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Nanotechnology in post-harvest management of ornamentals: Innovations beyond conventional preservatives

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Abstract
Nanotechnology has emerged as a promising tool in floriculture, offering innovative solutions for extending vase life and improving post-harvest quality of ornamental crops. Conventional preservatives such as sucrose, silver thiosulfate (STS), and germicides, although widely used, often exhibit limited efficacy, phytotoxicity, and environmental concerns. In contrast, nanoparticles including silver (AgNPs), zinc oxide (ZnO NPs), chitosan (ChNPs), copper oxide (CuO NPs), silicon dioxide (SiO_2 NPs), cerium oxide (CeO_2 NPs), carbon nanotubes (CNTs), and gold nanoparticles (AuNPs)—demonstrate multifunctional properties such as antimicrobial activity, anti-ethylene effects, antioxidant capacity, and enhancement of water uptake. These attributes not only improve vase life and delay senescence but also reduce dependence on hazardous chemicals. This review highlights the mechanisms by which nanoparticles influence post-harvest physiology, compares their efficacy with conventional preservatives, and evaluates safety and environmental considerations. Furthermore, it discusses recent advances in green synthesis, multifunctional nanoparticle development, and integration with omics technologies, underscoring their potential for sustainable applications in floriculture. Future research must address standardization, regulatory frameworks, and risk assessment to ensure safe and effective commercialization. Collectively, nanotechnology represents a paradigm shift in ornamental horticulture, offering eco-friendly and innovative alternatives for post-harvest management.

Keywords: Nanotechnology, nanoparticles, floriculture, post-harvest management, cut flowers, vase life, green synthesis, sustainable horticulture

Introduction
Floriculture is one of the fastest-growing branches of horticulture, with global demand for cut flowers and ornamentals steadily increasing due to their economic and cultural significance (Jena *et al*., 2025) [13]. Despite this demand, the short post-harvest life of cut flowers remains a major constraint, resulting in significant economic losses. Factors such as microbial proliferation in vase solutions, vascular occlusion, ethylene sensitivity, and water stress contribute to reduced vase life and poor post-harvest quality (Jhanji *et al*., 2025) [11].
Conventional preservatives, including sucrose, 8-hydroxyquinoline, and silver thiosulfate, have been used extensively to improve longevity, but these compounds are associated with limitations such as environmental concerns, phytotoxicity, and limited efficacy across species (Verma *et al*., 2021) [20]. In this context, nanotechnology offers promising alternatives due to the unique physicochemical properties of nanoparticles (NPs). Nanoparticles such as silver, zinc oxide, titanium dioxide, and chitosan possess antimicrobial, antioxidant, and anti-ethylene characteristics that make them suitable for improving post-harvest physiology of ornamentals (Shang *et al*., 2019) [17]. Studies have reported extended vase life, improved water uptake, and delayed senescence in ornamentals treated with nanoparticles compared to traditional preservatives (Wang *et al*., 2022) [21]. This review explores these applications, focusing on how nanotechnology is transforming post-harvest management of ornamentals.

2. Nanotechnology in agriculture and floriculture

Nanotechnology has been widely applied in agriculture for crop enhancement, precision farming, and environmental sustainability. Nanoparticle-based fertilizers enable controlled nutrient release and improved nutrient uptake efficiency (Chen & Yada, 2011) [4]. Similarly, nano-formulated pesticides and fungicides provide targeted delivery with reduced chemical residues, while nano sensors are used for real-time monitoring of soil health, water quality, and plant stress responses (Kah *et al*., 2013) [12]. These applications highlight the versatility of nanotechnology in improving crop productivity while minimizing environmental risks.

