International Journal of Advanced Biochemistry Research 2024; 8(1): 702-708

International Journal of Advanced Biochemistry Research

ISSN Print: 2617-4693
ISSN Online: 2617-4707
IJABR 2024; 8(1): 702-708
www.biochemjournal.com
Received: 27-11-2023
Accepted: 28-12-2023

Akshay Mehta
Department of Horticulture, CCS Haryana Agricultural University, Hisar, Haryana, India

Alkesh Yadav
Department of Horticulture, CCS Haryana Agricultural University, Hisar, Haryana, India

Aman Kumar
Department of Horticulture, CCS Haryana Agricultural University, Hisar, Haryana, India

Kanika
Department of Genetics and Plant Breeding, CCS Haryana Agricultural University, Hisar, Haryana, India

Manish
College of Agriculture, CCS Haryana Agricultural University, Hisar, Haryana, India

Corresponding Author:
Akshay Mehta
Department of Horticulture, CCS Haryana Agricultural University, Hisar, Haryana, India

Role of nanotechnology in horticulture: An overview

Akshay Mehta, Alkesh Yadav, Aman Kumar, Kanika and Manish

DOI: https://doi.org/10.33545/26174693.2024.v8.i1i.481

Abstract
Nanotechnology, a cutting-edge field, has gained prominence in horticulture for its transformative impact on crop production, plant health, and resource management. Nanoparticles, due to their unique properties, offer innovative solutions in crop improvement and protection. Nanomaterials such as nanofertilizers enhance nutrient uptake efficiency, reducing environmental impact and optimizing resource utilization. Similarly, nanopesticides exhibit increased efficacy in pest and disease management, reducing the need for conventional chemical treatments. Nanotechnology also plays a pivotal role in plant growth regulation. Nanoscale delivery systems enable controlled release of growth regulators, facilitating precise modulation of plant development and flowering. This targeted approach enhances crop yield and quality while minimizing environmental repercussions. Furthermore, nanosensors contribute to real-time monitoring of environmental parameters, offering valuable insights for precision agriculture. Nanomaterial-based sensors detect changes in soil moisture, nutrient levels, and plant health, enabling timely interventions for optimal crop management. Despite the promising applications, the integration of nanotechnology in horticulture faces challenges related to environmental impact, ethical considerations, and regulatory frameworks. Addressing these concerns is crucial to ensure responsible and sustainable deployment of nanotechnology in agriculture. The role of nanotechnology in horticulture is dynamic and expansive. From enhancing nutrient management to revolutionizing pest control and growth regulation, nanotechnology holds immense potential for advancing sustainable and efficient practices in horticultural systems. However, a balanced approach is essential, considering ethical, environmental, and regulatory aspects to harness the full benefits while mitigating potential risks associated with nanotechnology in horticulture. The present review focuses on the Role of Nanotechnology in Horticulture.

Keywords: Nanotechnology, nanoparticles, efficacy, nanosensors

Introduction

The global population is steadily increasing, presenting a significant challenge in meeting both current and future demands for food worldwide. To address this challenge, there is a pressing need to boost crop production, with estimates suggesting an increase of up to 70%. While traditional fertilizers have been instrumental in supporting farmers, their intensive use has been found to adversely impact soil quality and pose risks to human health and the environment. The advancement of the agriculture sector hinges on improving resource efficiency and adopting modern technologies judiciously. Nanotechnology emerges as a promising avenue to enhance the sustainability of agriculture, particularly in developing nations. Nanostructured formulations employ targeted delivery, slow/controlled release, and conditional release mechanisms, responding to biological demands and potentially transforming agricultural systems. The nano-sizing of fertilizers enhances nutrient availability to plant pores at the nano-scale, leading to increased nutrient utilization efficiency. Nanoparticles contribute to faster seed germination, elevated agricultural yields, and improved chlorophyll content, facilitating enhanced plant growth through efficient absorption (Hayat *et al*., 2023) [14]. A notable application of nanotechnology is found in nanofertilizers, which enhance a plant's nutrient absorption capabilities. Nanofertilizers like Zn, Cu, and Fe address soil fixation challenges and optimize photosynthetic efficiency. Studies indicate that the use of nanofertilizers improves nutrient utilization efficiency, mitigates soil toxicity, reduces the adverse effects of overdosing, and decreases the frequency of required treatments (Ditta, 2012) [9]. In the pursuit of sustainable agriculture, nanotechnology holds considerable potential, providing innovative solutions to address the complexities of food production and environmental impact (Shilpa *et al*., 2022) [34].

