



Nanotechnology Meets Agriculture: A New Era of Smart Farming

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Article History

Received: 1. 1.2026

Revised: 5. 1.2026

Accepted: 10. 1.2026

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INTRODUCTION

The global agricultural sector stands at a critical juncture, tasked with meeting the nutritional demands of a projected 10 billion people by 2050 while simultaneously mitigating its severe environmental impact. Traditional farming practices, characterized by the high-volume application of bulk chemicals, suffer from notorious inefficiencies, leading to nutrient loss, groundwater contamination, and rapidly declining soil health. Nanotechnology, the engineering of materials at the atomic and molecular scale (1–100 nm), offers a radical, systems-level solution. By creating "smart" agricultural inputs, nanotechnology is enabling a transformative shift toward Precision Agriculture, promising to maximize crop productivity and resource utilization while ensuring the long-term sustainability of agro-ecosystems. The integration of nanotechnology into agronomy is not merely an incremental improvement; it is a fundamental re-engineering of the farm-to-table supply chain. This comprehensive approach leverages nanoparticles, nanocapsules, and nanosensors to address key challenges across the entire crop lifecycle: optimizing nutrient delivery, enhancing water use, improving resistance to pests and stress, and extending post-harvest quality (Fig.1). The following sections detail how this revolutionary technology is advancing future farming practices.

Smart Management of Nutrients

The most immediate and impactful application of nanotechnology is the development of Nanofertilizers (NFs), which directly address the massive wastage associated with conventional fertilizers. Standard fertilizers often exhibit a low Nutrient Use Efficiency (NUE), with up to 70% of applied nitrogen and phosphorus being lost to runoff, leaching, or chemical fixation in the soil. NFs overcome this inefficiency through two primary mechanisms: targeted delivery and controlled release (Zahra et al., 2022). Due to their nanoscale size, NFs can achieve direct cellular penetration, bypassing natural barriers to be absorbed through stomatal pores in leaves (foliar application) or through root cell walls (soil application). This precision ensures that nutrients reach the plant's metabolic centers exactly where they are needed, rather than remaining dormant in the soil (Ali et al., 2021).

The second critical feature is the use of specialized carriers, such as nanozeolites or polymer matrices, to encapsulate the nutrient core. This nanoencapsulation creates a protective shell that prevents the nutrient from degrading or being washed away, enabling its slow, steady release over an extended period. This controlled-release mode perfectly aligns nutrient availability with the plant's actual physiological demand

throughout its growth cycle, dramatically reducing nutrient loss mechanisms like volatilization and denitrification (Gade et al., 2023). As a result, farmers can achieve equivalent or better yields with significantly lower application rates, leading to substantial economic savings and a cleaner environment. Commercial products of nanofertilizers given in Table 1.