In floriculture, nanotechnology applications extend beyond cultivation to include both pre-harvest and post-harvest phases. Pre-harvest uses include nanoparticle-based growth stimulants and protective coatings that enhance stress tolerance and plant vigor (Jena *et al*., 2025) [13]. Post-harvest applications are particularly promising, as nanoparticles can effectively manage microbial growth in vase solutions, improve water uptake, and reduce oxidative stress in cut flowers. For example, silver nanoparticles (AgNPs) have been shown to significantly extend the vase life of roses and carnations by suppressing bacterial growth. Zinc oxide and titanium dioxide nanoparticles exhibit antimicrobial activity, while chitosan nanoparticles delay senescence through antioxidant mechanisms (Naing *et al*., 2020) [15].

Thus, nanotechnology provides a sustainable and innovative approach that bridges conventional preservative limitations and the demand for eco-friendly solutions in post-harvest management of ornamentals.

3. Mechanisms of Nanoparticles in Post-Harvest Management

Nanoparticles (NPs) improve the post-harvest quality and vase life of ornamentals through multiple mechanisms, including antimicrobial activity, ethylene regulation, enhanced water uptake, and antioxidant protection (Fatima *et al*., 2025) [5]. These mechanisms address the major limitations associated with conventional preservatives and are summarized below (Fig.1.):

3.1 Antimicrobial activity

Microbial proliferation in vase solutions leads to vascular occlusion, reduced water uptake, and premature wilting of cut flowers. Silver nanoparticles (AgNPs) and zinc oxide nanoparticles (ZnO NPs) exhibit strong antimicrobial properties, effectively suppressing bacterial and fungal growth (Naing *et al*., 2020) [15]. AgNPs, in particular, have been reported to extend the vase life of roses and carnations by reducing microbial populations and maintaining stem hydraulic conductance (Zeng *et al*., 2024) [22].

3.2 Regulation of ethylene and senescence

Ethylene accelerates senescence in ethylene-sensitive ornamentals such as carnations and lilies. Chitosan nanoparticles (ChNPs) and some metal oxide NPs interfere with ethylene biosynthesis and signaling, delaying flower senescence (Fatima *et al*., 2025) [5]. For example, chitosan-based nanomaterials significantly reduced ethylene production in cut gerbera, leading to delayed wilting and improved vase life.

3.3 Enhancement of water uptake

Maintaining water balance is critical for post-harvest quality. Nanomaterials such as carbon nanotubes (CNTs) and silicon dioxide nanoparticles (SiO_2 NPs) improve hydraulic conductance by reducing xylem blockage and enhancing water absorption (Zeng *et al*., 2024). Improved water uptake has been correlated with increased turgidity and delayed petal desiccation in roses and gladiolus.

3.4 Antioxidant and stress modulation

Reactive oxygen species (ROS) accumulation accelerates petal senescence and membrane damage in cut flowers. Nanoparticles such as cerium oxide (CeO_2 NPs) and ChNPs act as ROS scavengers, stabilizing cellular structures and prolonging freshness (Jhanji *et al*., 2025) [11]. By mitigating oxidative stress, these NPs contribute to delayed senescence and extended vase life in several ornamental species.