Nanofertilizers

Nanofertilizers, nano-dimensioned nutrient carriers ranging from 1 to 100 nm, are exclusively or collaboratively utilized to enhance plant growth, yield, and overall performance. These innovative fertilizers are crafted by coating conventional fertilizers, extracted from various plants or plant parts, with nanomaterials. Referred to by various names such as nano-carriers, nano-enabled fertilizers, bio-nanofertilizers, controlled-release nanofertilizers, NPs-based nutrient, and nano-based delivery systems of micronutrients, these formulations ensure precise nutrient delivery at optimal times and locations (Gomes *et al*., 2021) [13]. The impact of nanofertilizers extends to pivotal roles in physiological and biochemical processes. They enhance nutrient availability, fostering improved metabolic processes and stimulating meristematic activities, ultimately leading to heightened apical growth and expanded photosynthetic areas (Chaupoo *et al*., 2023) [6]. This enhancement proves critical for augmenting both vegetative and reproductive growth, including flowering, thereby elevating productivity, product quality, and the shelf life of fruits. Crucially, nanofertilizers maintain a balanced release of nitrogen, phosphorus, and other macronutrients, preventing nutrient losses and undesirable interactions with water, air, and microorganisms (Blois and Lay-Ekuakille, 2018) [5]. Their adaptability to environmental factors, such as temperature fluctuations, soil moisture levels, and soil acidity, enables nanofertilizers to fine-tune the pace of nutrient supply, maximizing their effectiveness for plant growth. Distinguishing themselves from traditional fertilizers, nanofertilizers exhibit superior efficiency and easy absorption by shoots and roots through controlled nutrient delivery (Khan and Rizvi, 2017) [16]. They effectively mitigate nitrogen loss from leaching, emissions, and prolonged interactions with soil microorganisms. Categorized into micronutrient Nano-formulations, macronutrient nanoformulations, and nutrients-loaded nanomaterials, nanofertilizers can adopt various designs, including pH release, heat release, ultrasonic release, magnetic release, specific release, slow release, rapid release, and moisture release. Their application enhances nutrient delivery to the soil, minimizing nutrient loss through leaching (Manjunatha *et al*., 2016) [21].

Use of Nanofertilizers in Horticulture

Nano-fertilizers are gaining increased importance in horticulture as they hold the potential to address the distinct requirements and challenges associated with cultivating fruits, vegetables, and ornamental crops. In horticulture, precise management of nutrients is paramount for achieving optimal crop quality and yields. Nano-fertilizers present a promising solution by enabling the controlled and targeted release of nutrients to plants. This precision guarantees that crops receive the correct nutrients at the appropriate times and in optimal quantities, resulting in healthier plants with enhanced resilience against diseases and pests. Moreover, nano-fertilizers can be tailored to tackle specific nutrient deficiencies commonly found in horticultural crops. Their nanoscale characteristics facilitate more effective penetration of plant tissues, promoting improved nutrient uptake and utilization. This not only reduces fertilizer wastage but also contributes to sustainable farming practices by minimizing nutrient runoff and groundwater contamination. Additionally, nano-fertilizers hold the potential to alleviate the environmental impact of horticulture. By enhancing nutrient utilization efficiency, they can help mitigate the adverse consequences associated with excessive fertilizer application, such as soil degradation and water pollution. As horticulturists strive to meet the escalating demand for high-quality fruits, vegetables, and ornamental plants, nano-fertilizers emerge as a valuable tool for achieving these objectives while simultaneously addressing sustainability and environmental considerations. However, their integration in horticulture necessitates careful research, responsible application practices, and adherence to regulatory guidelines to ensure their safe and effective use.

Nanosensors

Nanosensors are instrumental in detecting or sensing various quantities like temperature, humidity, and moisture. Leveraging the unique properties of nanomaterials, nanosensors have the capability to identify and measure physical volumes on the nanoscale. These nanoscale devices play a crucial role in measuring physical quantities, converting them into detectable signals for analysis. The fabrication of nanosensors involves several approaches, including top-down lithography, bottom-up assembly, and molecular self-assembly. In today's landscape, diverse types of nanosensors have been introduced to the market and are under development for a range of applications, prominently in the defense, environmental, and healthcare sectors. Despite their varied applications, these sensors follow a common workflow: selectively binding to an analyte, generating signals through interaction with the bio-element, and processing the signal into meaningful metrics.

Use of Nanosensors in Horticulture

Nano sensors are bringing significant advancements to horticulture, transforming the monitoring and management of crops. Comprising nanomaterials, these minuscule sensors are employed in agricultural settings to collect real-time data on factors critical for crop well-being and productivity. In horticulture, nano sensors play a pivotal role in monitoring soil conditions, including moisture levels, nutrient content, and pH, exhibiting exceptional precision. This data empowers horticulturists to optimize irrigation schedules, ensure timely nutrient supply to plants, and maintain ideal soil conditions for optimal crop growth. Tailoring resource management to the specific requirements of crops and soil, nano sensors contribute to water conservation, reduced fertilizer usage, and the promotion of sustainable farming practices. Additionally, nano sensors prove invaluable in disease and pest management. They can identify early signs of pathogen infestations or pest attacks by monitoring changes in plant physiology or the presence of specific biomarkers. This early detection enables growers to implement timely interventions, minimizing crop losses and decreasing the reliance on chemical treatments. Nano sensors also play a crucial role in precision agriculture in horticulture by providing insights into microclimatic conditions such as temperature, humidity, and light levels. By gathering data at the microscale, horticulturists can create optimal growing environments in greenhouses or controlled settings, ensuring year-round cultivation of high-value crops. In summary, nano sensors enhance the efficiency, sustainability, and productivity of horticultural practices. They empower growers with data-driven decision-making tools, enabling higher crop yields, improved crop quality, and reduced environmental impacts, establishing nano sensors as valuable assets in contemporary horticulture.