Table. 1 Commercial products of nanofertilizers

Commercial Product	Description & Composition	Manufacturer / Location
Nano Urea (Liquid)	A nitrogen supplement designed to replace conventional bulk urea for crops.	Indian Farmers Fertilizer Cooperative Ltd. (IFFCO), India
Nano-Gro™	Functions as a plant growth regulator and immunity enhancer.	Agro Nanotechnology Corp., USA
Nualgi Foliar Spray	Contains 12 essential nutrients loaded into a nano-silica carrier.	Nualgi America, Inc., USA
Nano Bor 20%	A specific micronutrient formulation containing Nano Boron.	Alert Biotech, India
Fosvit K30	A macronutrient fertilizer with high concentrations of Phosphorus (30%) and Potassium (20%).	Kimitec Group, Spain
Nano Zinc Chelate	A growth enhancer fertilizer focused on Zinc delivery.	AFME Trading Group, UK
Master Nano Chitosan	An organic fertilizer composed of water-soluble liquid chitosan, salicylic acids, and phenolic compounds.	Pannaraj Intertrade, Thailand
Biozar Nano-Fertilizer	A combination of organic materials, macromolecules, and micronutrients.	Fanavar Nano-Pazhoohesh Markazi Company, Iran
Nano Iron & Calcium	A chelated fertilizer acting as a plant growth regulator and accelerator.	AFME Trading Group, UK
Neem Coated Urea	A nitrogen supplement coated with neem to improve efficiency.	Aditya Birla Nuvo Ltd., India
NovaLand-Nano	Contains nano-macro and micro-elements specifically for promoting plant growth.	Land Green & Technology Co., Ltd., Taiwan
Nano Max NPK Fertilizer	Multiple organic acids chelated with major nutrients (NPK), amino acids, vitamins, and probiotics.	JU Agri Sciences Pvt. Ltd., India
TAG NANO	Proteino-lacto-gluconate chelated with NPK, micronutrients, seaweed extracts, and humic acid.	Tropical Agrosystem India (P) Ltd., India
Nano Green	Extracts of corn, grain, soybeans, potatoes, coconut, and palm.	Nano Green Sciences, Inc., India
Nano-Ag Answer®	Contains microorganisms, sea kelp, and mineral electrolytes.	Urth Agriculture, USA
Hibong Biological Fulvic Acid	Contains chitosan oligosaccharides, NPK, organic matter, and humic acid.	Qingdao Hibong Fertilizer Co., Ltd., China
Seaweed Nano Organic Carbon	Blend of NPK (2-3-3), seaweed extract, humic acid, and amino acids.	Qingdao Hibong Fertilizer Co., Ltd., China
Titanium Dioxide (TiO ₂)	Universal pigment (20 nm).	Land Green & Technology Co., Ltd., Taiwan
Silicon Dioxide (SiO ₂)	Universal stabilizer agent (20–60 nm).	Land Green & Technology Co., Ltd., Taiwan
Selenium Colloid (Se)	Universal antioxidant (1–20 nm).	Land Green & Technology Co., Ltd., Taiwan
Poly Olefin Resin-Coated Urea	A nitrogen supplement coated for controlled release.	Japan
Nano Calcium (Magic Green)	A complex mix containing CaCO ₃ , MgCO ₃ , SiO ₂ , and various trace elements (Fe, Sr, Ba, Mn, Zn).	AC International Network Co., Ltd., Germany
EcoStar Nano Micronutrient	Contains Zinc, Boron, Copper, Iron, Molybdenum, Manganese, and Aminos.	Shan Maw Myae Trading Co., Ltd., India
Nano Ultra-Fertilizer	A formulation of organic matter, Nitrogen, Phosphorus, Potassium, and Magnesium.	SMTET Eco-technologies Co., Ltd., Taiwan
PPC Nano	Contains M protein, Na ₂ O, K ₂ O, and (NH ₄) ₂ SO ₄ .	WAI International Development Co., Ltd., Malaysia

Enhancing Water Management and Efficiency

The escalating demand for water in agriculture necessitates technologies that boost Water Use Efficiency (WUE). Nanotechnology provides solutions that improve both the soil's capacity to retain water and the plant's ability to manage water stress. The most prominent tool in this area is the development of nanomaterial-enhanced hydrogels. Traditional hydrogels are known for their high-water absorption capacity, but incorporating nanomaterials like nanoclays or

specialized polymers enhances their mechanical stability, absorption rate, and longevity in the soil. These enhanced hydrogels are mixed into the soil, where they act as miniature reservoirs, holding significant volumes of water and slowly releasing it in response to the soil drying out. This mechanism not only reduces the frequency and volume of irrigation required but also mitigates the effects of short-term drought on crop health and yield.

Furthermore, nanoparticles, particularly those based on metal oxides, can influence the plant's internal water balance. By modulating the regulation of stomata and promoting the synthesis of osmolytes (substances that help cells maintain water potential), they enable the plant to better cope with water deficits at the cellular level. This leads to increased drought tolerance and overall plant resilience, making farming viable in previously marginal or water-scarce regions.

Precision Pest and Disease Management

Nanotechnology is transforming plant protection by replacing broad-spectrum, high-volume chemical spraying with highly effective, low-dosage nano-agrochemicals, ensuring better efficacy and greater environmental safety. Nanopesticides and nano-fungicides are designed using encapsulation technology, where the active chemical ingredient is encased within a protective nanoshell. This encapsulation provides three significant advantages:

- **Reduced Dosage:** Nanoparticles exhibit high surface area-to-volume ratios, making them far more reactive and effective at lower concentrations than bulk materials, thus reducing the amount of chemical needed.
- **Increased Stability:** The protective shell shields the active ingredient from premature degradation caused by UV radiation, heat, or humidity, ensuring its potency remains high until it reaches the target.
- **Targeted Delivery:** Formulations can be engineered for stimulus-responsive release, where the agrochemical is released only when a specific trigger is encountered, such as the low pH found near a fungal infection site or the enzymatic activity of a target insect.

