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Nanotechnology applications in floriculture and ornamental horticulture: A review

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Abstract

Nanotechnology has emerged as a transformative discipline with wide-ranging implications for modern agriculture, particularly in the specialized domain of floriculture and ornamental horticulture. Ornamental plants including cut flowers, potted flowering plants, foliage plants, and landscape plants represent a multi-billion-dollar global industry that faces mounting challenges related to vase life extension, disease management, stress tolerance, and sustainability. Nanoparticles (NPs) of diverse chemical compositions, including silver (AgNPs), zinc oxide (ZnO NPs), titanium dioxide (TiO₂ NPs), silicon dioxide (SiO₂ NPs), carbon nanotubes (CNTs), iron oxide (Fe₃O₄ NPs), chitosan NPs, and gold NPs, have been extensively investigated for their capacity to modulate plant growth, enhance post-harvest longevity, improve stress resilience, and combat phytopathogens in ornamental crops. This review comprehensively synthesizes the current state of knowledge regarding nano-based interventions in floriculture, examining mechanisms of nanoparticle uptake and translocation in ornamental species, their dose-dependent effects on germination, vegetative growth, flowering, and post-harvest quality. Special emphasis is placed on the role of nano-fertilizers and nano-pesticides, the application of nanoparticles for vase life extension in cut flowers such as roses (*Rosa* spp.), carnations (*Dianthus caryophyllus*), chrysanthemums (*Chrysanthemum morifolium*), and gerbera (*Gerbera jamesonii*), and the integration of nano-delivery systems for controlled release of plant growth regulators. The review also addresses phytotoxicological concerns, regulatory frameworks, and future research directions necessary for the safe and effective commercialization of nano-horticultural technologies.

Keywords: Nanoparticles, floriculture, ornamental horticulture, vase life, nano-fertilizers, silver nanoparticles, post-harvest, phytotoxicology, cut flowers, stress tolerance

1. Introduction

Ornamental Horticulture falls under the domain of floriculture and constitutes a major segment of agriculture that is economically as well as aesthetically very important. According to statistics, the global Ornamental Plants market that includes cut flowers, pot plants, bedding plants, nursery plants, and landscape plants has been estimated to have revenues of more than USD 50 billion in 2023 and will continue to grow at a CAGR higher than 6%. The main producers in this global interconnected chain of production include Netherlands, Colombia, Ecuador, Kenya, India, and China (Usman *et al.*, 2020) ^[81].

In spite of all the economic importance associated with this industry, there are several major challenges facing the industry in various ways. Losses in cut flowers post-harvest occur through ethylene-induced aging, presence of stem-blocking microbes in vase water, water stress, and physical damage in transit amounting to 20-40 percent of the losses (Hussain *et al.*, 2019) ^[79]. In production itself, ornamental crops face many problems from the abiotic conditions such as drought, salinity, heat, and excessive heavy metals which decrease their quality and vase life along with reduction in flower size and coloring. Biotic dangers arise from fungi like *Botrytis cinerea*, *Fusarium*, and *Pythium* and bacteria like *Pseudomonas cichorii*, *Erwinia chrysanthemi* cause significant crop losses and necessitate extensive pesticide inputs with attendant environmental consequences (Tímár and Gáborjányi, 2012) ^[79].

Against this backdrop, nanotechnology has proven itself to be a valuable array of tools that can tackle multiple factors simultaneously. Being defined as the technology of engineering at the nanoscale (1-100 nm), nanotechnology results in the creation of materials possessing

unique physicochemical properties due to their high surface-to-volume ratio, quantum effect, and higher reactivity (Sekhon, 2014; Sanzari *et al.*, 2019) ^[68, 70]. Such properties allow nanoparticles to interact with biological processes of plants at the molecular level, thus affecting enzyme activity, gene regulation, cell membrane permeability, ROS scavenging, and hormones in ways that cannot be achieved with the help of conventional chemicals (Nair *et al.*, 2010; Van Aken, 2015) ^[56, 82].

Nanotechnology is used throughout the lifecycle of plants, as it has found application in the enhancement of seed germination and seedling emergence, stimulating plant growth and flowering, acting as a carrier of controlled-release fertilizers and plant growth regulator, increasing vase life of cut flowers, providing nano-fungicides and bactericides, and imparting resistance to environmental stressors (Khan *et al.*, 2017; Paramo *et al.*, 2020) ^[37, 59]. In particular, silver nanoparticles (AgNPs) have gained significant interest as vase life enhancers, capitalizing on the well-established antimicrobial potential of these particles to minimize bacterial counts in vase solutions and thereby avoid stem clogging a key factor contributing to early

wilting (Jokar & Sarraf-Mamoory, 2013; Malekian & Souiri, 2020) ^[35, 51]. Nano-silicon, nano-zinc, and nano-titanium dioxide have been explored as growth, coloring, and stress resistance enhancers for ornamental plants (Reyes-Pérez *et al.*, 2019; Shafeek *et al.*, 2021) ^[66, 71].

This review will address the wide spectrum of nanotechnology uses in floriculture and ornamental horticulture by discussing current research findings regarding the modes of action of nanoparticles, crop-specific responses, post-harvest applications, nano-fertilizers, nano-pesticides, phytotoxicity, and regulation, with the objective of pinpointing potential benefits and pitfalls associated with the adoption of nanotechnologies in ornamental crops cultivation.

2. Types of Nanoparticles used in floriculture

Nanoparticles employed in ornamental horticulture research span a chemically diverse array of materials, each with distinct physicochemical properties, modes of action, and suitability for specific horticultural applications. A systematic classification is presented in Table 1.

Table 1: Classification of nanoparticles used in floriculture and ornamental horticulture with their primary applications

NP Type	Chemical Formula	Size Range (nm)	Key Properties	Primary Floriculture Use	Nair <i>et al.</i> (2010) ^[56] , Sekhon (2014) ^[70] , Sanzari <i>et al.</i> (2019) ^[68] , Paramo <i>et al.</i> (2020) ^[59] .
Silver NPs (AgNPs)	Ag ⁰	5-50	Antimicrobial, antifungal, anti-ethylene	Vase life extension, post-harvest preservation	
Zinc Oxide NPs (ZnO)	ZnO	20-100	Micronutrient supply, ROS modulation	Growth promotion, stress tolerance, nano-fertilizer	
Titanium Dioxide NPs (TiO ₂)	TiO ₂	10-80	Photocatalytic, photosynthesis enhancement	Photosynthesis boost, chlorophyll enhancement	
Silicon Dioxide NPs (SiO ₂)	SiO ₂	15-50	Cell wall strengthening, stress buffering	Drought/salinity tolerance, flower quality	
Gold NPs (AuNPs)	Au ⁰	5-30	Inert, biocompatible, plasmon resonance	Growth enhancement, signaling modulation	
Carbon Nanotubes (CNTs)	C (SWCNT/MWCNT)	1-50 (dia.)	Water channel enhancement, electrical conductivity	Germination stimulation, root growth	
Chitosan NPs	C ₆ H ₁₁ NO ₄) _n	50-300	Biopolymer, biodegradable, antimicrobial	Controlled release fertilizer/pesticide carrier	
Iron Oxide NPs (Fe ₃ O ₄)	Fe ₃ O ₄	10-50	Magnetic, micronutrient supply	Iron nutrition, enzyme activation	
Copper Oxide NPs (CuO)	CuO	20-100	Antifungal, micronutrient	Fungal disease management (low doses)	