Nanopesticides

Nano-pesticides present an alternative to address the limitations associated with conventional insecticides. These are plant protection chemicals where either the active ingredient or the carrier molecule is developed using nanotechnology. The term 'nano' derives from the Greek word meaning dwarf, emphasizing the significantly reduced size of the particles. The primary objective in creating nano-pesticides is to mitigate the environmental risks associated with pesticide active ingredients by enhancing chemical efficacy. The advantage lies in the extremely small size of the particles, typically ranging from 1 to 100 nanometers, with a nanometer being one billionth of a meter. At this scale, particles offer a substantial surface area, enabling more extensive contact with pests. The ability of nanoparticles to permeate is attributed to their minute size and shape. Similar to other pesticide formulations, nano-pesticide formulations consist of the active ingredient, the carrier molecule, and surfactants. Key advantages of nanoparticles include improved solubility of active ingredients, enhanced formulation stability, gradual release of the active ingredient, and increased mobility due to smaller particle size and larger surface area. Nano-pesticides are expected to enhance the mode of action against target pests compared to bulk materials. Additionally, nano-formulations provide systemic properties, uniform leaf coverage, and improved soil characteristics, supporting their constructive application in agriculture (Rana *et al*., 2021) [28].

Use of Nanopesticides in Horticulture

Nano pesticides have emerged as a groundbreaking tool in contemporary horticulture, catering to the demand for more efficient, eco-friendly, and sustainable pest management approaches. These innovative formulations leverage nanoparticles to deliver pesticides precisely and effectively, presenting several benefits in horticultural contexts. A key advantage of nano pesticides lies in their capacity for targeted pest control. Their nanoscale dimensions enable superior adherence to plant surfaces, ensuring comprehensive coverage and facilitating penetration of pests' protective barriers, such as exoskeletons. This targeted strategy amplifies pest control efficacy while minimizing the quantity of pesticides needed, thereby reducing environmental impact and potential harm to non-target organisms. Moreover, nano pesticides can be designed to release their active ingredients gradually, providing prolonged protection against pests and diseases. This controlled release not only improves crop yield and quality but also diminishes the need for frequent pesticide applications, resulting in cost savings for growers and a reduced environmental footprint. In horticulture, where the aesthetics and quality of produce are paramount, nano pesticides represent a transformative tool. Their precise application minimizes the risk of pesticide residues on harvested fruits, vegetables, or ornamental plants, ensuring consumer safety and meeting rigorous quality standards. While nano pesticides offer numerous advantages, their responsible use is paramount. Adhering to regulatory guidelines and safety assessments is crucial to unlock their full potential and ensure their contribution to sustainable and safe horticultural practices. Overall, nano pesticides signify a significant leap forward in modern horticulture, empowering growers to safeguard their crops effectively while mitigating environmental impacts and fostering the sustainability of agricultural practices.

Use of Nanomaterials for seed coating in Horticulture

The application of nanomaterials in seed coating has garnered considerable attention in horticulture, offering the potential to optimize plant growth, crop yield, and resource utilization. In the precision-driven realm of horticulture, nanomaterial seed coatings provide numerous advantages. Engineered at the nanoscale, these coatings create a protective layer for seeds, ensuring safe germination and early development. A key benefit of nanomaterial seed coatings is their ability to shield seeds from environmental stressors, including pests, diseases, and adverse weather conditions. Operating as a barrier, nanoscale materials protect seeds during vulnerable germination and early growth, improving germination rates and fostering the production of healthier and more resilient plants. Furthermore, nanomaterials in seed coatings can encapsulate essential nutrients, growth-promoting substances, or beneficial microorganisms, allowing precise and controlled delivery to emerging seedlings. This ensures that plants receive the necessary resources for robust growth and development. By enhancing nutrient uptake and fostering symbiotic relationships with beneficial microorganisms, nanomaterial seed coatings contribute to overall crop vigor and yield. Additionally, these coatings improve seed adhesion to the soil, reducing seed wastage during planting and enhancing planting efficiency critical factors in horticulture where precise spacing and seed placement are paramount for optimal crop growth. While the potential benefits of nanomaterial seed coatings in horticulture are promising, responsible use is essential, taking into account safety and regulatory considerations. When applied judiciously and in compliance with guidelines, nanomaterial seed coatings have the potential to revolutionize horticultural practices by elevating crop quality, increasing yields, and promoting sustainable and efficient cultivation methods.

