

# FROM NANO TO BLOOM: NANOTECHNOLOGY TRANSFORMING ORNAMENTAL HORTICULTURE

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## ABSTRACT:

Nanotechnology has emerged as a promising approach for improving ornamental plant production by overcoming limitations associated with conventional practices. This review synthesizes recent advances in the application of engineered nanoparticles for enhancing the growth, quality, stress tolerance and post-harvest performance of ornamental plants. A structured literature search of Scopus, Semantic Scholar and Google Scholar identified 95 relevant peer-reviewed studies published between 2015 and 2025. Evidence indicates that nanoparticles can improve seed germination, plant growth, photosynthetic efficiency, nutrient acquisition and the quality and longevity of cut flowers. Their effects are associated with nanoparticle uptake and translocation, which influence physiological and biochemical processes, including reactive oxygen species (ROS) signalling, antioxidant defence and gene expression. Nanoparticles also enhance tolerance to drought, salinity, heavy-metal toxicity and temperature stress and may support disease management through antimicrobial activity and activation of plant defence mechanisms. Nano-fertilizers and nano-pesticides can improve input-use efficiency by enabling targeted delivery at lower application rates, while nanosensors facilitate real-time monitoring of plant health and environmental conditions. However, their effects are concentration-dependent, and excessive application may pose risks to plants, ecosystems and human health. Future research should therefore emphasize green synthesis, optimized application strategies, biosafety assessment and responsible deployment to promote sustainable ornamental plant production.

**KEYWORDS:** nanoparticles; nanosensors; ornamental plant; phytotoxicity; precision technology; stress.

## 1. INTRODUCTION

Ornamental plants are a leading commodity in the floriculture industry due to their immense importance in the world trade. The major cause behind their surging demand in the market is due to urbanisation, landscape design, interior-scaping and green space concept in private and public areas. Ornamental plants can be broadly categorized into flowering and foliage types. Flowering plants include *Rosa* sp. (rose), *Calendula officinalis* (pot marigold), *Tagetes* sp. (marigold) and *Petunia* sp. (petunia) while foliage plants include *Dracaena*, *Syngonium* and *Philodendron*. The cultivation of these plants emphasizes characteristics beyond yield which are quality, uniformity, visual appeal and sustainability in production and maintenance for their successful commercialization. Considering the limited care provided to these plants, their capability to survive under low-maintenance condition is an essential trait.

Nanotechnology is the science and technology of manipulating and controlling matter at the nanoscale, typically in the size range of approximately 1–100 nm, where materials exhibit novel physical, chemical and biological properties that differ from those of their bulk counterparts (1). The reason why it is suitable for the sustainable production of ornamental plants rests on its unique physicochemical properties like high surface to volume ratio, enhanced reactivity and high penetrability into biological barrier (2).

The market demand for ornamental plants is rapidly increasing. Addressing this growing demand in a sustainable manner requires a high level of precision that can be achieved through nanotechnology. This review deals with the classification of nanomaterials, their applications in the production, monitoring, enhancement and maintenance of ornamental plants using sustainable approach.

## 2. METHODOLOGY

A comprehensive literature search was conducted from December 2025 to February 2026 using electronic databases - “Scopus”, “Semantic Scholar” and “Google Scholar” to identify relevant publications on nanotechnology in ornamental plant production. The search terms exploited were “Nanotechnology”, “Ornamental Plants”, “Flowers” along with Boolean operators like “AND” and “OR” yielding 444 documents. The peer reviewed English journals published between 2015 and 2025 were included. The conference abstracts, editorials, duplicates and papers that are not relevant were excluded resulting in 289 retrieved documents. The

title, abstracts and full text screening was carried out leaving a total of 95 documents that were used to write this paper.