2.1 Metal and Metal oxide nanoparticles

Metallic nanoparticles, especially silver nanoparticles (AgNPs) and gold nanoparticles (AuNPs), have been some of the most widely investigated materials in ornamental plants. Silver nanoparticles can be produced by chemical reduction, biological synthesis, and green synthesis techniques based on plant extract or fungi/bacteria (Guilger-Casagrande and Lima, 2019) ^[27]. The mode of action of silver nanoparticles in plants includes modulation of ethylene biosynthesis and inhibition of microbial cell membranes, thus making them effective in post-harvest treatments (Sharma *et al.*, 2012) ^[73]. Gold nanoparticles

have also been shown to induce growth in *Arabidopsis thaliana* and *Brassica juncea* due to their remarkable biocompatibility and plasmon resonance characteristics by modulating the activity of ROS scavenging enzymes (Kumar *et al.*, 2013; Arora *et al.*, 2012; Govorov and Carmeli, 2007) ^[5, 26, 42].

Even more diverse are metal oxide nanoparticles. ZnO NPs provide zinc, which is a micronutrient necessary for proper plant growth, in nano form and simultaneously trigger enzymes for antioxidants (Burman *et al.*, 2013; Raliya and Tarafdar, 2013) ^[11, 64]. TiO₂ NPs have been effectively used for enhancing chlorophyll production and increasing

photosynthesis efficiency by virtue of their light-catalysis effect in ornamental plants (Hong *et al.*, 2005; Feizi *et al.*, 2012) [22, 29]. Iron oxide nanoparticles deal with iron deficiency in ornamental plants cultivated in alkaline and waterlogged soil conditions (Kim *et al.*, 2015; Martinez-Fernandez *et al.*, 2023) [40, 53].

2.2 Carbon-based nanoparticles

The Carbon Nanotubes (CNTs), which include Single-Walled CNTs (SWCNTs) and Multi-Walled CNTs (MWCNTs), constitute a special group of nano-materials having extremely high tensile strength, electrical conductivity, and biological properties. In plant science, CNTs are known to increase water absorption and water transport through formation of channels similar to that produced by aquaporins for water movement, as well as induce cell division by activating water channels proteins (Khodakovskaya *et al.*, 2012; Lahiani *et al.*, 2013; Wang *et al.*, 2012) [38, 43, 83]. The observation on increased germination and root growth in ornamental plants such as tobacco and tomato suggest their applicability to ornamentals seedlings production.

2.3 Biopolymer-based nanoparticles

The use of chitosan nanoparticles has gained much attention because of their biodegradability, biocompatibility, and natural antimicrobial nature (Kadam and Bhatt, 2021; Saharan *et al.*, 2013) [36, 67]. In decorative horticulture, chitosan NPs play two functions: first, they work as carrier agents for macronutrient and micronutrient delivery to plant roots and leaves, second, as fungicidal substances protecting plants from phytopathogens like *Botrytis cinerea* and *Alternaria* species, which normally cause damage to cut flowers. Choudhary *et al.* (2019) [14] observed that Cu-chitosan NPs could promote resistance gene expressions in decorative plants. Li *et al.* (2019) [46] found better growth results in wheat seedlings.

3. Nanoparticle uptake, translocation, and mechanisms of action

Understanding how nanoparticles enter, move through, and interact with plant tissues is fundamental to both optimizing beneficial applications and assessing phytotoxicological risks. Multiple routes of NP entry into ornamental plant systems have been characterized (Ali *et al.*, 2021; Nair *et al.*, 2010) [3, 56]

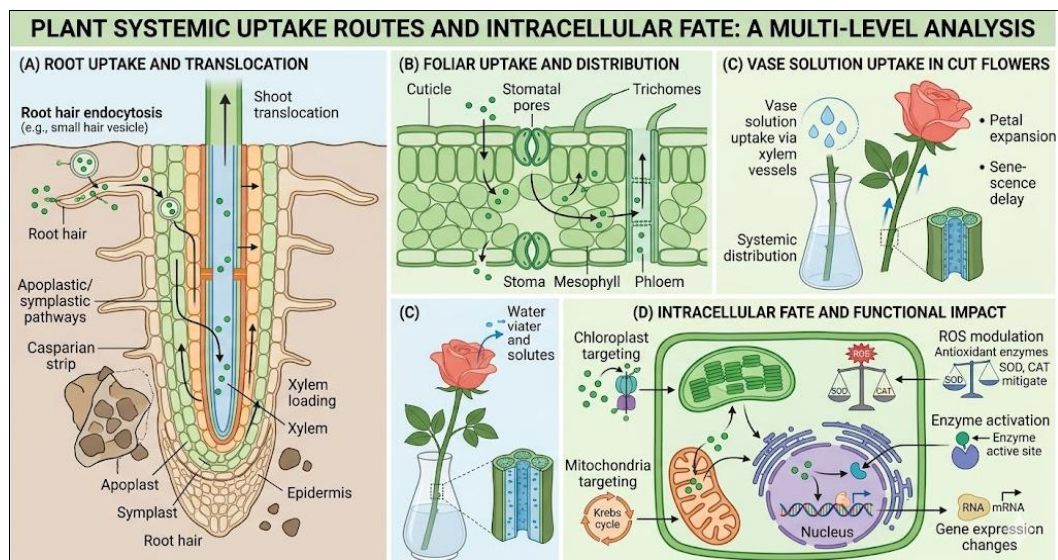


Fig 1: Schematic Overview of Nanoparticle Uptake and Translocation Pathways in Ornamental Plants

(A) Root uptake via apoplastic/symplastic pathways and root hair endocytosis → xylem loading → shoot translocation; (B) Foliar uptake via cuticle, stomatal pores, trichomes → phloem loading → systemic distribution; (C) Vase solution uptake via xylem vessels in cut flowers. Intracellular fate: chloroplast & mitochondria targeting, ROS modulation, enzyme activation, gene expression changes. [Conceptual diagram based on Nair *et al.* (2010) [56]; Ali *et al.* (2021) [3]; Larue *et al.* (2012) [44]]

3.1 Root uptake and Translocation

Nanoparticles in either soil or hydroponics solution come into contact with the roots and can bind onto the cell walls of plant tissues, enter via endocytosis, or translocate apoplastically (between cells) or symplastically (inside cells) (Larue *et al.*, 2012) [44]. Nanoparticles with smaller sizes (<20 nm) are able to diffuse through cell wall pores, which vary between 3-8 nm across different plants, and enter into the symplast; on the other hand, nanoparticles with larger sizes tend to travel apoplastically until they reach the Casparian strip, at which point they cannot proceed anymore without entering into the symplast. Afterward, NPs get loaded into the xylem of the plant and transported upward to aerial parts of the plant body. The journey of TiO₂ NPs has been traced via synchrotron X-ray

fluorescence studies in wheat plants (Larue *et al.*, 2012) [44].

