GreenariA
Go Green, Learn Green
An Agricultural Monthly e-Magazine
Volume 03, Issue 07, 2025
ISSN: 2584-153X
Article ID: G-25-0717

ADVANCED NANOTECHNOLOGY SOLUTIONS FOR AGRICULTURAL AND HORTICULTURAL CHALLENGES

Shakila Sadasivam[1], Vinothini. N[2], Akshaya S B[3], Jeyajothi R[4] and Akino Asokan[5]

[1]Department of Floriculture and Landscape Architecture, [2]Depatment of Seed Science and Technology, [3]Department of Plant Pathology, [4]Department of Agronomy, [5]Department of Fruit Science, SRM College of Agricultural Sciences, SRM Institute of Science and Technology, Baburayanpettai, Chengalpattu District – 603 201, Tamil Nadu, India.

Introduction

Nanotechnology, the science of manipulating materials at the atomic or molecular scale, specifically less than 100 nanometers. It has emerged as one of the most transformative fields of the 21st century. While its initial applications were seen in electronics, medicine, and material sciences, nanotechnology is now increasingly entering the fields of agriculture and horticulture, presenting immense potential to reshape the future of farming. In agriculture and horticulture, where resource efficiency, productivity, and environmental sustainability are ongoing concerns, nanotechnology provides innovative tools and approaches to enhance input efficiency, reduce losses, protect crops, and improve the shelf life and nutritional value of produce. The unique properties of nanoparticles, *viz.,* high surface area, reactivity, and controlled release, allow them to perform specific tasks at the cellular and molecular levels in plants, soil, and agro-ecosystems compared to conventional tasks. As food security, climate resilience, and environmental protection become intertwined global goals, nanotechnology stands as a cross-disciplinary solution with the capacity to make agriculture both smarter and cleaner.

Nano-Fertilizers: Smart Nutrient Delivery

One of the earliest and most impactful uses of nanotechnology in agriculture is the development of nano-fertilizers. Traditional fertilizers, particularly urea, are highly inefficient, with only 30–50% of the nutrients being absorbed by plants. The rest is lost through leaching, volatilization, or runoff, causing not only economic loss but also environmental degradation such as eutrophication and groundwater contamination. Nano-fertilizers, on the other hand, allow for the precise and slow release of nutrients directly to plant roots, thereby improving nutrient use efficiency, reducing application frequency, and minimizing losses. For instance, nano-urea developed by Indian scientists is a liquid fertilizer that contains nanoparticles of urea. Plants can absorb more efficiently compared to bulk urea. Applied in smaller quantities, it reduces nitrogen wastage while maintaining or improving crop yields. Additionally, nano-chelated micronutrients such as zinc, iron, and manganese are being developed to correct deficiencies more effectively than conventional formulations. Their nanoscale size allows them to enter plant systems via foliar sprays or soil application more easily, enabling targeted and sustained nutrition.

Nano-Pesticides: Targeted Crop Protection

The use of nano-pesticides has been shown to improve the issues of overuse, pest resistance, and ecological toxicity associated with conventional pesticides. These nano-formulations, which include nano-encapsulated insecticides, fungicides, and herbicides, provide controlled release and enhanced stability of active ingredients. Unlike traditional pesticides that degrade rapidly under sunlight or rain, nano-pesticides are more resistant to environmental breakdown and can maintain efficacy for longer durations. This results in minimal requirement of doses and fewer applications, thereby reducing chemical residues on produce thereby minimizing harm to non-target organisms like pollinators and beneficial soil microbes. Metallic nanoparticles such as silver, copper, and zinc oxide also exhibit strong antimicrobial properties and are being used to prevent postharvest spoilage and bacterial infections in crops. Additionally, carbon-based nanoparticles like fullerenes and graphene derivatives are being explored for their ability to deliver agrochemicals and enhance plant growth by influencing gene expression and biochemical pathways.

Postharvest and Packaging Innovations

Postharvest handling and storage are critical areas where nanotechnology is making valuable contributions, especially in horticulture, where produce like fruits, vegetables, and flowers is perishable and prone to quality degradation. Nanotechnology-based coatings and films, composed of biopolymers enriched with nanoparticles, are being used to extend the shelf life of produce by forming protective barriers that reduce moisture loss, delay ripening, and inhibit microbial growth. For example, nano-chitosan coatings have been used to preserve the freshness of strawberries, bananas, and tomatoes during transport and storage. These edible nano-coatings are biodegradable, non-toxic, and add value by maintaining visual appeal, nutritional content, and flavor. In addition, nano-packaging materials integrated with intelligent nanosensors are being developed to detect spoilage indicators such as ethylene gas, microbial toxins, or pH changes, providing real-time feedback to handlers and consumers about produce quality. These smart systems can significantly reduce food waste and ensure better compliance with food safety standards.

Smart Farming with Nano-Sensors

In the realm of precision farming, nanotechnology is revolutionizing how farmers monitor and manage their fields. Nano-biosensors, designed to detect minute changes in soil nutrients, moisture content, pest activity, and plant stress levels, are enabling real-time decision-making and site-specific interventions. These sensors can be embedded in the soil, mounted on drones, or applied to plant surfaces, where they collect data and communicate it via digital platforms. For instance, nanosensors that detect nitrate or phosphate levels in soil can inform farmers about the optimal timing and quantity of fertilizer application, thereby preventing overuse and saving costs. Similarly, sensors detecting early symptoms of fungal or viral infections in crops can alert farmers before visible symptoms appear, allowing for prompt treatment and preventing crop loss. These innovations are aligned with the goals of climate-smart agriculture, as they promote input efficiency, reduce greenhouse gas emissions, and conserve resources while maintaining or improving productivity.