### 3. Types of nanoparticles used in ornamental horticulture

There are several nanoparticles classified based on their chemical nature, complexity and application such as metallic, carbon-based, nano-fertilisers and nano-pesticides. Metallic nanoparticles include silver, gold, zinc oxide, titanium dioxide etc. Silver nanoparticles have been extensively studied for their antimicrobial properties against *Pseudomonas syringae* and *Alternaria alternata* and ability to extend vase life in cut flowers (3,4). Silver nanoparticles (AgNPs) have high antibacterial activity that prevents vascular blockage in cut stems and maintains their water uptake efficiency (5). Gold nanoparticles capped with Bovine serum albumin are efficient in enhancing photosynthetic efficiency and relieving abiotic stress (6). Zinc Oxide (ZnO) nanoparticles enhance plant growth as micronutrient source and prevents plant disease by its antimicrobial nature (7). Carbon nanotubes (CNTs) prolonged the vase life of carnation and chrysanthemum (8,9). CNTs and graphene increased the flowering yield of *Catharanthus roseus* (10). Nano-encapsulated fertilizers provide controlled-release mechanisms, improving nutrient use efficiency and reducing environmental pollution. Similarly, nano-formulated pesticides offer targeted delivery with reduced application rates (11).

## 4. Applications in ornamental plant production

### 4.1. Enhancement of growth and development

Nanoparticles can influence various aspects of plant growth and development from seed germination to flowering. Several studies have demonstrated that appropriate concentrations of nanoparticles can enhance seed germination rates and seedling vigour in ornamental species. The nanoparticles achieve this effect by improving water imbibition, activation of germination-related enzymes and enhancing nutrient availability, as shown in Figure 1. Studies examining the effects of Ag NPs on crops like watermelon, zucchini, and corn have shown enhanced seed germination (12). Other nanoparticles like ZnO NPs were also found to be effective in onion (13).

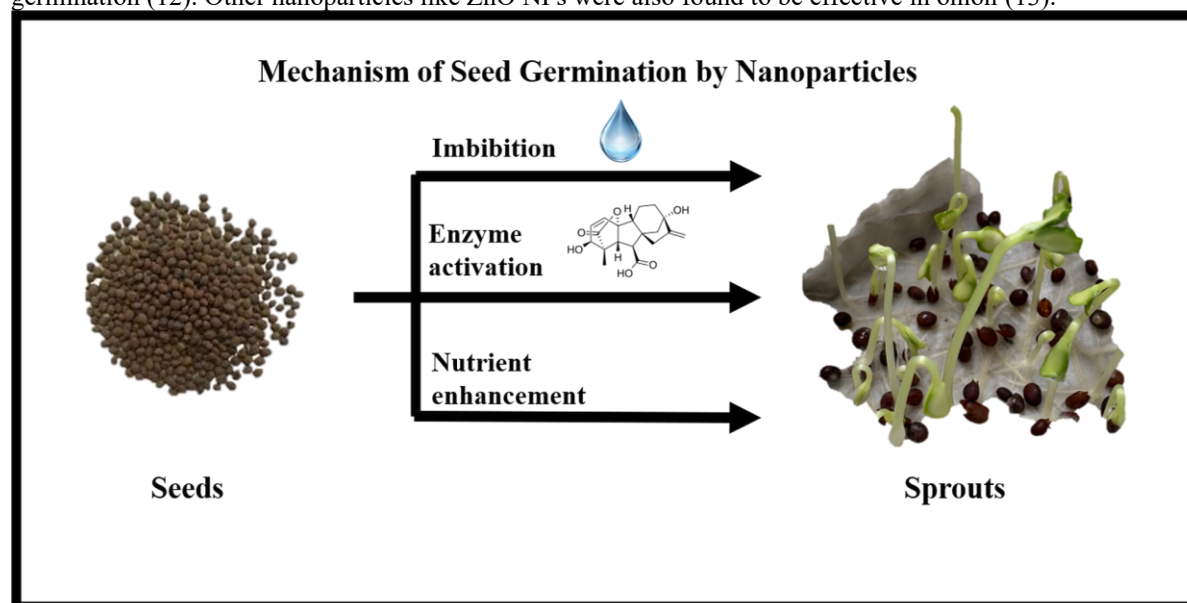


Figure 1 Mechanism of seed germination by nanoparticles

Nanoparticles were also found to influence the vegetative growth of plants. When applied at optimal concentrations, they have been shown to promote shoot and root growth, increased leaf area and enhanced overall biomass accumulation. For example, Titanium dioxide (TiO<sub>2</sub>) nanoparticles have been reported to stimulate photosynthesis and chlorophyll synthesis in *Liliums* (14). Some nanoparticles can influence flowering time, flower size, colour intensity, and flower longevity which are critical parameters in ornamental plant production. Salachna et al. (15) found that Ag NPs induced early flowering and prolonged the vase life in oriental lilies.