3.2 Foliar uptake

Foliar treatment is one of the major routes of application used in the management of ornamental crops where NPs may enter via stomatal openings, cuticular waxes, and trichomes present in the leaf (Ali *et al.*, 2021) [3]. Stomatal openings (which range between 5-15 μm when opened) enable the entry of clusters of NPs into the substomatal cavity, whereas hydrophobic pathways enable the entry of lipid-coated and/or functionalized NPs through the cuticle. Foliar-absorbed NPs can eventually enter the phloem stream and move throughout the plant, including its reproductive structures. Nano-silicon sprayed onto gerbera plants was

absorbed in its petals (Shafeek *et al.*, 2021) ^[71].

3.3 Molecular mechanisms of action

Nanoparticles at the molecular level have multiple impacts on the physiology of ornamental plants to enable growth promotion, enhanced tolerance to stresses, and extended shelf life after harvest. These molecular-level impacts include: (i) regulation of ROS balance through induction or inhibition of various antioxidant enzymes like superoxide dismutase, catalase, ascorbate peroxidase, and peroxidases by NPs; (ii) disruption of hormones' biosynthesis and signaling, especially ethylene due to inhibition of its key enzyme ACC oxidase by AgNPs, and auxin; (iii) nutrient acquisition through increased availability due to solubilization by NPs and enhanced uptake from roots; (iv) stimulation of stress-responsive gene expression, such as heat shock protein 70, metallothioneins, and aquaporins; and (v) direct antibacterial activity against pathogenic microbes, including bacteria blocking vascular tissues. (Khan *et al.*, 2017; Van Aken, 2015 and Tripathi *et al.*, 2019) ^[37, 80, 82].

4. Post-harvest applications: Vase life extension of cut flowers

Post-harvest handling is the most economically significant and studied field of application of nanotechnology in the field of floriculture. Life expectancy of cut flowers depends on the interaction between such processes as ethylene-mediated senescence, clogging of vessels with biofilms of microorganisms, oxidative stress, water metabolism, and

carbohydrate exhaustion (Hussain *et al.*, 2019) ^[31]. Among all other nanoparticles, AgNPs have been found to be very efficient in this regard.

4.1 Silver nanoparticles and Vase life

The AgNPs have probably become the most commonly used nano-additive in cut flower vase life studies. The dual role played by AgNPs in inhibiting bacteria blocking stems, and their ability to inhibit ethylene production by acting as competitors for ethylene receptors in the process of releasing silver ions makes them highly efficient for improving vase life in flowers. According to Jokar and Sarraf-Mamoory (2013) ^[35], AgNPs were highly efficient in extending vase life in cut roses (*Rosa hybrida*). Optimal concentrations of AgNPs ranged between 30-60 mg L⁻¹, which increased the vase life without any adverse phytotoxic symptoms. In another study, Malekian and Souri (2020) ^[51] indicated that 20 mg L⁻¹ nano-silver spray significantly increased gladiolus (*Gladiolus grandiflorus*) vase life by 34%, while preserving high levels of anthocyanin and chlorophyll content.

Additionally, in their study involving *Pelargonium hortorum* plants stored under dark conditions, Hatami and Ghorbanpour (2014) ^[28] found that 50 mg L⁻¹ AgNPs performed better than STS and control treatments in terms of membrane stability, fresh weight, and enhanced antioxidant enzyme activities. AgNPs were also confirmed by Sharma *et al.* (2012) ^[73] to be highly efficient in improving oxidative stress tolerance in *Brassica juncea*.

4.2 Nano-silver in specific ornamental crops

Table 2: Summary of nano-silver (AgNP) effects on vase life and post-harvest quality of major ornamental species

Ornamental Species	AgNP Concentration	Application Method	Vase Life Increase	Key Findings	Reference
<i>Rosa hybrida</i> (Rose)	30-60 mg L ⁻¹	Vase solution	+28-35%	Reduced bacterial colony counts, inhibited ethylene	Jokar & Sarraf-Mamoory (2013) ^[35]
<i>Gladiolus grandiflorus</i>	20 mg L ⁻¹	Foliar spray	+34%	Maintained anthocyanin, chlorophyll integrity	Malekian & Souri (2020) ^[51]
<i>Dianthus caryophyllus</i> (Carnation)	25 mg L ⁻¹	Vase solution	+30%	Reduced ethylene evolution, preserved petal color	Hussain <i>et al.</i> (2019) ^[31]
<i>Pelargonium hortorum</i>	50 mg L ⁻¹	Pulsing + foliar	+25%	Higher SOD, CAT; maintained membrane integrity	Hatami & Ghorbanpour (2014) ^[28]
<i>Chrysanthemum morifolium</i>	40 mg L ⁻¹	Vase solution	+22%	Enhanced photosynthetic rate, flower diameter	Chen & Wang (2018) ^[13]
<i>Gerbera jamesonii</i>	30 mg L ⁻¹	Vase + foliar	+31%	Reduced MDA, increased antioxidant capacity	Shafeek <i>et al.</i> (2021) ^[71]

MDA = Malondialdehyde; SOD = Superoxide Dismutase; CAT = Catalase

4.3 Other nanoparticles in post-harvest management

Apart from AgNPs, some other types of nanoparticles have been found useful after harvest. Nano-silicon dioxide has been used in preservative solutions for roses and lilies, developing a biocompatible film over the walls of the xylem vessels that inhibits microbial growth without causing any plant toxicity linked with metal ions (Rastogi *et al.*, 2019) ^[65]. Nano-titanium dioxide in vase solutions has proven effective in preserving chlorophyll content in chrysanthemums through PSII efficiency maintenance and lowering chlorophyllase enzyme activity (Chen and Wang, 2018) ^[13]. Chitosan nanoparticles coating on cut flower

stems have been found to form a semi-permeable nanofilm which inhibits water loss but allows gas exchange, thus increasing the shelf life of roses and alstroemeria (Xing *et al.*, 2011; Kadam and Bhatt, 2021) ^[36, 84].

Sub-phytotoxic concentrations (1-10 mg L⁻¹) of nano-zinc oxide in vase solutions have antimicrobial action against pseudomonads and bacilli, the main stem blocking bacteria, while also providing zinc, the co-factor of antioxidant enzyme systems in senescing petals (Srivastava and Srivastava, 2020) ^[75]. Yassen *et al.* (2020) ^[85] found that spraying nano-iron on stock flowers (*Matthiola incana*) increased their bloom period and improved anthocyanin concentration under water stress conditions.

5. Nanoparticles for growth promotion and flowering enhancement

Growth promotion through nanomaterial application has been documented across diverse ornamental and floriculture species. Effects manifest at multiple developmental stages, from germination through vegetative growth, flower initiation, and quality parameters including stem length, flower size, color intensity, fragrance compound accumulation, and dry matter content.