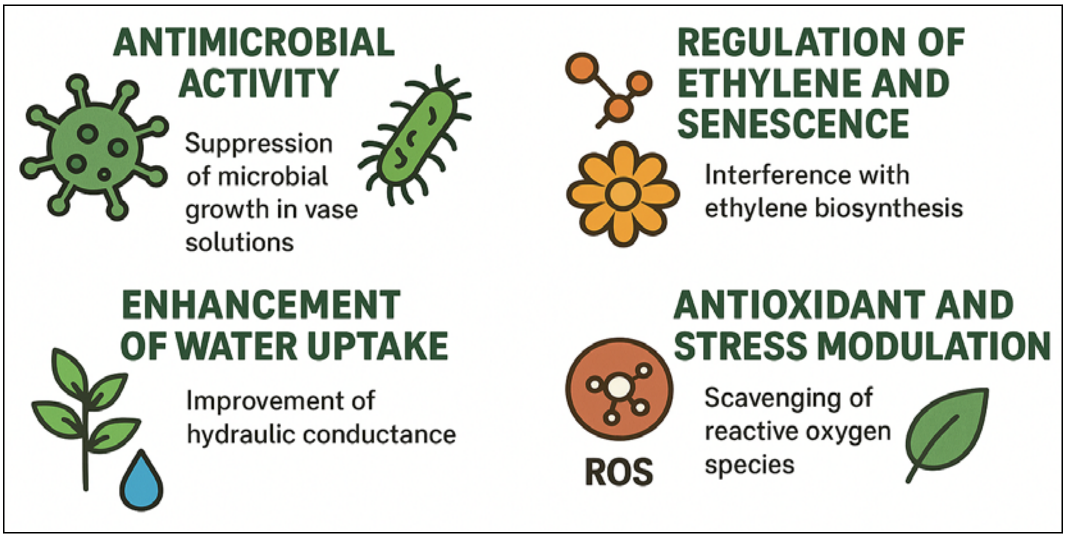

Fig 1: Mechanisms of Nanoparticles in Post-harvest Management

Table 1. Nanoparticles used in post-harvest management of ornamentals and their reported effects.

Sl. No	Nanoparticle type	Mechanism of Action	Ornamental species studied	Citation
1.	Silver nanoparticles (AgNPs)	Antimicrobial activity; reduces microbial growth in vase solution	Rose (*Rosa hybrida*), Carnation (*Dianthus caryophyllus*)	Naing *et al*., 2020 [15], Zeng *et al*., 2024 [22]
2.	Zinc oxide nanoparticles (ZnO NPs)	Antimicrobial properties; prevents xylem blockage	Gerbera (*Gerbera jamesonii*)	Zeng *et al*., 2024 [22]
3.	Chitosan nanoparticles (ChNPs)	Anti-ethylene and antioxidant activity; delays senescence	Gerbera (*Gerbera jamesonii*), Lily (*Lilium longiflorum*)	Fatima *et al*., 2025 [5]
4.	Carbon nanotubes (CNTs)	Improves water uptake by maintaining stem hydraulic conductance	Gladiolus (*Gladiolus grandiflorus*)	Zeng *et al*., 2024 [22]
5.	Silicon dioxide nanoparticles (SiO_2 NPs)	Improves water balance, reduces cavitation	Rose (*Rosa hybrida*)	Zeng *et al*., 2024 [22]
6.	Cerium oxide nanoparticles (CeO_2 NPs)	Antioxidant activity; scavenges reactive oxygen species (ROS)	Carnation (*Dianthus caryophyllus*)	Fatima *et al*., 2025 [5]
7.	Copper oxide nanoparticles (CuO NPs)	Antimicrobial and stress-modulating activity; controls microbial contamination in vase solutions	Chrysanthemum (*Chrysanthemum morifolium*), Rose (*Rosa hybrida*)	Zeng *et al*., 2024 [22]

Nanoparticles influence post-harvest physiology of ornamentals through several mechanisms, including antimicrobial activity, regulation of ethylene and senescence, enhancement of water uptake, and antioxidant protection. These mechanisms are illustrated in Figure 2, which highlights how different classes of nanoparticles contribute to extended vase life and delayed senescence in cut flowers.

A wide range of nanoparticles, such as silver, zinc oxide, chitosan, carbon nanotubes, silicon dioxide, cerium oxide, and copper oxide, have been successfully tested in roses, carnations, gerbera, lilies, gladiolus, and chrysanthemums. Their reported effects are summarized in Table 1, which outlines the nanoparticle type, mechanism of action, ornamental species studied, and supporting citations. Together, these findings demonstrate the potential of nanotechnology to replace or complement conventional preservatives in post-harvest management of ornamentals.