### 4.2. Improvement of photosynthetic efficiency

Nanoparticles influence the physiological activities of plants. Among these physiological processes, photosynthesis is particularly important, as it plays a fundamental role in biomass accumulation, which is closely associated with flower yield. NPs enhance photosynthetic performance through several mechanisms. These mechanisms include increase in chlorophyll content and stability, light harvesting potential, enzyme activity and stomatal conductance, as illustrated in Figure 2.

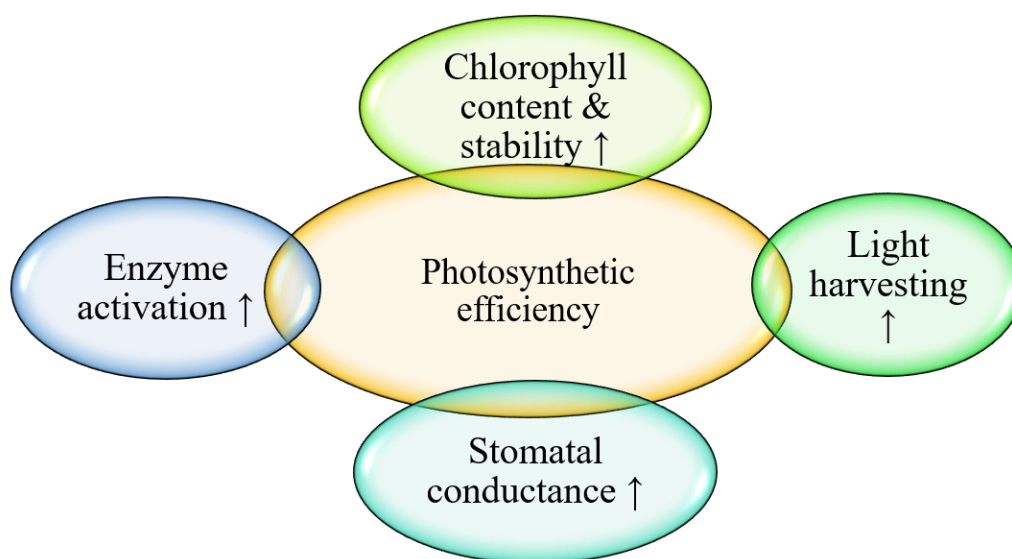


Figure 2. Mechanisms of Photosynthetic Efficiency

Studies have shown that appropriate concentrations of nano-TiO<sub>2</sub> and nano-SiO<sub>2</sub> can significantly improve photosynthetic rates in various ornamental plants (14).

#### 4.3. Stress tolerance enhancement

Plant stress is an unfavourable condition that affects the growth and development of plants (16). The stress is classified into biotic and abiotic. Biotic stress is caused by pest and diseases. Abiotic stress is caused by unfavourable environment and heavy metals (HMs). Abiotic stresses include drought, salinity, temperature and heavy metals. As these stress factors adversely affect plant growth and flowering, mitigating their effects is essential for maintaining optimal plant growth and reproductive performance. Under conditions of drought stress, nanoparticles can improve water retention, enhance antioxidant enzyme activity and maintain membrane integrity under water deficit conditions (17). NPs help maintain ion homeostasis, reduce Na<sup>+</sup> accumulation and enhance osmotic adjustment during salinity stress (18). Nanoparticles can induce expression of heat shock proteins and cold-responsive genes during extreme temperatures (19). Certain nanoparticles can chelate toxic metals or activate detoxification mechanisms in heavy-metal-affected plants; for instance, Fe NPs reduced the adverse effects of HMs in scarlet sage (20). Regarding biotic stress, pests and diseases are the major causes of yield loss in several plants which can spread quickly and destroy almost all.