5.1 Seed germination and Seedling establishment

Seed germination is an essential bottleneck in ornamental plant cultivation, especially for ornamental species having dormancy demands or refractory germination characteristics. Several studies have shown that NP seed priming or priming solutions enhance germination via means such as enhanced seed water imbibition rates due to nano-channel formation (in case of CNTs), enzyme activation (α -amylase, protease) to utilize the seed reserves, and promotion of mitosis in root tip meristematic cells (Lu *et al.*, 2002; Lin and Xing, 2007) [47, 49]. The addition of CNTs (10-40 $\mu\text{g/mL}$) significantly boosted germination rates and seedling fresh biomass in tomato an extensively grown ornamental plant by boosting aquaporin-mediated water absorption (Khodakovskaya *et al.*, 2012) [38]. Low concentrations of ZnO NPs (<50 mg/L) boosted germination rates and root length of ornamental grasses and bedding plants, whereas high doses (>200 mg/L) exhibited inhibitory impacts, emphasizing dose-dependent responses (Lee *et al.*, 2013; Almutairi and Alharbi, 2015) [4, 45].

5.2 Vegetative growth and Photosynthesis

Nano-TiO₂ has gained prominence as an effective photosynthesis stimulant in ornamentals. According to Hong *et al.*, nano-TiO₂ increased photosynthesis in spinach through promotion of the Hill reaction and activation of PSI leading to improved light energy conversion efficiency.

Chen and Wang (2018) [13] furthered the study in ornamental crops by demonstrating that 0.25% (w/v) of TiO₂ NPs resulted in increased levels of chlorophyll a and b, higher rates of net photosynthesis, and improved stomata conductivity, culminating in increased stem length and early floral initiation. Similar observations regarding photosynthesis stimulation in ornamental canola were reported by Mahmoodzadeh *et al.* (2013) [50] and attributed to improvement in thylakoid membrane activities with exposure to nano-TiO₂.

Nano-silicon dioxide formulations appear particularly effective in improving ornamental plant quality characteristics such as leaf area index, stem diameter, and internodal length. The studies by Suriyaprabha *et al.* (2012) [78] and Azimi *et al.* (2014) [7] showed considerable growth stimulation with SiO₂ NP treatment in grass varieties of importance in turf and landscaping, with improved growth due to increased silicon content leading to increased structural strength and pest resistance in cell walls.

5.3 Flowering quality and Pigmentation

Nanoparticles impact flowering phenology, flower morphology, and biochemical properties of ornamentals by diverse mechanisms. The use of nano-ZnO enhances the enzymatic processes related to the biosynthesis of anthocyanins and flavonoids via stimulating PAL and CHS activities; this results in improved petal coloration in ornamentals (Singh *et al.*, 2016; Patra *et al.*, 2013) [60, 74]. Nano-silicon application caused an increase in flower diameter, ray florets, and pigmentation levels (anthocyanins and carotenoids) in gerberas, with the optimum SiO₂ NP concentration being 2 mM (Shafeek *et al.*, 2021) [71]. Low concentrations of gold nanoparticles (< 10 $\mu\text{g mL}^{-1}$) have been found to stimulate the synthesis of volatile compounds in Pelargonium and Lavandula species via upregulating terpene synthase gene transcription (Kumar *et al.*, 2013; Govorov & Carmeli, 2007) [26, 42].

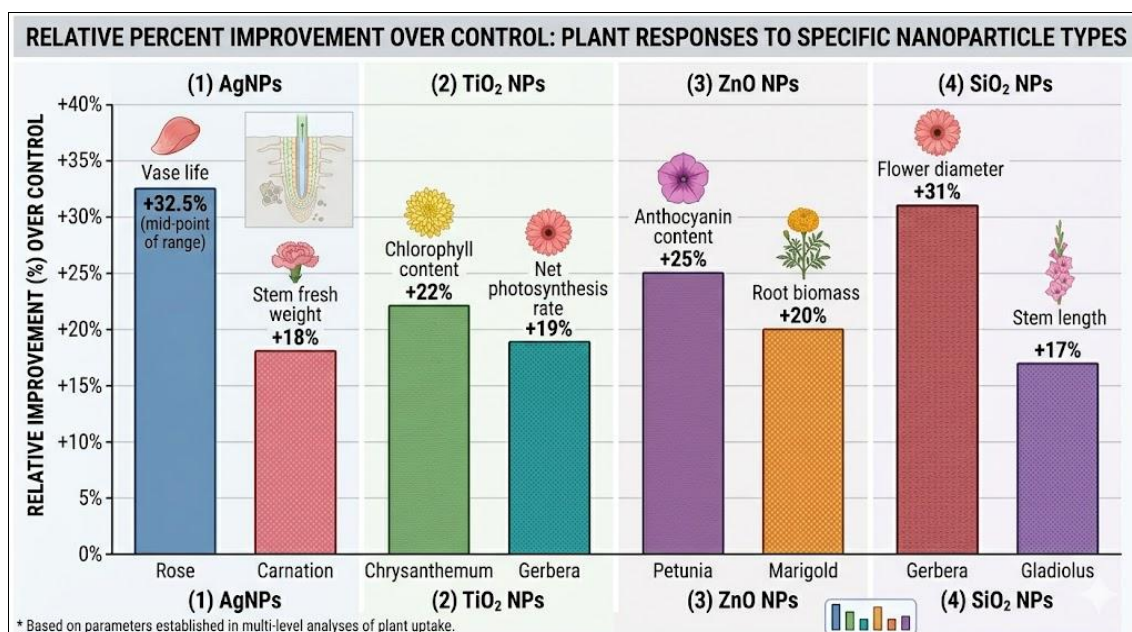


Fig 2: Bar graph representation showing relative improvements (%) over control: AgNPs: Vase life +28-35% (Rose), Stem fresh weight +18% (Carnation). TiO₂ NPs: Chlorophyll content +22% (Chrysanthemum), Net photosynthesis rate +19% (Gerbera). ZnO NPs: Anthocyanin +25% (Petunia), Root biomass +20% (Marigold). SiO₂ NPs: Flower diameter +31% (Gerbera), Stem length +17% (Gladiolus): [Chen & Wang (2018) [13]; Shafeek *et al.* (2021) [71]; Malekian & Souri (2020) [51]; Reyes-Pérez *et al.* (2019) [66]]

6. Nano fertilizer in ornamental crops

Traditional fertilization practices for ornamental crops are known to cause nutrient losses via leaching, as well as gaseous emissions and contamination of water sources due to runoffs. Nano-fertilizers are a class of nanoparticles that may carry nutrients essential for plant growth either in nano-scale themselves or function as intelligent carriers to facilitate timely nutrient release (Bhatt *et al.*, 2020; Liu *et al.*, 2006; Rahmani *et al.*, 2016) ^[10, 48, 63].