Soil Health and Environmental Applications

Soil health and environmental remediation are other major focus areas of agricultural nanotechnology. Soil degradation due to heavy metal contamination, excessive chemical usage, and declining organic matter is a growing threat to sustainable farming. Nanotechnology offers several solutions through the development of nano-remediation agents. For example, iron oxide nanoparticles can adsorb arsenic or lead from polluted soils and water bodies, making them safer for agriculture. Similarly, nano-zeolites and nano-clays have been employed to improve water retention, reduce salinity stress, and enhance soil structure. These particles act as carriers for beneficial microbes or enzymes, facilitating their sustained release and promoting microbial diversity in the rhizosphere. Moreover, nanotechnology can help reclaim degraded lands and restore soil fertility by supporting the targeted delivery of compost activators, nitrogen-fixing bacteria, or plant growth-promoting rhizobacteria (PGPR). In the long run, such interventions contribute to resilient agro-ecosystems and reduce the ecological footprint of farming activities.

Horticultural Advances through Nanotech

Horticultural crops such as ornamentals, herbs, and medicinal plants have economic value and are also benefiting from nanotechnology-based interventions. Nanoparticle-mediated seed priming is a technique being studied to enhance seed germination, vigor, and disease resistance in vegetable and flower crops. For example, zinc oxide nanoparticles used in tomato seed treatment have shown improved seedling growth and early establishment. In floriculture, nano-silica sprays are being evaluated to enhance cut flower longevity by reducing microbial load in vase water and minimizing transpiration losses. Additionally, nanotechnology is enabling the efficient extraction and encapsulation of bioactive compounds from medicinal plants, making them more stable and bioavailable for pharmaceutical and nutraceutical applications.

Challenges and Future Directions

Despite its potential, the adoption of nanotechnology in agriculture and horticulture is still at an early stage and faces several challenges. One major concern is the lack of comprehensive risk assessments regarding the long-term effects of nanoparticles on human health, soil microbiota, and aquatic systems. Since nanoparticles can penetrate biological barriers and accumulate in tissues, their interactions with living organisms need careful evaluation. Another limitation is the cost of developing and deploying nano-agri inputs, which may currently be unaffordable for small and marginal farmers without governmental support. Regulatory frameworks governing the use of nanomaterials in agriculture are also still evolving in many countries, leading to uncertainty about product approval and safety standards. Moreover, public awareness and extension services must be strengthened to ensure informed and responsible use of nano-based technologies on the farm.

Conclusion

Looking ahead, the integration of nanotechnology with other modern approaches such as biotechnology, artificial intelligence, and Internet of Things (IoT) can further accelerate agricultural transformation. For instance, combining nanosensors with cloud-based analytics could enable large-scale data collection and predictive modeling of crop behaviour under various conditions. In protected cultivation systems such as greenhouses and vertical farms, nanotechnology could help maintain optimal microclimates and automate nutrient delivery through smart systems. Governments and research institutions must invest in interdisciplinary research, farmer education, and product standardization to unlock the full potential of nanotechnology in farming. Collaborative models involving scientists, startups, agri-tech companies, and farmer cooperatives will be essential in translating laboratory innovations into field-ready solutions. In conclusion, nanotechnology offers a suite of transformative tools that can make agriculture and horticulture more productive, efficient, and sustainable. From nano-fertilizers and smart pesticides to intelligent sensors and eco-friendly packaging, these technologies are addressing some of the deepest-rooted challenges in food production and environmental conservation. While careful assessment and responsible deployment are crucial, the ongoing advancements in nano-agriculture signal a future where science and sustainability go hand in hand. As farmers and students become more engaged with emerging agri-tech, nanotechnology will likely play a central role in building a resilient, climate-smart, and nutrition-secure agricultural system in the years to come.

References

1. Rana, R. A., Siddiqui, M. N., Skalicky, M., Brestic, M., Hossain, A., Kayesh, E., ... & Islam, T. (2021). Prospects of nanotechnology in improving the productivity and quality of horticultural crops. *Horticulturae*, *7*(10), 332.
2. Mehta, A., Yadav, A., Kumar, A., Kanika, & Manish. (2024). Role of nanotechnology in horticulture: an overview. *Int J Biochem Res Rev*, *8*(1), 702-708.
3. Yadav, R. K., Singh, N. B., Singh, A., Yadav, V., Bano, C., Khare, S., & Niharika. (2020). Expanding the horizons of nanotechnology in agriculture: recent advances, challenges and future perspectives. *Vegetos*, *33*(2), 203-221.
4. Upadhyay, T. K., Kumar, V. V., Sharangi, A. B., Upadhye, V. J., Khan, F., Pandey, P., ... & Hakeem, K. R. (2022). Nanotechnology-based advancements in postharvest management of horticultural crops. *Phyton*, *91*(3), 471.