Use of Nanomaterials for crop protection in Horticulture

Nanomaterials have become a promising frontier in horticulture, offering innovative solutions for crop protection in the cultivation of fruits, vegetables, and ornamental plants. Engineered at the nanoscale, these materials address the unique challenges faced in horticulture, providing precision and efficiency in safeguarding plants from pests, diseases, and environmental stressors. One notable application is in the field of nano pesticides, where nanoparticles encapsulate pesticide active ingredients, enabling targeted and controlled release. This precision ensures effective pest targeting while minimizing environmental impact and reducing the quantity of pesticides required. Nanomaterials also play a role in developing protective coatings for plant surfaces, acting as physical barriers against pathogens, insects, and environmental stressors. This protection contributes to plant health and enhances overall crop quality. Additionally, nanoparticles can be loaded with antimicrobial agents or compounds that induce plant defense mechanisms, providing proactive protection against diseases and pests. In the realm of soil and water management, nanomaterials offer advantages in horticulture by improving water retention in soil, enhancing nutrient availability, and enabling real-time monitoring of soil conditions. This facilitates more efficient resource utilization, reducing water and nutrient waste. Overall, the application of nanomaterials in horticulture holds great promise for sustainable and efficient crop protection and resource management.

Use of Nanotechnology for soil improvement in Horticulture

Nanotechnology holds great potential for soil improvement in horticulture, addressing the crucial aspects of soil health and crop quality. In the precise management of soil conditions within horticultural practices, nanotechnology provides innovative solutions tailored to specific challenges. The use of nanoparticles and nanomaterials proves beneficial for enhancing soil fertility and nutrient management. These nanoscale carriers can encapsulate crucial nutrients, including nitrogen, phosphorus, and micronutrients, facilitating controlled and targeted release directly to the plant root zone. This approach maximizes nutrient uptake, minimizes wastage, and reduces the environmental impact associated with excess fertilizers. Furthermore, nanotechnology contributes to the enhancement of soil structure and moisture management in horticultural contexts. Nanoparticles play a role in improving soil aggregation, water retention, and aeration, resulting in enhanced root growth, increased resistance to drought, and overall improvement in plant health. These properties are particularly advantageous for crops that necessitate precise moisture control and well-structured soil for optimal growth. In addition to these benefits, nanotechnology offers solutions for remediating contaminated soils in horticulture. Nanoparticles have the capacity to bind to pollutants and heavy metals, immobilizing them and diminishing their bioavailability to plants. This restorative action aids in revitalizing soil health and ensures the cultivation of safe and high-quality crops.

Sr. No.	Crop	Nanomaterial	Effect of nanomaterial	Reference
1.	Apple	Nano ZnO	Improved the shelf life and Lowered the degradation	X. Li *et al*., 2011
		Nano Biofertilizer	Increased the plant height, plant diameter, leaf area and content of chlorophyll	Mohasedat *et al*., 2018 [23]
		Nano Ca	Enhanced the overall quality of the fruit by augmenting its antioxidant activity, phenolic compound levels, starch content, and fiber content.	Ranjbar *et al*., 2020 [29]
2.	Pomegranate	Nano Zn & Nano B	Increased the fruit yield, quality, TSS and juice content. Decreased total acidity.	Davarpanah *et al*., 2016 [7]
		Se-NPs	The application of SeNPs on the leaves of pomegranate plants helps to reduce the negative impact of drought stress on both the leaves and fruits. It achieves this by improving the activity of antioxidant enzymes.	Zahedi *et al*., 2021 [44]
3.	Mango	Chitosan/spermidine	Triggered the immune response against anthracnose disease and enhances the texture and prolongs the lifespan of the fruit.	Pornchan *et al*., 2017
		Chitosan	Helps in delaying senescence process, loss of water and firmness of fruits.	Silva *et al*., 2017
		Nano B	Increasing the yield and chemical characteristics of fruits has had a beneficial impact. It has improved the levels of chlorophyll and vital nutrients such as nitrogen, potassium, phosphorus, magnesium, manganese, zinc, boron, and iron in the leaves.	Abdelaziz *et al*., 2019
		Nano-Si	When mango seedlings were treated with a spray containing nanosilicon at a concentration of 1.0 g/L in a saline irrigation system, it led to an increase in antioxidant activity.	El-Dengawy *et al*., 2021
		Nano Chitosan & Nano Potassium Silicate	Both fertilizers had a beneficial impact on the growth and development of plants, including increased flowering, chlorophyll levels, fruit production, and overall yield. The Nano K silicate fertilizer specifically had added advantages such as longer panicles, higher yield, and superior fruit qualities. Additionally, it helped reduce floral malformation.	Gad *et al*., 2021
4.	Grape	Nano Ca	Increased foliage development, chlorophyll content and yield. Improved berry colouration	Sabir *et al*., 2014
		Amino Nanofertilizer	Enhanced the fruit quality	Wassel *et al*., 2017
		Chitosan, chitosan/chitosang-salicylic acid and salicylic acid	Boosts the efficiency of enzymes like chitinase, lyase, and glucanase. Reduces the rate of respiration, loss of weight, and occurrence of decay.	Shen *et al*., 2017
		Nano C	Berries, leaf area, and total carbohydrate levels were found to have been enhanced, accompanied by increased amounts of nitrogen, potassium, phosphorus, iron, and magnesium in the leaves.	Abdel-Hak *et al*., 2018
5.	Citrus	Nano NPK	Highest total leaf area, seedling stem diameter, dry weight of root and shoot.	Al-Jilihawi *et al*., 2020
6.	Date Palm	Nano NPK	Increased the growth rate, yield and quality.	Roshdy and Refai, 2016
7.	Peach	Nano Ag	Leaf area, chlorophyll concentration, shoot thickness, proportion of flowers, and fruit production all experienced an elevation, along with enhanced physical and chemical attributes of the fruits.	Mosa *et al*., 2021
8.	Strawberry	Chitosan-	The antimicrobial properties of the coating are efficient, and they have a positive	Shahbazi, 2018