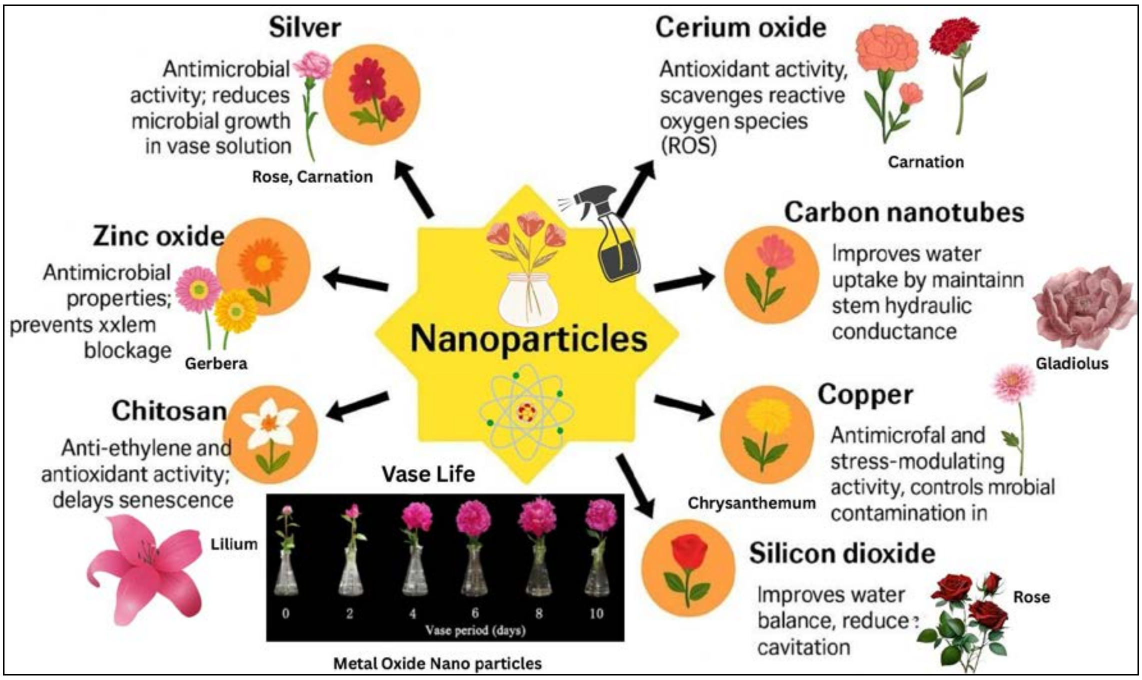

Fig 2: Nanoparticles in post-harvest management of ornamentals.

4. Nanotechnology for Vase Life Extension

Nanotechnology offers multiple strategies to extend the postharvest life of horticultural products, with potential to reduce postharvest losses by 20-30%. Innovations include nanocomposite packaging materials, disease control agents, protective coatings against harmful radiation and gases, and biosensors for freshness monitoring. Among various nanoparticles, silver nanoparticles (SNPs) are the most widely studied due to their potent antimicrobial properties, high electrical and thermal conductivity, catalytic activity, and chemical stability (Abou El-Nasr *et al*., 2025) [1].

SNPs, typically ranging from 1-100 nm, effectively inhibit microbial growth by disrupting bacterial and fungal cell walls, thereby preventing vascular blockage in cut stems and reducing ethylene biosynthesis. Their antimicrobial activity depends on particle size and concentration, with smaller particles (<10 nm) demonstrating stronger efficacy (Fatima *et al*., 2025) [5]. In cut flowers such as roses and carnations, SNPs enhance vase life by maintaining higher water uptake, delaying senescence, and improving overall fresh weight and stem condition (Silveira *et al*., 2014) [18]. SNP treatment also improves physiological parameters such as pigment synthesis, biomass accumulation, and stomatal regulation, thereby prolonging postharvest freshness.