Table 1 Role of nanoparticles in plant stress management

| Stress   | NPs                            | Mode of Action                                                 | References |
|----------|--------------------------------|----------------------------------------------------------------|------------|
| Salinity | Ag                             | Seed germination in Basil                                      | (21)       |
|          |                                | Improve plant resistance in Cumin                              | (22)       |
|          | Cu                             | Reduce oxidative stress in wheat                               | (23)       |
|          | ZnO                            | Increase dry weight of sunflower                               | (24)       |
|          | CeO                            | Increase photosynthetic efficiency of rapeseed                 | (25)       |
|          | Fe <sub>3</sub> O <sub>4</sub> | Reduce oxidative stress in mint                                | (26)       |
|          | TiO <sub>2</sub>               | Increase anti-oxidant activity in <i>Paeonia suffruticosa</i>  | (27)       |
| Drought  | ZnO                            | Enhance germination in soybean                                 | (28)       |
|          | TiO <sub>2</sub>               | Increase yield in wheat                                        | (29)       |
|          | MWCNT                          | Increase shoot and root growth in Caucasian alder              | (30)       |
|          | Chitosan                       | Improve plant defense in <i>Catharanthus roseus</i>            | (31)       |
|          | Si                             | Increase anti-oxidant activity in <i>Calendula officinalis</i> | (32)       |
|          | Ag                             | Enhance plant growth in <i>Festuca ovina</i>                   | (33)       |

|                    |                                |                                          |      |
|--------------------|--------------------------------|------------------------------------------|------|
| <b>Heavy metal</b> | Si                             | Relieve As stress in maize               | (34) |
|                    | Fe <sub>2</sub> O <sub>3</sub> | Relieve Pb, Zn, Cu, Cd toxicity in Wheat | (35) |

Although conventional chemical management able to control pests and diseases, it causes huge harm to the environment and human health. Nanoparticles with antimicrobial properties (Ag NPs, Cu NPs, ZnO-NPs) can effectively control bacterial and fungal pathogens in ornamental plants, offering eco-friendly alternatives to conventional pesticides (36).

#### 4.4. Post-harvest quality and vase life extension

Cut flowers are widely used in decorations and displays for their varied colours, shapes and fragrance. These are readily used for ornamentation as they are easy to handle compared to the potted plants. The major challenge associated with cut flowers is their limited vase life. Nanotechnology provides a sustainable alternative to extend its vase life more than that of conventional chemicals. The NPs used for this purpose are Ag, TiO<sub>2</sub>, Cu etc. Silver Nanoparticles are the most extensively studied NPs for cut flower preservation as they prevent microbial growth in vase solutions, reduce stem blockage and maintain water uptake. It was found that application of AgNPs on roses, gerberas, carnations and other cut flowers recorded significant vase life extension (37). Titanium dioxide (TiO<sub>2</sub>) NPs can reduce ethylene production and maintain membrane integrity, delaying senescence. Recent advancements like application of nano-based coatings on cut flowers, have proven effective in reducing transpiration and extending shelf life (38).

Table 2 Nanoparticles in vase life extension of flower crops

| <b>NPs</b>  | <b>Mode of action</b>                        | <b>Plant species</b>             | <b>References</b> |
|-------------|----------------------------------------------|----------------------------------|-------------------|
| <b>CNTs</b> | Increase water uptake                        | Carnation                        | (8)               |
|             | Expression of CgAQP & CgSUT for water uptake | Chrysanthemum morifolium 'Jinba' | (9)               |
|             | Reduced oxidative stress                     | Rosa hybrida c.v. 'Moonstone'    | (39)              |
|             | Delay the flower abscission                  | Alstroemeria                     | (40)              |
| <b>Ag</b>   | Prevent bacterial attack                     | Chrysanthemum cv. Puma           | (41)              |
|             | ROS scavenging                               | Dianthus caryophyllus cv. Dover  | (42)              |
|             | Minimize microbial population                | Mokara red orchid                | (43)              |
|             | Antimicrobial activity                       | Eustoma grandiflora cv. Echo     | (44)              |
|             | Inhibit bacterial growth                     | Alstroemeria cv. Summer sky      | (45)              |
| <b>Cu</b>   | Ethylene inhibition & antimicrobial          | Tulip                            | (46)              |
|             |                                              | Narcissus                        | (47)              |
|             | Antimicrobial activity                       | Carnation                        | (48)              |
|             |                                              | Chrysanthemum                    |                   |
| <b>CaO</b>  | Decrease stem bending                        | Gerbera                          | (49)              |
| <b>Se</b>   | Antioxidant capacity                         | Rose 'Black Magic'               | (50)              |
|             | Maintain petal moisture                      | Rosa hybrida                     | (51)              |

#### 4.5. Colour enhancement and modification

Nanoparticles were found to influence pigment biosynthesis and accumulation. They play a vital role in enhancement of anthocyanin production for intensified flower colours and stabilization of existing pigments. This property of nanoparticles has been applied to novel colour development through nanoparticle interactions with plant pigments in cut gerberas and antirrhinums (19,52).

