

The Role of Nanoparticles in Horticultural Crop Production

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ABSTRACT

Horticulture is essential for global food security, but it faces significant challenges. These include low nutrient use efficiency (NUE), a heavy dependence on agrochemicals, and major post-harvest losses. Nanotechnology can help to create sustainable and smart horticultural management. By using the unique properties of nanoparticles (1–100 nm), such as their high surface area and controlled release, nanotechnology can change traditional methods where nano-fertilizers can improve nutrient use by 20–40% and cut application rates by up to 50% through targeted delivery via stomata and root pathways. In terms of crop protection, nano-pesticides and metal-based nanoparticles (Ag, ZnO, Cu) offer better stability and natural antimicrobial properties, which help reduce chemical residues. Additionally, nano-sensors allow for real-time monitoring of soil health and early pathogen detection, improving precision in greenhouse management. To tackle post-harvest issues, edible nano-coatings and nanocomposite packaging can extend the shelf life of perishable fruits and vegetables. While these benefits are significant, but serious concerns about the long-term effects of nanoparticle is accumulation in soil and the food chain. Even though nanotechnology can boost yield and quality, moving toward biogenic synthesis and creating strong global regulatory frameworks are crucial for its safe and responsible use in sustainable horticultural value chains.

Keywords: Chemicals; Environment; Fertilizer and Nanoparticle

1. Introduction

Horticulture plays a significant role in global agriculture by providing fruits, vegetables, ornamental plants, and plantation crops. These products are vital sources of vitamins, minerals, antioxidants, and various bioactive compounds necessary for human health (FAO, 2017). However, modern horticultural production faces several challenges, including soil degradation, heavy use of agrochemicals, poor nutrient use, climate changes, and significant post-harvest losses, especially in developing areas where losses often exceed 25 to 30% of total output (FAO, 2017; Gogos *et al.*, 2012). Traditional fertilizer practices are often inefficient, with nitrogen use efficiency rarely exceeding 30 to 50%, phosphorus utilization staying below 20%, and potassium losses ranging from 40 to 60%. This inefficiency contributes to environmental pollution, groundwater contamination, and rising production costs (Subramanian & Tarafdar, 2011; Kah *et al.*, 2019).

Nanotechnology, defined as the science and application of materials at the nanoscale (1 to 100 nm) in agriculture field and has emerged as a significant innovation in agriculture due to the unique characteristics of nanoparticles. These include a high surface-area-to-volume ratio, increased reactivity, better solubility, and controlled release behaviour (Nair *et al.*, 2010; Prasad *et al.*, 2017). These features allow

nanoparticles to deliver nutrients, pesticides, and bioactive molecules precisely, matching agricultural inputs to plant needs. In horticulture, nanotechnology provides new opportunities to improve crop yield, enhance produce quality, and prolong shelf life while also reducing environmental impacts. This positions it as an important technology for smart and sustainable agriculture (Gogos *et al.*, 2012; Kah *et al.*, 2019).

2. Nanoparticles as Smart Nutrient Delivery Systems (Nano-fertilizers)

Nano-fertilizers are formulations designed to improve nutrient use efficiency. They achieve this by controlling nutrient release, ensuring that nutrients are available when plants need them (Subramanian & Tarafdar, 2011). By encapsulating nutrients in nano clays, polymeric nanoparticles, or metal oxide matrices, these fertilizers significantly reduce losses from leaching, volatilization, and soil fixation, which enhances their effectiveness (Kah *et al.*, 2019). Moreover, these nano-formulations can respond to environmental conditions like soil moisture, pH changes, and microbial activity, allowing for site-specific nutrient release and improving fertilizer performance across different climates (Prasad *et al.*, 2017).

Nanoparticles enter plants through both foliar and root pathways. When applied to leaves, the particles penetrate

through stomatal openings and cuticular pores. Soil-applied nanoparticles are absorbed through root epidermis and moved via apoplastic and symplastic pathways (Nair *et al.*, 2010). Particles between 20 and 40 nm can move through vascular tissues, efficiently transporting nutrients to growing parts of the plant, such as fruits and flowers (Rai *et al.*, 2012). Research shows that nano-fertilizers can improve nutrient use efficiency by 20 to 40% and allow reductions in fertilizer application rates of up to 50% without harming crop yield or quality (Subramanian & Tarafdar, 2011; Kah *et al.*, 2019). In India, nano-urea formulations have shown yield results similar to conventional urea when applied at about one-tenth of the nitrogen amount, along with reducing ammonia volatilization and nitrate leaching (ICAR reports; Prasad *et al.*, 2017).