Beyond silver, other metal nanoparticles have shown promise in enhancing vase life. Copper nanoparticles (CuNPs) prevent chlorophyll degradation and increase antioxidant enzyme activity, extending vase life in chrysanthemums and carnations (Jena *et al*., 2025) [13]. Zinc nanoparticles (ZnNPs) improve water uptake and reduce microbial proliferation in gerbera (Fatima *et al*., 2025) [5], while silicon nanoparticles (SiNPs) reduce ethylene biosynthesis, strengthen cell walls, and improve photosynthesis in cut roses and lisianthus (Zeng *et al*., 2024) [22]. Magnesium oxide nanoparticles (MgO NPs) have been reported to suppress petal blackening in lotus flowers by inhibiting ethylene biosynthetic gene expression. Carbon nanotubes (CNTs) further enhance solution uptake and delay senescence by maintaining stem hydraulic conductivity (Jena *et al*., 2025) [5].

The combined use of nanoparticles with conventional additives such as sucrose and plant growth regulators has shown synergistic effects. For instance, the integration of SNPs with gibberellic acid improved postharvest quality in gerbera by increasing water uptake and biomass (Maharana *et al*., 2025) [13]. Similarly, nanosil—a combination of hydrogen peroxide and silver ions—was found to improve antioxidant activity, carotenoid content, and vase life in roses (Azarhoosh *et al*., 2021) [2].

Collectively, these findings indicate that nanoparticles provide a multifaceted approach to postharvest management by controlling microbial growth, regulating ethylene responses, enhancing antioxidant defense, and improving water relations. Their application in diverse ornamental species underscores their potential as effective and eco-friendly alternatives to traditional preservative solutions.

5. Comparative Evaluation with Conventional Preservatives

The post-harvest life of ornamentals has traditionally been maintained using conventional preservatives such as sucrose, silver thiosulfate (STS), 8-hydroxyquinoline, citric acid, and commercial floral preservatives. These compounds function through diverse mechanisms, including supplying carbohydrates as an energy source (sucrose), inhibiting microbial growth (biocides such as 8-HQ), or reducing ethylene sensitivity (STS) (Verma & Singh, 2021) [20]. Although widely used in commercial practice, these treatments are often associated with significant limitations. For instance, sucrose, while effective as a metabolic substrate, can also promote microbial proliferation in vase solutions, necessitating the addition of antimicrobial agents. Similarly, STS, although highly effective in delaying ethylene-induced senescence in sensitive species like carnations and roses, poses environmental hazards due to its heavy metal residues, leading to restrictions on its use in several countries (Zeng *et al*., 2024) [22].

Comparative studies have consistently demonstrated that nanoparticles can overcome many of these drawbacks by providing multifunctional benefits at lower concentrations. Silver nanoparticles (AgNPs), for example, combine the antimicrobial properties of silver with nanoscale features that allow more effective interaction with microbial membranes. In roses and carnations, AgNPs have been shown to extend vase life significantly longer than STS, while also reducing microbial populations in vase solutions (Naing *et al*., 2015; Zeng *et al*., 2024) [15, 22]. Unlike STS, AgNPs do not primarily act on ethylene receptors but instead reduce vascular blockage and enhance water uptake, indicating a broader spectrum of action.

Zinc oxide nanoparticles (ZnO NPs) also outperform many conventional antimicrobial preservatives. Their strong antimicrobial activity helps maintain xylem conductivity, thereby reducing stem blockages and improving water relations. For example, gerbera treated with ZnO NPs showed extended vase life compared to flowers treated with standard biocides. Similarly, copper oxide nanoparticles (CuO NPs) exhibit both antimicrobial and stress-modulating activities. In chrysanthemum and rose, CuO NPs provided better microbial control and longer vase life extension compared to conventional preservatives, with the added advantage of inducing stress tolerance pathways (Fatima *et al*., 2025) [5].

Chitosan nanoparticles (ChNPs) offer another unique advantage over traditional antioxidants. Conventional antioxidants often reduce oxidative damage but do not interfere with ethylene signaling. ChNPs, however, combine antioxidant and anti-ethylene properties, making them highly effective in delaying senescence. In gerbera and lily, ChNPs not only scavenged reactive oxygen species (ROS) but also reduced ethylene biosynthesis, resulting in delayed petal wilting (Fatima *et al*., 2025) [5]. This dual functionality is rarely achieved by conventional preservatives, which usually target a single physiological pathway.