#### 4.6. Micropropagation

Nanoparticles are increasingly utilized in plant tissue culture to improve precision and reduce contamination, thereby enhancing the efficiency of in vitro propagation. They play an important role in various stages of tissue culture including surface sterilization, callus induction, organogenesis and somatic embryogenesis. The application of nanoparticles can be exploited for the propagation of ornamental plants that are difficult to multiply through conventional methods, thereby enhancing propagation efficiency and accelerating the production process. Ag NPs have been reported to reduce contamination in Gerbera capitulum and Chrysanthemum leaf explants and are effectively used as a surface sterilant due to their antimicrobial activity. Cu and Ag NPs have been shown to enhance embryogenic responses at lower concentrations. ZnO and Ag NPs promote shoot regeneration and rooting while reducing ethylene production (53).

## 5. Mechanisms of action

### 5.1. Cellular uptake and translocation

The entry of nanoparticles into the cell depends on their size. Large nanoparticles enter the plant cell through wounds, ion channels and carrier proteins whereas small nanoparticles enter the cell through nanopores, direct penetration and endocytosis through root or shoot. Root uptake is via aquaporins, ion channels or endocytosis and direct penetration through cell wall and plasma membrane (54). Foliar or shoot uptake is through stomata, cuticle or trichomes (55). Once inside, NPs can be translocated via xylem and phloem to various plant organs as in fig.3.