6.1 Macro-nutrient nano-fertilizers

There have been efforts to formulate nanocoatings containing nitrogen, phosphorus, and potassium using chitosan, alginate, and silica shell as matrices, allowing the gradual release of nutrient ions that can be absorbed by plants (Abdel-Aziz *et al.*, 2016; Choudhary *et al.*, 2019) ^[1, 14]. According to Abdel-Aziz *et al.* (2016) ^[1], the use of nano chitosan-NPK fertilizers has proven to promote greater ornamental wheat growth than traditional NPK fertilizers because of the continual release of nutrients and decreased loss due to leaching. Also, studies conducted by Farnia and Omid (2015) ^[21] proved the effectiveness of using nano zinc chelate fertilizers alongside biofertilizers in promoting vegetative growth in ornamental maize crops experiencing

drought stress.

6.2 Micro-nutrient nano-fertilizers

Deficiencies of microminerals, especially iron, zinc, manganese, and boron, are common in ornamentals grown in calcareous, alkaline, or weathered soils. Compared to traditional chelated micronutrients, nano-based formulations have much higher bioavailability, especially in alkaline conditions because traditional chelates tend to degrade rapidly at high pH levels (Ghafari & Razmjoo, 2013; Janmohammadi *et al.*, 2016; Tripathi *et al.*, 2019) ^[24, 33, 80].

According to Yassen *et al.* (2020) ^[85], the use of nano-iron in *Matthiola incana* plants experiencing drought resulted in increased chlorophyll content, stomatal conductance, and number of flowers as iron deficiency caused chlorosis in the plants. Foliar application of zinc oxide nanoparticles as a source of micronutrient in ornamental roses was found to increase leaf zinc content, PAL enzyme activity, and flower quality characteristics such as stem length and head diameter (Babaei *et al.*, 2017; Raliya & Tarafdar, 2013) ^[8, 64]. Kim *et al.* (2015) ^[40] explained the mechanism behind iron nanoparticle action as activating plasma membrane H⁺-ATPase and facilitating stomatal opening.

Table 3: Nano-fertilizer applications in ornamental and floriculture species: nutrients, formulations, and outcomes

Ornamental Crop	Nano-Fertilizer Type	Nutrient Supplied	Dose / Method	Key Outcome	Reference
<i>Matthiola incana</i> (Stock)	Nano-Iron Oxide	Iron (Fe)	20 mg L ⁻¹ foliar	Improved chlorophyll, flower yield under drought	Yassen <i>et al.</i> (2020) ^[85]
<i>Rosa hybrida</i> (Rose)	Nano-ZnO	Zinc (Zn)	10 mg L ⁻¹ foliar	Increased stem length, flower head diameter	Babaei <i>et al.</i> (2017) ^[8]
<i>Gerbera jamesonii</i>	Nano-SiO ₂	Silicon (Si)	2 mM foliar	Enhanced flower quality, antioxidant capacity	Shafeek <i>et al.</i> (2021) ^[71]
Ornamental Wheat (cut)	Nano chitosan-NPK	N, P, K	2 g L ⁻¹ soil drench	Superior growth vs. conventional NPK in sandy soil	Abdel-Aziz <i>et al.</i> (2016) ^[1]
<i>Chrysanthemum morifolium</i>	Nano-TiO ₂	Photocatalyst	0.25% foliar	Increased chlorophyll, stem elongation	Chen & Wang (2018) ^[13]
<i>Gladiolus grandiflorus</i>	Nano-Fe ₃ O ₄	Iron (Fe)	5 mg L ⁻¹ foliar	Reduced chlorosis, improved corm quality	Tripathi <i>et al.</i> (2019) ^[80]

Note: All doses cited are optimal doses from respective studies; phytotoxicity thresholds vary by species

7. Nanoparticle-mediated abiotic stress tolerance in ornamental plants

Abiotic stress factors such as drought, salinity, heavy metal toxicity, and extreme temperatures greatly impact the beauty and economic value of ornamentals. Nanoparticles have been found to be highly effective as stress-relieving substances that influence plant stress responses on physiological, biochemical, and molecular levels (Rastogi *et al.*, 2019; Usman *et al.*, 2020) ^[65, 81].

7.1 Drought stress

It is clear that silicon dioxide and zinc oxide nanoparticles can effectively reduce the impact of drought stress in ornamental plants. According to Ashkavand *et al.*, 2015 ^[6] SiO₂ NPs at 1 mM were able to increase drought tolerance in hawthorn seedlings that are commonly used for decorative purposes. Compared to drought-stressed plants, treated hawthorns showed a greater amount of water in their

leaves, less accumulation of proline, and lower membrane electrolyte leakage. Sun *et al.* indicated that nano-ZnO caused drought tolerance in ornamental varieties of maize through the involvement of melatonin signaling. Specifically, ZnO NP treatment caused the upregulation of SNAT1 and COMT genes responsible for melatonin synthesis. Moreover, Farnia and Omid (2015) ^[21] claimed that a mixture of nano-zinc chelates and nano-biofertilizer could greatly increase yield in water-stressed ornamentals.

7.2 Salinity stress

In addition to inhibiting the growth of many ornamental plants commercially valuable, salt stress also has a detrimental effect on many plants grown in arid and semi-arid areas where irrigation water contains a high concentration of salts. Nano-silicon was found to be effective in overcoming salt stress through: (i) selective intake of K⁺ by exclusion of Na⁺ ions; (ii) silicification of endodermal cells preventing Na⁺ bypass; (iii) stimulation of

plasma membrane H^+ -ATPase for active transport of K^+ ; and (iv) increased activity of antioxidant enzymes eliminating ROS generated due to salt stress (Garg and Bhandari, 2014; Reyes-Pérez *et al.*, 2019) [23, 66]. Reyes-Pérez *et al.* (2019) [66] reported that treatment with nano-silicon and nano-selenium together resulted in the mitigation of the negative impact of 50 mM NaCl on growth of chrysanthemum by sustaining higher stomatal conductance and CO_2 assimilation than salt stress alone.

Mohamed *et al.* (2017) [55] examined the interactive influence of salinity and AgNP treatment on plant physiology in wheat and ornamental grasses; their study showed that low doses of AgNPs (25 mg L^{-1}) alleviated the salt-induced reduction of photosynthesis and chlorophyll content, probably because of the silver-ion-mediated alteration in ethylene production. Chrysargyris *et al.* (2019) [15] reported that ornamental *Mentha* species exposed to combined salinity and copper stress showed significant

protective effects of nano-silicon supplementation on growth and essential oil quality.

7.3 Heavy metal stress

The presence of heavy metals in the substrate used for growing ornamental plants, especially cadmium, lead, zinc, and copper in urban soils and substrates, leads to adverse effects on the phytotoxicology of such plants and poses risks to human health. Iron oxide nanoparticles have been found to increase the complexation of metal ions and cause changes in soil redox reactions, thus lowering metal availability in rhizospheres of ornamental plants (De La Rosa *et al.*, 2013) [17]. The use of silicon nanoparticles decreases heavy metal translocation to aerial parts of the plants via silification of cell walls and increased gene expression of metallothioneins (Shahid *et al.*, 2014; Marchiol *et al.*, 2016) [72].