Beyond specific comparisons, nanomaterials demonstrate longer-lasting effects compared to conventional solutions, likely due to their sustained release and high reactivity at the nanoscale (Zeng *et al*., 2024) [22]. For example, commercial floral preservatives often lose efficacy within a few days, whereas nanoparticle treatments remain effective over the entire vase period. Furthermore, nanoparticles such as silicon dioxide (SiO_2 NPs) and carbon nanotubes (CNTs) improve water uptake and stem hydraulic conductance in ways that conventional preservatives do not address directly. By mitigating cavitation and enhancing water absorption, these materials maintain floral freshness beyond the capacity of sugar-based solutions (Zeng *et al*., 2024) [22].

However, it is important to note that while nanoparticles surpass conventional preservatives in efficacy and multifunctionality, their safety and environmental implications are still under evaluation. Conventional preservatives, despite their limitations, are well-studied and relatively predictable in their impacts, whereas nanomaterials may pose unknown risks if used indiscriminately. Green synthesis of nanoparticles using plant-based extracts has been proposed as an eco-friendly alternative, combining the benefits of nanotechnology with reduced toxicity (Patil *et al*., 2025) [16]. Comparisons between conventional preservatives and nanotechnology-based treatments reveal clear differences in efficacy and sustainability. Conventional preservatives such as sucrose, silver thiosulfate (STS), 8-hydroxyquinoline sulfate (8-HQS), essential oils, chemical preservatives, and germicides have long been employed to extend vase life, but their effectiveness is often limited by microbial contamination, phytotoxicity, and environmental concerns. In contrast, nanoparticles such as silver (AgNPs), zinc oxide (ZnO NPs), chitosan (ChNPs), copper oxide (CuO NPs), silicon dioxide (SiO_2 NPs), cerium oxide (CeO_2 NPs), carbon nanotubes (CNTs), and gold nanoparticles (AuNPs) offer multifunctional benefits including antimicrobial activity, anti-ethylene effects, antioxidant protection, improved water uptake, and eco-friendly potential. These comparative features are illustrated in Figure 3, which highlights the limitations of conventional preservatives alongside the diverse advantages of nanotechnology in post-harvest management of ornamentals.

In summary, comparative evaluations suggest that nanoparticles not only equal but frequently exceed the performance of conventional preservatives across multiple ornamental species. By providing antimicrobial, antioxidant, anti-ethylene, and water uptake-enhancing benefits simultaneously, nanomaterials present a holistic approach to post-harvest management.

Nevertheless, comprehensive toxicity studies, cost-effectiveness analyses, and regulatory frameworks are needed before their large-scale adoption in the floriculture industry can be realized (Zeng *et al.*, 2024) [22].

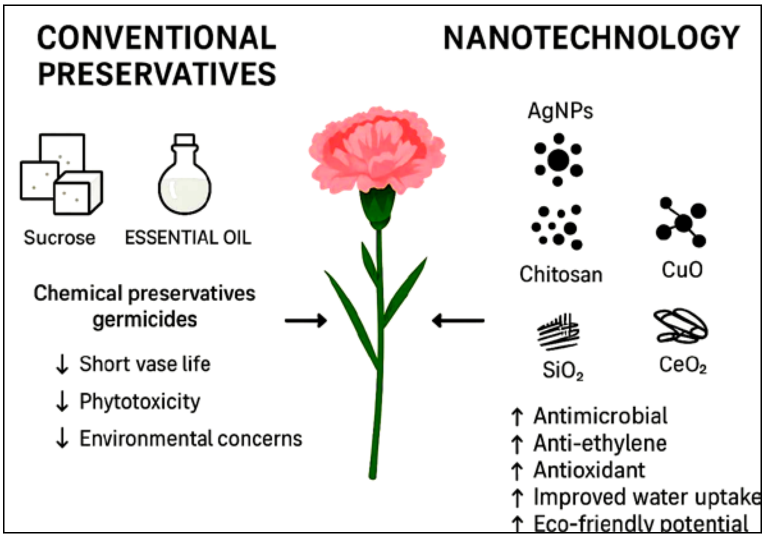

Fig 3: Comparative overview of conventional preservatives and nanotechnology in post-harvest management of cut flowers