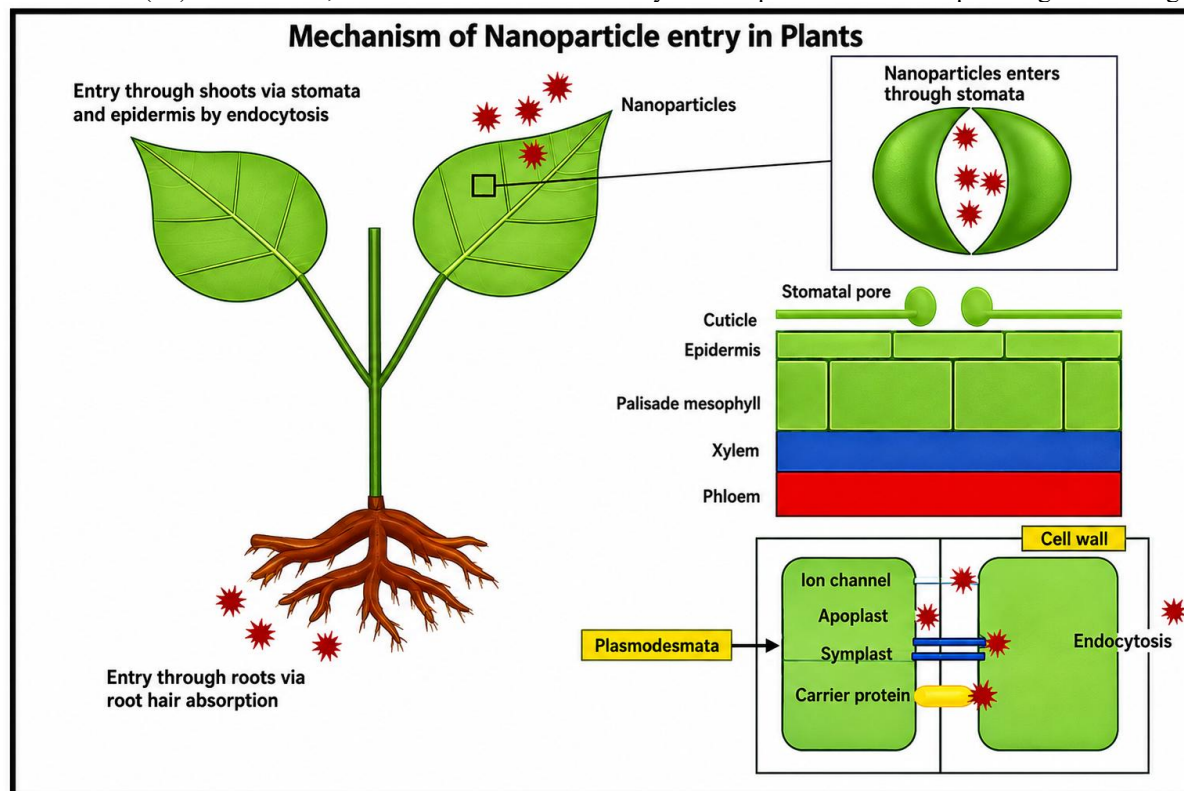


Figure 3 Mechanism of nanoparticle entry into the plant system

### 5.2. Physiological and molecular responses

Nanoparticles induce physiological responses in plants after their uptake and translocation through the plant system. The responses include ROS signalling, expression of stress related genes, change in enzyme activity and hormonal production. NPs can act as both pro-oxidants and antioxidants depending on concentration, influencing reactive oxygen species (ROS) signalling (19). They modulate expression of genes involved in stress responses, metabolism and development (56). This can enhance or inhibit various enzyme activities, affecting metabolic pathways (17). Some NPs like Nano-Selenium influence plant hormone biosynthesis and signalling (57).

## 6. Nano-formulated products for ornamental horticulture

There are many nanoproducts available on the market for ornamental plant production. These products are both eco-friendly and cost effective.

### 6.1. Nano-fertilizers

Plant nutrients are essential elements required by plants for normal growth and development. The major plant nutrients are down sized to form nano products to increase its efficiency and reduce its wastage by run-off and leaching. Nano-fertilizers have emerged as an effective alternative to conventional fertiliser due to its controlled and slow release of nutrients, enhanced nutrient use efficiency (up to 80% compared to 30-50% for conventional fertilizers), reduced leaching and environmental pollution, improved plant uptake due to small particle size (58). Nano-NPK fertilizers have been reported to enhance plant growth and development and improve flowering quality in *Gladiolus gandavensis* and *Platycodon grandifloras*. Fe NPs have been found to alleviate chlorosis in *Chrysanthemum morifolium*, while  $\text{TiO}_2$  NPs increased chlorophyll content in *Mesembryanthemum cordifolium* (59).

### 6.2. Nano-pesticides

Conventional pesticides cause high residual effects and are harmful to the environment, beneficial insects and micro-organisms. Nano-pesticides ensure targeted delivery of active ingredients to pest or pathogen sites with reduced application rates (by up to 90%) while enhancing stability and efficacy. Additionally, they exhibit a lower environmental impact compared to conventional pesticides (60). Nanocarrier systems such as polymeric nanoparticles, nano-emulsions, nano-capsules, solid lipid nanoparticles, and inorganic nanoparticles (e.g., silica and zinc oxide) are widely used in nano-pesticide formulations. These carriers improve the solubility, stability and bioavailability of pesticide molecules and enable controlled and sustained release at the site of action (61).

Cu-based nanoparticles have been reported to provide more efficient control of *Phytophthora infestans*, which causes late blight in tomato compared to conventional agrochemicals with reduced phytotoxic effects (62).

### 6.3. Nano-sensors

Nano-sensors function via stimulus-responsive mechanisms that enable the detection and monitoring of environmental and biological changes. The applications of nano-sensors in ornamental production are wide from monitoring weather and plants to the application of inputs. They are used in real-time monitoring of plant health parameters, early detection of stress or diseases by RGB imaging, Förster Resonance Energy Transfer (FRET) based imaging etc., precision nutrient management, smart greenhouse applications and so on (63–67).

Table 3 Nano-sensor and its applications

| Category      | Type              | Nano sensor                  | Composition                                          | References |
|---------------|-------------------|------------------------------|------------------------------------------------------|------------|
| Plant growth  |                   | Strain sensor                | Chitosan & CNTs                                      | (68)       |
| Environment   | Relative humidity | Capacitive humidity sensor   | