparticles interact with crops. Researchers can monitor minute biochemical and physiological changes that conventional techniques frequently overlook by combining AI with nanosensors, enabling safer and more effective uses of nanotechnology in agriculture. The development of standardized nanosensor platforms that can accurately measure a variety of nanoparticle plant interactions across crop species, the integration of nanosensor outputs with cutting-edge AI models for predictive risk benefit assessment in variable field conditions, and long-term field validations to comprehend ecological and food safety implications could be viewed as central goals for future research. By bridging the gap between lab research

and sustainable farming methods, these initiatives will guarantee that nanotechnology appropriately contributes to the world's food security.

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.

COPYRIGHT

This article is an open-access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<http://creativecommons.org/licenses/by/4.0/>).



REFERENCES

- Ahmed, S., Naqvi, S. M. Z. A., Awais, M., Ren, Y., Zhang, H., Wu, J., Li, L., Raghavan, V. and Hu, J., Bacterial network for precise plant stress detection and enhanced crop resilience, *BMC Bioinf.*, 26(1), 64(2025).
<https://doi.org/10.1186/s12859-025-06082-z>
- Alam, M. W., Junaid, P. M., Gulzar, Y., Abebe, B., Awad, M. and Quazi, S. A., Advancing agriculture with functional NM: pathways to sustainable and smart farming technologies, *Discov. Nano.*, 19(1), 197(2024).
<https://doi.org/10.1186/s11671-024-04144-z>
- Bharti, A., Jain, U. and Chauhan, N., From lab to field: Nano-biosensors for real-time plant nutrient tracking, *Plant Nano. Biol.*, 9, 100079(2024).
<https://doi.org/10.1016/j.plana.2024.100079>
- Chanu, N. B. and Singh, M. C., Applications of nanotechnology in precision agriculture, Nano-enabled Agrochemicals in Agriculture, *Elsevier*, 175–187(2022).
<https://doi.org/10.1016/B978-0-323-91009-5.00016-1>
- Chaturvedi, A., Tripathi, D. and Ranjan, R., Nano-enabled biosensors in early detection of plant diseases, *Front Nanotechnol.*, 7, 1545792(2025).
<https://doi.org/10.3389/fnano.2025.1545792>
- Dehghanian, Z., Bandehagh, A., Habibi, K., Balilashaki, K. and Asgari, L. B., Impact of Abiotic Stress on Plant Brassinosteroids, *Climate Change Microbiome.*, 63, 279–298(2021).
https://doi.org/10.1007/978-3-030-76863-8_14
- El-Saadony, M. T., Saad, A. M., Soliman, S. M., Salem, H. M., Desoky, E. S. M., Babalghith, A. O., El-Tahan, A. M., Ibrahim, O. M., Ebrahim, A. A. M., Abd El-Mageed, T. A., Elrys, A. S., Elbadawi, A. A., El-Tarabily, K. A. and AbuQamar, S. F., Role of Nanoparticles in Enhancing Crop Tolerance to Abiotic Stress: A Comprehensive Review, *Front Plant Sci.*, 13, 946717(2022).
<https://doi.org/10.3389/fpls.2022.946717>
- Elsheery, N. I., Helaly, M. N., Hoseiny, H. M. and Alam, E. S. M., Zinc Oxide and Silicone Nanoparticles to Improve the Resistance Mechanism and Annual Productivity of Salt-Stressed Mango Trees, *Agron.*, 10(4), 558(2020).
<https://doi.org/10.3390/agronomy10040558>
- Giraldo, J. P., Wu, H., Newkirk, G. M. and Kruss, S., Nanobiotechnology approaches for engineering smart plant sensors, *Nat. Nanotechnol.*, 14(6), 541–553(2019).
<https://doi.org/10.1038/s41565-019-0470-6>
- Gulati, S., Yadav, R., Kumari, V., Nair, S., Gupta, C. and Aishwari, M., Nanosensors in healthcare: transforming real-time monitoring and disease management with cutting-edge nanotechnology, *RSC Pharm.*, 2, 1003-1018(2025).
<https://doi.org/10.1039/D5PM00125K>
- Gupta, A., Rayeen, F., Mishra, R., Tripathi, M. and Pathak, N., Nanotechnology applications in sustainable agriculture: An emerging eco-friendly approach, *Plant Nano. Biol.*, 4, 100033(2023).
<https://doi.org/10.1016/j.plana.2023.100033>
- Haase, R., Royer, L. A., Steinbach, P., Schmidt, D., Dibrov, A., Schmidt, U., Weigert, M., Maghelli, N., Tomancak, P., Jug, F. and Myers, E. W., CLIJ: GPU-accelerated image processing for everyone, *Nat. Methods*, 17, 5–6 (2020).
<https://doi.org/10.1038/s41592-019-0650-1>
- Kaliyaperumal, G., CK, R. K. and Mitra, N., Nano-sensors in Precision Agriculture, *Comput. Sci. Eng. Int. J.*, 15(1), 219–227(2025).
<https://doi.org/10.5121/cseij.2025.15125>
- Lew, T. T. S., Koman, V. B., Silmore, K. S., Seo, J. S., Gordiichuk, P., Kwak, S. Y., Park, M., Ang, M. C. Y., Khong, D. T., Lee, M. A., Chan-Park, M. B., Chua, N. H. and Strano, M. S., Real-time detection of wound-induced H₂O₂ signalling waves in plants with optical nanosensors, *Nat. Plants*, 6(4), 404–415(2020).
<https://doi.org/10.1038/s41477-020-0632-4>
- Mamatha, K. M., Srinivasa, M. V., Thammanna, B. M., Naveen, K. T., Jahagirdar, A. A., Naveen, K. A., Murthy, M., Ravikumar, C. R. and Ananda, M. H. C., Electrochemical sensor of carboxymethyl cellulose and photocatalytic degradation of Navy-Blue dye by sonochemically synthesized Titanium oxide nanoparticles, *Sensors*, 4, 100239(2023).
<https://doi.org/10.1016/j.sintl.2023.100239>