6. Safety and Environmental Considerations

While nanoparticles hold exceptional promise for extending the vase life of ornamentals and addressing many shortcomings of traditional preservatives, their application must be carefully evaluated for potential phytotoxic and ecological impacts. Unlike well-understood conventional agents, engineered nanoparticles bring unique risks related to their small size, high reactivity, and persistence in the environment.

6.1 Phytotoxicity and concentration-dependent effects

The toxicity of nanoparticles often depends on concentration, size, and exposure duration. In *Arabidopsis thaliana*, citrate-stabilized silver nanoparticles (20-80 nm) exhibited a dose-dependent inhibition of root elongation, and accumulated more in roots than equivalent silver ion treatments—implying direct nanoparticle uptake and phytotoxic effects (Zeng *et al.*, 2024) [22]. Similarly, green-synthesized AgNPs at high concentrations (2-4 g/L) caused significant oxidative stress and growth inhibition in *Camelina sativa* seedlings, evidenced by increased proline, malondialdehyde, and enzymatic antioxidant activity (Mirmoeni *et al.*, 2021) [14]. These studies underscore that while NPs can be beneficial at low doses, they may become harmful when dosage is not optimized.

6.2 Environmental fate and ecological risks

Nanoparticles can undergo transformations aggregation, dissolution, and interaction with organic matter altering their mobility and toxicity in natural ecosystems. In aquatic environments, silver nanoparticles may become sulfurized and settle into sediments or interact with dissolved organic matter, complicating the assessment of their long-term ecological impact (Gottschalk *et al.*, 2010) [6]. Furthermore, modeling studies estimate significant release of AgNPs into wastewater and sludge—suggesting risk of soil accumulation and uptake by non-target organisms (Fatima *et al.*, 2025) [5].

6.3 Human and occupational health concerns

The small size and high surface area of nanoparticles raise concerns for human exposure during handling and application. Reviews indicate that carbon-based nanoparticles, metal oxides, and other nanomaterials could elicit adverse respiratory and systemic effects without proper exposure controls (Buzea *et al.*, 2007 [3]; emphatically discussing broader nanomaterials general toxicity).

6.4 Green synthesis and safer design approaches

To address these risks, researchers are focusing on green or plant-mediated nanoparticle synthesis. Such methods utilize natural reducing and capping agents from plant extracts that produce eco-friendly, biodegradable, and less toxic nanoparticles (Jena *et al.*, 2023) [7]. Bio-mediated copper oxide (CuO) and silver nanoparticles synthesized through these methods have shown lower toxicity and better environmental compatibility relative to chemically synthesized counterparts (Zeng *et al.*, 2024) [22].

6.5 Need for risk assessment and regulation

Despite their promise, there remains a dearth of standardized protocols or regulatory frameworks for assessing nanoparticles in floriculture. Comprehensive life cycle assessments, ecotoxicological profiling, and safe exposure thresholds must be developed to ensure responsible application (Gottschalk *et al.*, 2010; Buzea *et al.*, 2007) [6, 3].

In summary, while nanoparticles outperform conventional preservatives in many functional aspects, their safe integration into ornamental horticulture demands dose optimization, green synthesis, and rigorous environmental and human health assessments. These steps are vital to ensure that the benefits of nanotechnology are realized without compromising safety.