		carboxymethyl cellulose/Mentha spicata essential oil	impact on titratable acidity, the rate of weight loss, resistance to water vapor, pH levels, and the rate of respiration.	
		$nSiO_2$	The usage of $nSiO_2$ can mitigate the detrimental effects of salinity stress on strawberry plants by improving water loss control and preserving chlorophyll and water levels.	Avestan *et al.*, 2019
		Se-NPs	The application of Se-NPs on the leaves improved the effectiveness of antioxidant enzymes like SOD and POD, consequently decreasing the lipid peroxidation and H_2O_2 levels caused by stress in strawberries.	Zahedi *et al.*, 2019 [43]
		SA and Fe-NPs	The utilization of SA and iron (INs) resulted in an improvement of SOD and POD activity, an increase in protein and proline levels, and a decrease in H_2O_2 and MDA production in strawberry plantlets that were grown in vitro.	Dedejani *et al.*, 2021 [8]
		Se-NPs and MeJA	The use of methyl jasmonate (MeJA) and silicon (Si) nanoparticles on strawberry plants triggers the activation of genes associated with salinity tolerance and their subsequent processes, suggesting an improvement in the plant's ability to withstand high salt levels. This response is observed over a specific period of time.	Moradi *et al.*, 2022 [24]
		Fe-NPs	The use of FeNPs in the treatment alleviated the negative impacts of PEG-induced water stress on physical and functional characteristics by enhancing the activity of antioxidant enzymes and reducing levels of MDA and H_2O_2.	Yosefi *et al.*, 2022 [42]
9.	Sweet Orange	SiO_2–NP	The utilization of SiO_2–NPs improved the development of roots, boosted the amount of chlorophyll, and reduced the negative impacts of osmotic stress on plants treated with NaCl, in comparison to plants that were under normal stress conditions.	Mahmoud *et al.*, 2022 [19]
10.	Banana	SiO_2–NPs	The use of SiO_2 nanoparticles leads to enhanced chlorophyll content, improved K+ uptake, ensured regulation of Na+ levels, and decreased cell wall damage in plants experiencing abiotic stress, in comparison to plants that have not been treated.	Mahmoud *et al.*, 2020 [18]
		Chitosan-NPs	Chitosan-NPs treatment in banana plants lowered the adverse effects of chilling stress.	Wang *et al.*, 2021 [40]
		Chitosan and chitosan-NPs (CSNPs)	The use of chitosan or chitosan nanoparticles resulted in reduced chilling injury and weight loss, while enhancing firmness, hue angle, total antioxidant activity, and total phenolic content in comparison to the control samples.	Elbagoury *et al.*, 2022 [11]
11.	Persimmon	Cs-Phe-NPs	Using a solution consisting of persimmon fruit and Cs-Phe-NPs at concentrations of 2.5 and 5 mM, it was observed that chilling injury was significantly decreased and the fruit maintained its desirable taste and texture while being stored in cold conditions.	Nasr *et al.*, 2021 [21]
12.	Plum	CTS-Arg-NPs	CTS-Arg-NPs exhibited a decrease in H_2O_2 buildup in comparison to the control group of fruits. This decrease was linked to the improved functioning of antioxidant enzymes like CAT, POD, APX, and SOD. Additionally, the use of 0.5% CTS-Arg-NPs was found to be the most successful treatment in postponing chilling injury and prolonging the storage duration of plum fruit.	Mahmoudi *et al.*, 2022 [19]
13.	Pineapple	Ag-NPs	The utilization of silver nanoparticles (AgNPs) significantly enhanced the development of shoots, raised the levels of chlorophyll a/b and total/carotenoid ratios, and increased the production of proline in response to stress.	Tejada-Alvarado *et al.*, 2023 [39]
14.	Blueberry	Chitosan/procyanidin	Reduces the proliferation of mould and yeast, maintains firmness, and enhances the effectiveness of antioxidants.	Mannozzi *et al.*, 2018 [22]
15.	Guava	Chitosan	Decreases weight loss, breathing rate, the process of protecting against oxidative damage, and improves firmness.	Silva *et al.*, 2018 [36]