- Miguel, R. C. and Pérez, L. A., Nanobiosensors and nanoformulations in agriculture: new advances and challenges for sustainable agriculture, *Emerg. Top Life Sci.*, 7(2), 229–238(2023). <https://doi.org/10.1042/ETLS20230070>
- Parimalagandhi, K., Sudha, D., Banupriya, K., Karthik, K. and Revathi, A., Emerging Diagnostic Methods Using Paper-based Electrochemical Biosensors, *J. Environ. Nanotechnol.*, 13(3), 418–423(2024). <https://doi.org/10.13074/jent.2024.09.242720>
- Pinki, K., Anza, R. K., Archana, K. and Ravi, K. S., Nanosensors for Monitoring and Detecting Nanoparticle Effects on Crops, *J. Environ. Nanotechnol.*, 14(1), 37–51(2025). <https://doi.org/10.13074/jent.2025.03.2511272>
- Prasad, R., Bhattacharyya, A. and Nguyen, Q. D., Nanotechnology in Sustainable Agriculture: Recent Developments, Challenges, and Perspectives, *Front Microbiol.*, 8, 1014(2017). <https://doi.org/10.3389/fmicb.2017.01014>
- Rowe, J. H., Rizza, A. and Jones, A. M., Quantifying phytohormones in vivo with FRET biosensors and the frenator analysis toolset, *Methods Mol. Biol.*, 2494, 239-253 (2022). https://doi.org/10.1007/978-1-0716-2297-1_17
- Sampedro, G. J., Vives, P. V., Gomez, C. A. and Clausell, T. C., Efficient strategies for controlled release of nanoencapsulated phytohormones to improve plant stress tolerance, *Plant Methods*, 19, 1–20 (2023). <https://doi.org/10.1186/s13007-023-01025-x>
- Singh, J., Kumar, V., Kim, K. H. and Rawat, M., Biogenic synthesis of nanoparticles and their applications: a review, *J. Nanobiotechnol.*, 11(6), 2598 (2021). <https://doi.org/10.3390/app11062598>
- Singh, D. and Gurjar, B. R., Nanotechnology for agricultural applications: facts, issues, knowledge gaps, and challenges in environmental risk assessment, *J. Environ. Manag.*, 322, 116033 (2022). <https://doi.org/10.1016/j.jenvman.2022.116033>
- Shaw, D. S. and Honeychurch, K. C., Nanosensor Applications in Plant Science, *Biosens.*, 12(9), 675(2022). <https://doi.org/10.3390/bios12090675>
- Subodh., Ravina., Priyanka., Narang, J. and Mohan, H., Biosensors for phytohormone Absciscic acid and its role in humans: A review, *Sens. Int.*, 4, 100234(2023). <https://doi.org/10.1016/j.sintl.2023.100234>
- Ur, R. H., Qaswar, M., Uddin, M., Giannini, C., Herrera, M. L. and Rea, G., Nano-Enable Materials Promoting Sustainability and Resilience in Modern Agriculture, *Nanomater.*, 11(8), 2068(2021). <https://doi.org/10.3390/nano11082068>
- Wong, M. H., Giraldo, J. P., Kwak, S. Y., Koman, V. B., Sinclair, R., Lew, T. T. S., Bisker, G., Liu, P. and Strano, M. S., Nitroaromatic detection and infrared communication from wild-type plants using plant nanobionics, *Nat. Mater.*, 16(2), 264–272(2017). <https://doi.org/10.1038/nmat4771>
- Zain, M., Ma, H., Nuruzzaman, Md., Chaudhary, S., Nadeem, M., Shakoor, N., Azeem, I., Duan, A., Sun, C. and Ahamad, T., Nanotechnology-based precision agriculture for alleviating biotic and abiotic stress in plants, *Plant Stress*, 10, 100239(2023). <https://doi.org/10.1016/j.stress.2023.100239>
- Zhang, Q., Ying, Y. and Ping, J., Recent Advances in Plant Nanoscience, *Adv. Sci.*, 9(2), 2103414(2022). <https://doi.org/10.1002/advs.202103414>