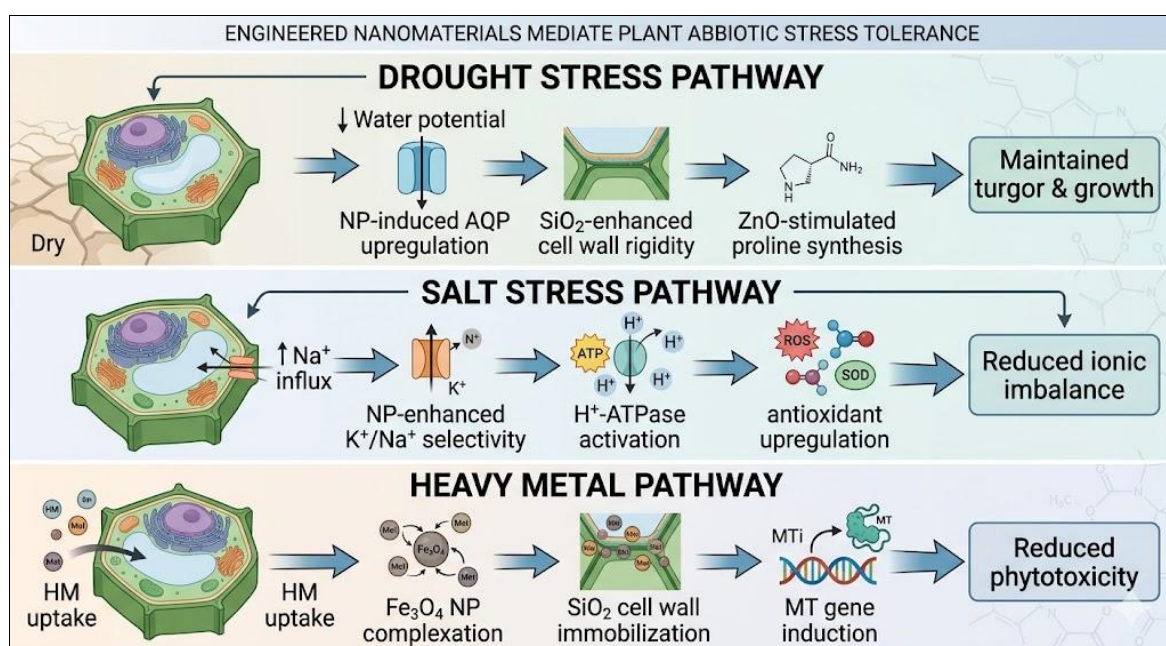


Fig 3: Nanoparticle-Mediated Stress Tolerance Mechanisms in Ornamental Plants

[Conceptual diagram based on Rastogi *et al.* (2019) [65]; Reyes-Pérez *et al.* (2019) [66]; Shahid *et al.* (2014) [72]]

8. Nano-pesticides and disease management in floriculture

Plant disease management in ornamental horticulture has historically relied heavily on broad-spectrum synthetic fungicides and bactericides, with attendant risks of pathogen resistance development, environmental contamination, and phytochemical residues on marketable flowers (Jampilek and Králová, 2017; Hosmani, 2014). [30, 32] Nanotechnology offers alternatives through nano-formulated pesticides with enhanced target specificity, reduced dose requirements, and controlled release profiles, as well as through inherently antimicrobial nanoparticles.

8.1 Nano-silver as antimicrobial agent

The broad spectrum antimicrobial properties of the AgNPs have also been thoroughly studied among the main floriculture pathogens. Pham *et al.* (2019) [61] noted that AgNPs decorated onto graphene oxide composites had strong antibacterial activity against the *Pseudomonas*

cichorii, one of the major causative agents of bacterial spots in ornamental plants, but much less phytotoxicity than the same amount of silver ions. El-Temsah & Joner (2012) [20] assessed the effectiveness of both AgNPs and iron NPs as antimicrobial tools to control pathogens borne within seeds of ornamental plants and found the former to be much more effective than the latter. Guilger-Casagrande & Lima (2019) [27] provided an overview on plant-based synthesis of AgNPs, highlighting the ability to generate AgNPs with different functionalization properties through greener approaches.

8.2 Chitosan nanoparticle fungicides

Chitosan is a natural polymer made from crustacean chitin and exhibits inherent antifungal potential by interfering with the membrane stability of fungi and their ergosterol biosynthesis pathway. The preparation of chitosan in the form of nanoparticles significantly improves antifungal potency through an increase in the contact surface area and

better adhesion to plants (Saharan *et al.*, 2013; Kadam and Bhatt, 2021) [36, 67]. Saharan *et al.* (2013) [67] demonstrated that the antifungal effectiveness of chitosan NPs at 0.1% (w/v) was much better than chitosan powder in terms of inhibiting the germination of *Botrytis cinerea*, the pathogen responsible for gray mold in roses and other cut flowers. Choudhary *et al.* (2019) [14] took the study further by showing that Cu-chitosan NPs activated systemic disease resistance in ornamental plants through the upregulation of PR-protein gene expression (PR-1, PR-5) and β -1,3-glucanase activity.

8.3 RNA interference and nano-delivery for pest management

A novel approach to ornamental crops is the delivery of dsRNA nanoparticles that initiate an RNAi gene silencing response against targeted pests or pathogens. According to Mitter *et al.* (2017) [54], the novel approach involves the utilization of clay nanosheets to deliver the dsRNA nanoparticles. Their research indicates that bionanoparticles of clay-dsRNA remain active on the plants' surfaces for up to 30 days during natural weathering, which represents a remarkable improvement compared to the conventional unprotected dsRNA nanoparticles that degrade within a few hours. The proposed technology would provide an enormous potential for the management of economically important ornamental horticultural pests such as Thrips palmi, *Frankliniella occidentalis*, and various aphids.

9. Phytotoxicology of nanoparticles in ornamental plants

Despite numerous reports of beneficial effects, nanoparticles also carry significant phytotoxicological potential that must be rigorously characterized before widespread deployment in ornamental crop systems. Phytotoxicity is dose-dependent, species-specific, nanoparticle type-specific, and strongly influenced by soil physicochemistry and plant growth stage (Stampoulis *et al.*, 2009; Dimkpa *et al.*, 2012) [18, 76].

9.1 Mechanisms of phytotoxicity

The primary modes of action that result in NP-induced toxicity among ornamentals include: (i) excessive production of ROS beyond the antioxidative capabilities of the plant, resulting in membrane lipid peroxidation (high MDA content), protein oxidation, and DNA damage (Ahmed *et al.*, 2017; Ghosh *et al.*, 2010) [2, 25]; (ii) disruption of the chloroplast thylakoid membranes and vascular bundles, demonstrated in cucumbers due to high doses of ZnO NPs (Nhan *et al.*, 2015) [58]; (iii) direct genotoxicity involving DNA double-strand breaks caused by NPs measured using a comet assay on root meristem tips (Ghosh *et al.*, 2010) [25]; and (iv) metal ion competition, which refers to an excess of NP-provided metal ions that interfere with other essential metal ions (Zhao *et al.*, 2014; Patra *et al.*, 2013) [60, 86].