7. Future Perspectives and Research Opportunities

Nanotechnology in floriculture is still in its early stages, yet it offers vast opportunities for innovation in post-harvest management, stress tolerance, and ornamental crop improvement. While the majority of studies have focused on vase life extension of cut flowers through antimicrobial and antioxidant nanoparticles, future research is likely to expand toward broader, more integrated applications.

One promising direction is the development of smart nanomaterials capable of controlled and sustained release. Such formulations could maintain optimal nanoparticle concentrations around the floral tissue over extended durations, avoiding both rapid depletion and toxicity. This approach has already shown potential in agriculture, where nano-encapsulation of fertilizers and pesticides enhances stability and reduces overuse (Kah *et al*., 2013) [12]. Translating this technology into ornamental horticulture could provide precise post-harvest treatments with minimal environmental impact.

Another frontier is the use of green-synthesized nanoparticles. Plant- and microbe-mediated methods not only minimize hazardous byproducts but also impart biocompatibility and eco-safety to nanoparticles. These strategies align with consumer preferences for sustainable floriculture and may facilitate regulatory approval in the future (Singh *et al*., 2018) [19]. Multi-functional nanoparticles represent another exciting avenue. For instance, a single nanomaterial with combined antimicrobial, anti-ethylene, and antioxidant properties could replace the cocktail of preservatives currently used in cut flower solutions. Hybrid nanomaterials or composites (e.g., silver-chitosan blends) may provide synergistic effects while lowering the required dosage.

Furthermore, integration of nanotechnology with omics and molecular tools could enable a deeper understanding of plant-nanoparticle interactions. Transcriptomic and metabolomic studies may identify pathways influenced by nanoparticles, opening doors for designing nanomaterials tailored to specific ornamentals or physiological processes.

Despite these opportunities, challenges such as high production costs, safety concerns, and lack of commercial formulations still need to be addressed. Collaboration between material scientists, floriculture researchers, and industry stakeholders will be critical to transition nanotechnology from experimental studies to practical applications in the floral industry.

In summary, future research should prioritize safe design, green synthesis, and multifunctional applications of nanoparticles, along with the development of regulatory frameworks. Such efforts will pave the way for sustainable, commercially viable nanotechnology-based solutions for the global floriculture market.

8. Conclusion

Nanotechnology is emerging as a transformative approach in the post-harvest management of ornamental crops. Compared to conventional preservatives, nanoparticles offer multifunctional benefits, including antimicrobial action, antioxidant activity, anti-ethylene effects, and improved water uptake, all of which contribute to prolonged vase life and delayed senescence in cut flowers. Studies across diverse ornamental species—roses, carnations, gerbera, lilies, gladiolus, and chrysanthemums—demonstrate the superior efficacy of nanoparticles such as silver, zinc oxide, chitosan, copper oxide, silicon dioxide, carbon nanotubes, cerium oxide, and gold.

However, the adoption of nanotechnology in floriculture must be balanced with careful consideration of safety, environmental impact, and regulatory challenges. While nanoparticles outperform conventional preservatives, issues related to phytotoxicity, ecological accumulation, and human exposure require thorough evaluation. Green synthesis methods, controlled-release formulations, and multifunctional nanomaterials represent promising strategies to overcome these challenges.

The future of nanotechnology in floriculture lies in sustainable and targeted applications, integrating innovations from materials science with advances in plant physiology and omics tools. By addressing safety concerns and ensuring cost-effectiveness, nanotechnology can play a pivotal role in modernizing the global floriculture industry, providing eco-friendly alternatives to conventional preservatives, and meeting consumer demand for longer-lasting and sustainably produced ornamentals.

In conclusion, while challenges remain, nanotechnology presents a paradigm shift for ornamental horticulture. Its successful integration will depend on interdisciplinary collaboration, rigorous safety assessments, and supportive regulatory frameworks that together ensure both innovation and sustainability.

Disclaimer (Artificial Intelligence)

Author(s) hereby declares that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

Competing interests

Authors have declared that no competing interest exists.

Authors' Contributions

All authors read and approved the final manuscript.

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