Benefits of Nanotechnology in Horticulture

- Precision in nutrient delivery is achieved through nanoscale carriers, ensuring plants receive optimal nutrients, reducing fertilizer use, and minimizing environmentally harmful nutrient runoff.
- Enhanced and targeted pest control is provided by nano pesticides, penetrating insect exoskeletons and plant tissues more effectively, minimizing pesticide application and reducing environmental impact.
- Improved soil structure and moisture retention by nanomaterials lead to better aeration, reduced soil erosion, and increased drought resistance in crops, fostering healthier plant growth.
- Regulating gas exchange, moisture, and temperature within packaging materials using nanotechnology extends the shelf life of harvested fruits and vegetables, reducing food waste and maintaining product quality.
- Nanotechnology promotes sustainable horticultural practices by reducing chemical usage, optimizing resource utilization, and minimizing environmental impact.
- Real-time data on soil and environmental conditions from nano sensors and monitoring systems enable precise decision-making and resource allocation, enhancing resource use efficiency and crop management.
- Controlled release of beneficial microorganisms or biopesticides, facilitated by nanotechnology, supports natural pest control methods, reducing dependence on chemical pesticides.
- Improved overall health and productivity of plants through nanotechnology result in increased crop yields and enhanced crop quality.

- Nanoscale sensors and moisture management technologies support efficient water use in irrigation, conserving this vital resource in agriculture.
- Tailoring solutions to specific horticultural needs is facilitated by nanotechnology, offering precision and flexibility in crop management.

Constraints of Nanotechnology in Horticulture

In horticulture, nano fertilizers prove to be valuable assets for farming systems and sustainable agricultural practices, offering a multitude of advantages in cultivating high-quality, high-yield crops. The potential uptake of nanoparticles by plants, along with their biotransformation and translocation pathways, yields both positive and negative consequences. However, the lack of recognized formulations, comprehensive monitoring, and risk management impedes the development and deployment of nanoparticles as nanofertilizers (Iqbal, 2019) [15]. Nanomaterials exhibit associations with soil microbes, influencing nutrient uptake in plants due to their ability to modify intercellular activity (Singh, 2017) [37]. Concerns arise in human health as nanoparticles can readily enter biological systems and cross cell membranes during spraying, potentially reaching vital organs like the liver, brain, or heart (Suppan, 2017) [38]. Findings suggest negative impacts of nanofertilizers, emphasizing the need for systematic assessments covering risks to human health, food security, ecosystem impacts, standardized crop formulas, and guidelines. The development of nanofertilizers with stable, standardized formulations is essential to ensure safety and prevent harmful effects. Despite the considerable advantages, nanotechnology in horticulture presents certain limitations and challenges. Safety and environmental concerns are paramount, as improperly managed nanoparticles may accumulate in soil and water ecosystems, affecting non-target organisms and the environment. Ongoing research into the long-term consequences of nanoparticle exposure is crucial for responsible use. Cost remains a limiting factor, as the development and production of nanomaterials can be expensive, hindering accessibility for small-scale farmers or resource-limited horticultural operations. Scaling up nanotechnology solutions cost-effectively is imperative for broader adoption. Additionally, the regulatory framework for nanotechnology in agriculture is evolving, necessitating the establishment of safety guidelines. Balancing innovation and safety is a critical challenge. Implementation of nanotechnology requires specialized knowledge and expertise, emphasizing the need for training horticultural professionals in its applications. Public perception and acceptance also pose challenges, emphasizing the importance of transparent communication about nanotechnology's benefits and potential risks to gain public trust.