9.2 Species-specific and Dose-dependent effects

One of the key lessons learned from the phytotoxicology literature relates to the dose dependency of the influence of nanoparticles on ornamental plants, which follows the hormesis pattern where low dosages stimulate and higher ones inhibit plant growth (Lin & Xing, 2007; Savithramma *et al.*, 2012) [47, 69]. Stampoulis *et al.* (2009) [76] pointed out another important issue, stating that phytotoxicity studies are strongly assay dependent, with hydroponic bioassays always resulting in higher measured toxicity when compared to soil tests, an important consideration for the study of ornamental crops, which can grow in various mediums including rock wool and peat. Ko *et al.* (2019) [41] found that ZnO NPs affect the soil bacterial population structure near the roots of ornamental legumes, even at dosages where no visible plant phytotoxic effects were observed.

Table 4: Phytotoxicity thresholds of key nanoparticles in ornamental and model plant species

Nanoparticle	Plant Species	Toxic Threshold	Toxic Symptoms	Endpoint	Reference
ZnO NPs	Cucumber (<i>Cucumis sativus</i>)	> 200 mg kg ⁻¹	Chloroplast disruption, vascular damage	Biomass, histology	Nhan <i>et al.</i> (2015) [58]
AgNPs	<i>Arabidopsis thaliana</i>	> 100 mg L ⁻¹	Root elongation inhibition, DNA damage	Germination, comet assay	Lin & Xing (2007) [47]
CuO NPs	Wheat (<i>Triticum aestivum</i>)	> 100 mg kg ⁻¹	Elevated MDA, root oxidative burst	Biomass, antioxidant enzymes	Dimkpa <i>et al.</i> (2012) [18]
TiO ₂ NPs	Spinach (<i>Spinacia oleracea</i>)	> 2000 mg L ⁻¹	Lipid peroxidation at very high doses	Chlorophyll, enzyme assays	Ghosh <i>et al.</i> (2010) [25]
Carbon Nanotubes	Radish (<i>Raphanus sativus</i>)	> 500 mg L ⁻¹	Shoot biomass reduction	Biomass, root length	Stampoulis <i>et al.</i> (2009) [76]
SiO ₂ NPs	Tall Fescue (<i>Festuca</i> spp.)	> 500 mg L ⁻¹	Marginal growth reduction at extreme doses	Root elongation	Azimi <i>et al.</i> (2014) [7]

MDA = Malondialdehyde; Note: Thresholds are indicative and highly dependent on growth media, pH, plant age, and NP surface coating

10. Nano-delivery systems and controlled release technologies

A distinguishing advantage of nanotechnology over conventional agrochemicals is the capacity to engineer smart delivery systems that release active substances in response to environmental or plant-derived cues a concept with enormous implications for the precision management of ornamental crops (Khot *et al.*, 2012; Nair *et al.*, 2010) [39,

56]. Controlled-release formulations reduce the frequency of application, minimize losses to leaching and volatilization, and can be engineered for pH-, temperature-, or enzyme-triggered release.

10.1 Polymer nanoparticle carriers

Nanoparticles from biopolymers such as chitosan and alginate have been designed as carriers for PGR delivery to

ornamental plants for regulated release of hormones such as gibberellic acids, cytokinins, and auxins. The review by Kadam and Bhatt (2021) ^[36] provides evidence on nano-chitosan encapsulated gibberellin GA3 delivery for stem elongation in ornamental bulbous plants, whereby they show higher effectiveness than bulk GA3 due to their continuous release and efficient absorption. Chitosan NPs with plant elicitors, such as salicylic acid and jasmonic acid, have also been tested as primers for SAR induction in ornamental roses and carnations (Saharan *et al.*, 2013; Choudhary *et al.*, 2019) ^[14, 67].

10.2 Mesoporous silica nanoparticles

MSNs can be defined as a very flexible nanocarrier system with adjustable pores (2-50 nm), large surface area (> 700 m² g⁻¹), and surface functionalization capability. In decorative horticulture, MSNs have been considered as carriers for the transportation of herbicides (for weed control in decorative gardens), fungi encapsulation, and the sustained release of micro-nutrients. Due to their high carrying capability and pH-sensitive release behavior, MSNs have become very interesting carriers for agrochemicals in soilless ornamental cultivation practices (hydroponics, aeroponics, and NFT) where pH adjustment is relatively easier (Rastogi *et al.*, 2019; Paramo *et al.*, 2020) ^[59, 13].

10.3 Clay nanocomposites

The potential of halloysite nanotubes and LDH clay nanocomposites as carriers of organic pesticides, phytohormones, and RNA has been evaluated for their application in ornamental crops. Being highly biocompatible and cost-effective, along with their availability, makes them promising candidates for use on a commercial scale. Mitter

et al. (2017) ^[54] revealed that using BioClay, which is essentially halloysite clay nanoparticles containing dsRNA, can be used to provide long-lasting protection against viral infection of ornamental pepper and tobacco crops. The clay matrix ensures that the dsRNA remains protected from exposure to UV radiation and RNase enzyme degradation, making it available for a sustained period.

11. Green synthesis of nanoparticles for floriculture

NP synthesis employing highly toxic chemical reducing and stabilizing agents poses the potential dangers of toxicity associated with the by-products formed during the process, high energy consumption, and pollution of agricultural products by residual chemicals (Guilger-Casagrande and Lima, 2019; Chakravarthy and Bhatt, 2021) ^[12, 27]. The method of green synthesis of nanoparticles employs plant extracts, microbial metabolites, and agricultural waste streams as reducing agents and capping agents and presents a more environmentally friendly strategy for NP production. AgNP synthesis using plant extracts involves the use of extracts derived from plants of horticultural origin, such as rose (*Rosa damascena*), jasmine (*Jasminum sambac*), chrysanthemum leaves, and marigold (*Tagetes erecta*) flower extracts (Chakravarthy and Bhatt, 2021; Guilger-Casagrande and Lima, 2019) ^[12, 27]. The phytochemicals present in these plant extracts act not only as reducing agents but also as capping agents and produce nanomaterials with a particular surface chemistry that is more plant-compatible than that produced through conventional chemical means. The idea of synthesizing NPs using the waste material generated from flower cultivation operations can be an ideal example of recycling the product in the floriculture industry (Chakravarthy and Bhatt, 2021) ^[12].

12. Crop-Specific Responses: Synthesis of Key Findings

Table 5: Summary of nanotechnology research in major ornamental and floriculture crop species

Ornamental Species	Most Studied NPs	Optimal Dose Range	Major Beneficial Effects	Key Concern	References
<i>Rosa hybrida</i> (Rose)	AgNPs, SiO ₂	20-60 mg L ⁻¹	Vase life +28-35%, reduced senescence, antimicrobial	Ag toxicity at > 100 ppm	Jokar & Sarraf-Mamoory (2013) ^[35]
<i>Chrysanthemum morifolium</i>	TiO ₂ , ZnO, AgNPs	25-100 mg L ⁻¹	Enhanced photosynthesis, flower quality, vase life	Dose-dependent toxicity	Chen & Wang (2018) ^[13]
<i>Gerbera jamesonii</i>	SiO ₂ , AgNPs	2 mM / 30 mg L ⁻¹	Flower diameter, pigmentation, antioxidant	pH-sensitive Si uptake	Shafeek <i>et al.</i> (2021) ^[71]
<i>Gladiolus grandiflorus</i>	AgNPs, Fe NPs	20 mg L ⁻¹	Vase life +34%, maintained petal color	Foliar residues	Malekian & Souri (2020) ^[51]
<i>Dianthus caryophyllus</i> (Carnation)	AgNPs, CNTs	25-50 mg L ⁻¹	Ethylene inhibition, extended display life	STS comparison required	Hussain <i>et al.</i> (2019) ^[31]
<i>Matthiola incana</i> (Stock)	Nano-Fe, ZnO	20 mg L ⁻¹	Improved bloom under water deficit	Soil NP accumulation	Yassen <i>et al.</i> (2020) ^[85]
<i>Pelargonium hortorum</i>	AgNPs, AuNPs	30-50 mg L ⁻¹	Dark storage tolerance, SOD/CAT enhancement	Species sensitivity variation	Hatami & Ghorbanpour (2014) ^[28]
<i>Lisianthus</i> (Eustoma)	ZnO, SiO ₂	10-30 mg L ⁻¹	Stem strength, flower longevity	Limited published data	Srivastava & Srivastava (2020) ^[75]

STS = Silver Thiosulfate (conventional ethylene inhibitor for comparison)

13. Regulatory frameworks and safety considerations

The application of nanotechnology in ornamental horticulture involves complicated regulation frameworks that vary considerably from one region to another (Usman *et*

al., 2020; Sekhon, 2014) ^[70, 81]. Nano-pesticides and nano-fertilizers in the European Union are regulated according to Regulation (EC) No. 1107/2009 (plant protection products) and Regulation (EC) No. 2003/2003 (fertilizers), with

amendments made in the context of nanomaterials' risks. Nano-scale pesticides in the USA are regulated by the EPA under the Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA), whereas FDA monitors nanomaterials' use in food and agriculture under the Food Safety Modernization Act (FSMA). Moreover, the OECD provides special ecotoxicological test guidelines for soil and aquatic nanomaterials, which are applicable to ornamental horticulture.

Regulatory challenges associated with nano-products in ornamental horticulture comprise worker exposure to nanomaterials during the application process, consumer exposure to nanomaterial residues on the product, nanomaterial fate and persistence in growing media and drainage, ecotoxicity of NPs toward soil fauna and pollinators, soil NP accumulation in cultivation facilities (Paramo *et al.*, 2020; Jampílek and Král'ová, 2017) ^[32, 59]. The lack of food safety regulatory obstacles should be considered as a distinguishing feature of ornamental flowers compared to crops, which can significantly expedite the process of obtaining the necessary regulatory approval pathway for nano-horticultural products in some jurisdictions. However, occupational exposure standards and environmental release regulations remain critical compliance requirements (Van Aken, 2015) ^[82].

14. Challenges, research gaps, and future perspectives

While the body of research on nanotechnology applications in floriculture has expanded substantially over the past two decades, several critical gaps and methodological challenges must be addressed before widespread commercial adoption can be responsibly achieved (Usman *et al.*, 2020; Sanzari *et al.*, 2019; Das and Maiti, 2022) ^[16, 68, 81].

14.1 Methodological standardization

One major issue that comes up while reviewing the literature on nanotechnology applications in floriculture is the great variation in experimental protocols, such as the methods used to prepare NPs and their physical characteristics, stabilization and coating techniques, plant media composition, modes of administration, growth phases, and environmental conditions. Standard protocols for biological assays, standardized reporting criteria for NP physicochemical characteristics (hydrodynamic diameter, zeta potential, agglomeration), and consistent metrics are sorely needed (Stampoulis *et al.*, 2009; Dimkpa *et al.*, 2012) ^[18, 76]. While the OECD Testing Programme on nanomaterials offers a guideline, its application to floriculture needs to be adapted.

14.2 Long-term soil and environmental fate

Most studies involving nanotechnology and floriculture involve experimentation with NPs on a short time scale, which is inadequate for the characterization of NP fate in crop-growing media that can be used more than once throughout several cropping periods. In soil, silver nanoparticles, zinc oxide nanoparticles, and carbon nanotubes are able to persist and reach toxic amounts during several cropping periods (Ko *et al.*, 2019; Nekrasova *et al.*, 2011) ^[41, 57]. Field-scale experiments using commercial crops grown in greenhouses such as roses and outside like chrysanthemums are critical but have not been reported.

14.3 Economic feasibility and scalability

The economic viability of nano-technology based treatments compared to existing methods should be carefully analyzed. Although nano-silver solutions prove themselves more efficient than regular vase preservative treatments, the price per liter still is significantly higher compared to that of STS, aluminium sulfate, and other biocide preservatives (Malekian and Souri, 2020; Jokar and Sarraf-Mamoory, 2013) ^[35, 51]. The creation of economically viable processes of synthesis, usage of waste from agriculture to produce NPs, and the economies of scale in production may help make nano-horticultural technologies economically viable. Das and Maiti (2022) ^[16] especially emphasize the need to conduct techno-economic analysis for nano-fertilizers used in floriculture.

14.4 Integration with Precision Horticulture

One very promising direction for the future lies in the convergence of nanotechnology with precision horticulture, which includes sensor systems, growth-monitoring by Internet of Things, machine learning-based decision support systems, and precision applicators. Real-time sensors that can detect stress signals from plants, pathogens, or nutrients deficiency can be integrated with nano-formulations of treatments to develop precision management systems for ornamental crops (Khot *et al.*, 2012; Sekhon, 2014) ^[39, 70]. In such scenarios, NP efficiency will increase, environmental pollution will be minimized, and profits will be maximized at the same time.

15. Conclusion

The application of nanotechnology presents a revolutionary paradigm shift for floriculture and ornamental horticulture, which entails highly efficient solutions to the problems of plant production and post-harvest care that impede economic viability in this important area. Based on the literature presented above, a range of promising applications of various NPs can be highlighted: silver NPs for increasing vase life and managing microorganisms, nano-silicon and zinc for improving stress tolerance, TiO₂ for enhancing photosynthesis, chitosan nanoparticles for nutrient and biological agent release, and nano-clays for RNA bioagents. While much progress has been made in terms of elucidating the mechanism underlying NP activity in ornamental plants from simple observation of growth and longevity improvement to molecular analysis of ROS regulation, alterations in gene expression, and hormone interaction there are still many unresolved issues related to the long-term persistence of NPs in the environment, species-specific standardization of dosage, and regulatory coordination. It should be taken into account that, similar to other biological responses, NP activities in ornamental plants exhibit a concentration-dependent dualism.

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