For disease control, specific nanomaterials are being developed that possess inherent antimicrobial properties. For example, Zinc-based nanomaterials have demonstrated significant efficacy in both diagnosing and managing a wide spectrum of bacterial and fungal plant diseases, offering a potent, bio-friendly alternative to traditional synthetic

fungicides. This precision minimizes chemical runoff and reduces the selection pressure that leads to pesticide resistance in pest populations (Kalia et al., 2020).

Selective Weed Management

Weed management remains a labor-intensive and expensive component of crop production, often relying on non-selective herbicides that pose a risk to the primary crop and surrounding ecosystems. Nanotechnology is introducing selective and controlled-release nano-herbicides to combat this issue. Similar to other nano-agrochemicals, nano-herbicides use encapsulation to ensure the active ingredient is protected until the optimal moment for release. The innovation here is in selective targeting. Nano-herbicides can be functionalized to detect specific biochemical markers or environmental conditions unique to the target weed species. For example, the herbicide may be released only when exposed to a specific enzyme or high level of acidity found in the weed's rhizosphere or leaf surface, preventing the chemical from acting on the surrounding crop. This strategy leads to highly effective weed control at significantly lower concentrations, solving the problem of herbicide resistance by delivering lethal doses directly and efficiently. By dramatically reducing the total chemical load on the environment, nano-herbicides contribute significantly to soil health and biodiversity maintenance in agricultural landscapes.

Enhancing Plant Stress Tolerance

Global climate volatility necessitates crops that are resilient to sudden changes in temperature, salinity, and severe drought—collectively known as abiotic stresses. Nanotechnology provides molecular tools to bolster the plant's innate defenses. A key approach is the development of Nano-Biofertilizers (NBFs). NBFs combine beneficial microbial agents (like nitrogen-fixing bacteria) with a protective nanoscale matrix (often chitosan or zeolite). This encapsulation protects the delicate microbes from harsh environmental conditions, significantly improving their viability and shelf-life until they successfully colonize the plant's roots

(rhizosphere). Once established, these microbes enhance nutrient uptake, produce growth hormones, and actively help the plant cope with stress, translating into stronger, healthier, and more resilient crops. Beyond microbial agents, certain nanoparticles can act as signaling molecules when taken up by the plant. Materials like titanium dioxide (TiO₂) can stimulate the plant's systemic defense pathways, promoting the production of antioxidant enzymes and stress proteins that allow the crop to recover quickly from environmental shocks, ensuring consistent yields even under adverse conditions.

Post-Harvest Management and Food Safety

The utility of nanotechnology extends to the final stages of the supply chain, where it is revolutionizing post-harvest management by reducing spoilage and enhancing food safety and quality. A major application is in nanomaterial-infused packaging. Polymer films are embedded with potent antimicrobial agents, such as silver nanoparticles (AgNPs) or zinc oxide nanoparticles (ZnONPs). These nanoparticles continuously release ions that inhibit the growth of common post-harvest pathogens, including molds and spoilage bacteria, directly on the surface of the food. This active packaging approach significantly extends the shelf life of fresh produce, minimizing the massive food waste that occurs during storage and transit globally (Usman et al., 2020).

Furthermore, nanotechnology provides sophisticated tools for food safety monitoring. Highly sensitive nanosensors, often integrated into smart packaging or handheld devices, are capable of the rapid, real-time detection of minute contaminants. These sensors can flag the presence of harmful pathogens (like *E. coli*), mycotoxins, or pesticide residues in food products instantly, ensuring faster quality control checks and enhancing consumer protection across the entire supply chain.

Future Prospects

The next era of nanotechnology in agronomy promises to move beyond mere efficiency gains toward autonomous, cyber-physical farming systems. The future will see the complete integration of nanosensors with Artificial Intelligence (AI) and the Internet of Things (IoT), creating self-regulating fields

where plant needs are monitored continuously and met instantaneously. Nanosensors will detect the slightest nutrient deficiency or pathogen presence, and the AI will then wirelessly trigger the precise, localized release of nano-encapsulated inputs. This level of automation will minimize human error, optimize resource use to near-perfect levels, and dramatically increase yields. Furthermore, nanotechnology will become the key to unlocking advanced genetic engineering: future nanocapsules will be designed to deliver precise genetic material, such as siRNA or CRISPR/Cas components, directly into plant cells. This will allow researchers to instantly confer disease resistance or alter metabolic pathways without slow, conventional breeding, effectively providing a "molecular vaccine" for crops. Beyond the farm, nanomaterials will be engineered to actively remediate contaminated farmlands, acting as filters to remove heavy metals or pesticides from soil and irrigation water, ensuring the health and longevity of agricultural lands.