3. Crop Protection: Nano-pesticides and Nano-fungicides

Recent advances in nanotechnology have led to the creation of nano-pesticides, a new type of crop protection agent that improves the stability, solubility, and effectiveness of traditional pesticide formulations (Gogos *et al.*, 2012). These nano-formulated pesticides resist photodegradation, hydrolysis, and wash-off from rain, which enhances their persistence in the field and lessens the need for repeated applications (Kah *et al.*, 2019). Encapsulation methods using nanogels, liposomes, and polymeric nanocarriers allow for targeted delivery of active ingredients to pests or pathogens. This reduces overall chemical inputs in horticultural crop protection by 30 to 60% (Gogos *et al.*, 2012; Mishra *et al.*, 2017).

Metal-based nanoparticles, such as silver, zinc oxide, and copper, have natural antimicrobial properties. They work by disrupting membranes, generating reactive oxygen species, and inhibiting key enzymes in plant pathogens (Rai *et al.*, 2012). These nanoparticles have shown effectiveness against major horticultural diseases, including bacterial wilt, powdery mildew, downy mildew, and various post-harvest fungal rots (Mishra *et al.*, 2017). Integrating nano-pesticides into pest management systems offers a promising way to reduce chemical residues on crops while still effectively controlling diseases and pests (Kah *et al.*, 2019).

4. Precision Horticulture through Nano-sensors

Nano-sensors are a breakthrough in precision horticulture. They allow for continuous and real-time monitoring of soil and plant conditions with great sensitivity and speed (Duhan *et al.*, 2017). These sensors can detect changes in soil moisture, nutrient levels, pH, and salinity, which helps with informed decision-making for better irrigation and fertilization (Prasad *et al.*, 2017). Additionally, nano-biosensors can identify proteins related to pathogens, volatile organic compounds, and stress markers early in the infection process, often before visible symptoms appear (Duhan *et al.*, 2017).

In controlled environments like greenhouses, networks of nano-sensors connected to automated systems can regulate irrigation, lighting, and temperature in real time. This results in a 20 to 30% savings in water use and improved crop yields (Prasad *et al.*, 2017). These precision tools are especially beneficial for high-value horticultural crops, where slight enhancements in management can lead to significant improvements in quality and profitability (Gogos *et al.*, 2012).

5. Post-Harvest Management and Quality Enhancement

Post-harvest losses remain a major challenge in horticultural value chains. Nanotechnology presents innovative solutions through the creation of nano-coatings and active packaging systems (Rhim *et al.*, 2013). Edible nano-coatings made from chitosan, silica, and nano-cellulose create semi-permeable films on fruit surfaces. These films control gas exchange, reduce moisture loss, and decrease ethylene production, helping to delay ripening (Nair *et al.*, 2010). Studies have shown that nano-coatings can extend shelf life by 7 to 14 days in climacteric fruits like mango, tomato, and strawberry (Rhim *et al.*, 2013).

Nanocomposite packaging materials, which include antimicrobial nanoparticles and oxygen scavengers, further prevent microbial growth and degradation, thereby improving food safety and extending marketability (Rhim *et al.*, 2013). Additionally, nano-enabled micronutrient delivery systems show potential for nutritional enrichment, with improvements in iron and zinc levels in edible plant tissues without causing harm (Nair *et al.*, 2010; Prasad *et al.*, 2017).

6. Environmental and Safety Considerations

Despite the many advantages of nanotechnology in horticulture, concerns about its environmental and health impacts are significant (Kah *et al.*, 2019). Long-term accumulation of nanoparticles in soil may affect microbial diversity, enzymatic activity, and nutrient cycling. The effects depend mainly on particle size, concentration, and chemical makeup (FAO, 2017). Ecotoxicological studies have raised concerns about nanoparticles entering food chains, accumulating in organisms, and causing chronic exposure to humans. This highlights the need for strict risk assessment protocols (Kah *et al.*, 2019).

Currently, the lack of a global regulatory framework for agricultural nanomaterials complicates matters. Existing guidelines are inconsistent and vary by region (FAO, 2017). Creating uniform testing methods and evidence-based regulatory policies is essential for the safe and responsible use of nanotechnology in horticulture.

7. Future Prospects and Conclusion

The future of horticultural nanotechnology increasingly focuses on green or biogenic methods for synthesizing nanoparticles. These methods use plant extracts, microbes, or agricultural waste to reduce toxicity and environmental risks. These approaches align closely with sustainable agricultural principles and the circular bioeconomy. In conclusion, nanotechnology has the potential to transform horticultural crop production by enabling precise nutrient management, effective crop protection, real-time monitoring, and improved post-harvest quality. With proper regulatory oversight and ongoing research into safety and effectiveness, nanoparticle technologies can greatly support sustainable horticulture and enhance global food security.

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