References

1. Abdelaziz FH, Akl AMMA, Mohamed AY, Zakier MA. Response of keitte mango trees to spray boron prepared by nanotechnology technique. NY Sci. J. 2019;12:48-55.
2. Abdel-Hak RS, El-Shazly SA, El-Gazzar AA, Shaaban EA. Effects of nano carbon and nitrogen fertilization on growth, leaf mineral content, yield and fruit quality of flame seedless grape. Arab Universities Journal of Agricultural Sciences. 2018;26(Special issue (2D)):1439-1448.
3. Al-Jilihawi DAH, Merza TK. Effect of soil fertilization and foliar nano-npk on growth of key lemon *Citrus aurantifolia* rootstock saplings. Plant archives. 2020;20(2):3955-3958.
4. Avestan S, Ghasemnezhad M, Esfahani M, Byrt CS. Application of nanosilicon dioxide improves salt stress tolerance in strawberry plants. Agronomy. 2019;9:246.
5. Blois L, Lay-Ekuakille A. Reliability and metrology features for manufacturing process of nanoelements for geo-environmental protection. Nanotechnology for Instrumentation and Measurement (Nanofim) IEEE. 2018, 1-4.
6. Chaupoo AS, Dhakad A, Beese S, Kumar A, Kumar P, Pandey SK, *et al*. Transforming Horticulture: The Influence of Nanotechnology on Crop Enhancement. International Journal of Environment and Climate Change. 2023;13(11):3381-3400.
7. Davarpanah S, Tehranifar A, Davarynejad G, Abadía J, Khorasani R. Effects of foliar applications of zinc and boron nano-fertilizers on pomegranate (*Punica granatum* cv. *Ardestani*) fruit yield and quality. Scientia horticulturae. 2016;210:57-64.
8. Dedejani S, Mozafari A, Ghaderi N. Salicylic acid and iron nanoparticles application to mitigate the adverse effects of salinity stress under in vitro culture of strawberry plants. Iran. J Sci. Technol. Trans. A Sci. 2021;45:821–831.
9. Ditta A. How helpful is nanotechnology in agriculture? Advances in Natural Sciences: Nanoscience and Nanotechnology. 2012;3:10.
10. El-Dengawy E, EL-Abbasy U, El-Gobba M. Influence of nano-silicon treatment on growth behavior of ‘Sukkary’ and ‘Gahrawy’ mango root-stocks under salinity stress. J Plant Prod. 2021;12:49–61.
11. Elbagoury MM, Turoop L, Runo S, Sila DN, Madivoli ES. Postharvest treatments of banana (*Musa acuminata* cv. ‘Grand Nain’, AAA) during cold and ripening temperatures with chitosan and chitosan nanoparticles to alleviate chilling injury and maintain antioxidant activity. Hortic. Environ. Biotechnol. 2022;63:677–699.
12. Gad M, Abdel-Mohsen M, Zagzog O. Improving the yield and fruiting characteristics of Ewais Mango Cultivar by spraying with Nano-chitosan and Nano-potassium silicate. Scientific Journal of Agricultural Sciences. 2021;3(2):68-77.
13. Gomes DG, Pieretti JC, Rolim WR, Seabra AB, Oliveira HC. Advances in nano-based delivery systems of micronutrients for a greener agriculture. In: Advances in Nano-Fertilizers and Nano-Pesticides in Agriculture. Woodhead Publishing; c2021. p. 111-143.
14. Hayat F, Khanum F, Li J, Iqbal S, Khan U, Javed HU. Nanoparticles and their potential role in plant adaptation to abiotic stress in horticultural crops: A review. Scientia Horticulturae. 2023;321:112285.
15. Iqbal MA. Nano-fertilizers for sustainable crop production under changing climate: A global perspective. Sustainable crop production. 2019;8:1-13.
16. Khan MR, Rizvi TF. Application of nanofertilizer and nanopesticides for improvements in crop production and protection. In: Nanoscience and plant–soil systems. Springer; c2017. p. 405-427.