CONCLUSION

The integration of nanotechnology into agronomy is not merely an innovation; it is a necessary foundational pillar for securing a sustainable and productive global food system. By enabling unprecedented resource efficiency—delivering nutrients with controlled precision, enhancing water retention, and managing pests with targeted minimal chemicals—nanotechnology offers the most viable pathway to achieve high yields while drastically reducing agriculture's environmental footprint. However, the successful global adoption of these technologies hinges on proactively resolving the major challenges: chiefly, obtaining comprehensive long-term data on the ecotoxicity and bioaccumulation of nanomaterials in the food chain and environment, and establishing a harmonized, science-based global regulatory framework to govern their use. Overcoming these scientific and economic hurdles will be crucial for nanotechnology to fulfill its promise as the definitive tool for future smart farming.

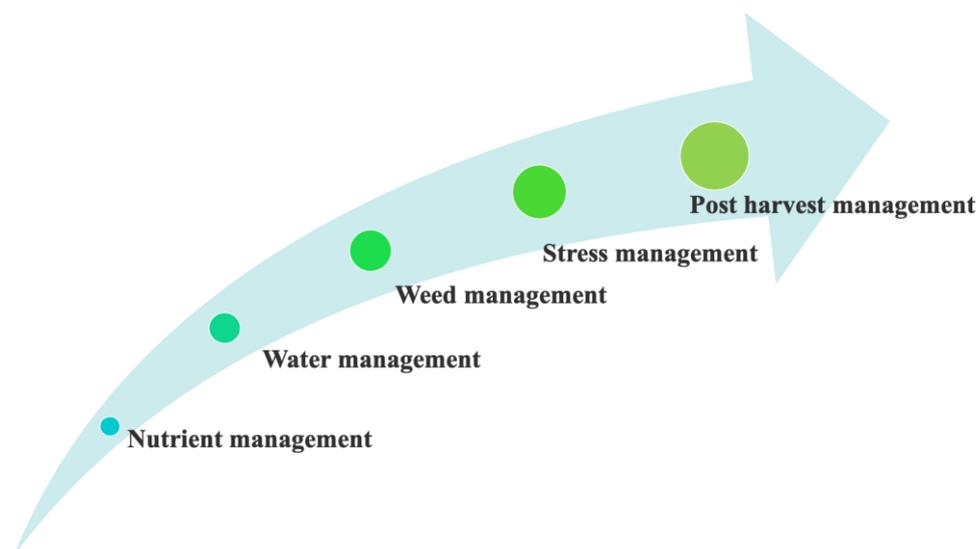


Fig.1. Applications of nanotechnology in farming practices

REFERENCES

- Gade, A., Ingle, P., Nimbalkar, U., Rai, M., Raut, R., Vedpathak, M., Jagtap, P., Abd-Elsalam, K. A., 2023. Nanofertilizers: the next generation of agrochemicals for long-term impact on sustainability in farming systems. *Agrochemicals*, 2(2), 257-278.
- Usman, M., Farooq, M., Wakeel, A., Nawaz, A., Cheema, S. A., ur Rehman, H., Ashraf, I., Sanaullah, M, 2020. Nanotechnology in agriculture: Current status, challenges and future opportunities. *Science of the total environment*, 721, 137778.
- Ali, S. S., Darwesh, O. M., Kornaros, M., Al-Tohamy, R., Manni, A., El-Shanshoury, A. E. R. R., Metwally, M. A., Elsamahy, T., Sun, J, 2021. Nano-biofertilizers: Synthesis, advantages, and applications. In *biofertilizers* (pp. 359-370). Woodhead Publishing.
- Kalia, A., Abd-Elsalam, K. A., Kuca, K, 2020. Zinc-based nanomaterials for diagnosis and management of plant diseases: Ecological safety and future prospects. *Journal of fungi*, 6(4), 222.
- Zahra, Z., Habib, Z., Hyun, H., & Shahzad, H. M. A, 2022. Overview on recent developments in the design, application, and impacts of nanofertilizers in agriculture. *Sustainability*, 14(15), 9397.