17. Li X, Li W, Jiang Y, Ding Y, Yun J, Tang Y. Effect of nano-ZnO-coated active packaging on quality of fresh-cut 'Fuji' apple. International Journal of Food Science & Technology. 2011;46(9):1947-1955.
18. Mahmoud LM, Dutt M, Shalan AM, El-Kady ME, El-Boray MS, Shabana YM, Grosser JW. Silicon nanoparticles mitigate oxidative stress of in vitro-derived banana (*Musa acuminata* 'Grand Nain') under simulated water deficit or salinity stress. S. Afr. J. Bot. 2020;132:155–163.
19. Mahmoud LM, Shalan AM, El-Boray MS, Vincent CI, El-Kady ME, Grosser JW, Dutt M. Application of silicon nanoparticles enhances oxidative stress tolerance in salt-stressed 'Valencia' sweet orange plants. Sci. Hortic; c2022. p. 295 (Amsterdam).
20. Mahmoudi R, Razavi F, Rabiei V, Palou L, Gohari G. Postharvest chitosan arginine nanoparticles application ameliorates chilling injury in plum fruit during cold storage by enhancing ROS scavenging system activity. BMC Plant Biol. 2022, 22.
21. Manjunatha SB, Biradar DP, Aladakatti YR. Nanotechnology and its applications in agriculture: A review. J farm Sci. 2016;29(1):1-13.
22. Mannozzi C, Tylewicz U, Chinnici F, Siroli L, Rocculi P, Dalla Rosa M, Romany S. Effects of chitosan-based coatings enriched with procyanidin by-product on quality of fresh blueberries during storage. Food Chem. 2018;251:18–24.
23. Mohasedat Z, Dehestani-Ardakani M, Kamali K, Eslami F. The effects of nano-bio fertilizer on vegetative growth and nutrient uptake in seedlings of three apple cultivars. Adv. In Biores. 2018;9(2).
24. Moradi P, Vafaee Y, Mozafari AA, Tahir NAR. Silicon nanoparticles and methyl Jasmonate improve physiological response and increase expression of stress-related genes in strawberry (cv. paros) under salinity stress. Silicon. 2022;14:10559–10569.
25. Mosa WF, El-Shehawi AM, Mackled MI, Salem MZ, Ghareeb RY, Hafez EE, Abdelsalam NR. Productivity performance of peach trees, insecticidal and antibacterial bioactivities of leaf extracts as affected by nanofertilizers foliar application. Scientific Reports. 2021;11(1):1-19.
26. Nasr F, Pateiro M, Rabiei V, Razavi F, Formaneck S, Gohari G, Lorenzo JM. Chitosan-phenylalanine nanoparticles (Cs-Phe Nps) extend the postharvest life of persimmon (*Diospyros kaki*) fruits under chilling stress. Coatings. 2021;11:819.
27. Pornchan J, Pranee R, Teerada W, Kanogwan S. Influence of chitosan coating combined with spermidine on anthracnose disease and qualities of "Nam Dok Mai" mango after harvest. Sci. Hort. 2017;224:180–187.
28. Rana RA, Siddiqui MN, Skalicky M, Brestic M, Hossain A, Kayesh E, *et al*. Prospects of nanotechnology in improving the productivity and quality of horticultural crops. Horticulturae. 2021;7(10):332.
29. Ranjbar S, Ramezanian A, Rahemi M. Nano-calcium and its potential to improve 'Red Delicious' apple fruit characteristics. Horticulture, Environment, and Biotechnology. 2020;61(1):23-30.
30. Roshdy KHA, Refaai MM. Effect of nanotechnology fertilization on growth and fruiting of zaghloul date palms. J Plant Production. Mansoura Univ. 2016;7(1):93-98.
31. Sabir A, Yazar K, Sabir F, Kara Z, Yazici MA, Goksu N. Vine growth, yield, berry quality attributes and leaf nutrient content of grapevines as influenced by seaweed extract (*Ascophyllum nodosum*) and nanosize fertilizer pulverizations. Scientia Horticulturae. 2014;175:1-8.
32. Shahbazi Y. Application of carboxymethyl cellulose and chitosan coatings containing Mentha spicata essential oil in fresh strawberries. Int. J. Biol. Macromol. 2018;112:264–272.
33. Shen Y, Yang H. Effect of preharvest chitosan-g-salicylic acid treatment on postharvest table grape quality, shelf life, and resistance to Botrytis cinerea-induced spoilage. Sci. Hort. 2017;224:367–373.
34. Shilpa RS, Kant C, Prashar N. Role of nanofertilizers in horticulture: A review. Pharma Innov. J. 2022;11:831-836.
35. Silva GMC, Silva WB, Medeiros DB, Salvador AR, Cordeiro MHM, da Silva NM, Santana DB, Mizobutsi GP. The chitosan affects severely the carbon metabolism in mango (*Mangifera indica* L. cv. Palmer) fruit during storage. Food Chem. 2017;237:372–378.
36. Silva WB, Silva GMC, Santana DB, Salvador AR, Medeiros DB, Belghith I, *et al*. Chitosan delays ripening and ROS production in guava (*Psidium guajava* L.) fruit. Food Chem. 2018;242:232–238.
37. Singh NA. Nanotechnology innovations, industrial applications and patents. Environ. Chem. Lett. 2017;15(2):185-191.
38. Suppan S. Applying nanotechnology to fertilizer: rationales, research, risks and regulatory challenges. The Institute for Agriculture and Trade Policy works locally and globally, Brazil; c2017.
39. Tejada-Alvarado JJ, Mel´endez-Mori JB, Ayala-Tocto YR, Gonas ˜ MO. Influence of silver nanoparticles on photosynthetic pigment content and mineral uptake in pineapple seedlings grown in vitro under aluminum stress. Agronomy. 2023;13:1186.
40. Wang A, Li J, Al-Huqail AA, Al-Harbi MS, Ali EF, Wang J, *et al*. Mechanisms of chitosan nanoparticles in the regulation of cold stress resistance in banana plants. Nanomaterials. 2021;11:2670.
41. Wassel AEH, El-Wasfy M, Mohamed M. Response of Flame seedless grapevines to foliar application of nano fertilizers. Journal of Productivity and Development. 2017;22(3):469-485.
42. Yosefi A, Mozafari A, Javadi T. In vitro assessment of strawberry (*Fragaria* × *ananassa Duch*.) plant responses to water shortage stress under nano-iron application. Vit. Cell. Dev. Biol. Plant. 2022;58:499–510.
43. Zahedi SM, Abdelrahman M, Hosseini MS, Hoveizeh NF, Tran LSP. Alleviation of the effect of salinity on growth and yield of strawberry by foliar spray of selenium-nanoparticles. Environ. Pollut. 2019;253:246–258.
44. Zahedi SM, Hosseini MS, Daneshvar Hakimi Meybodi N, Peijnenburg W. Mitigation of the effect of drought on growth and yield of pomegranates by foliar spraying of different sizes of selenium nanoparticles. J Sci. Food Agric. 2021;101:5202–5213.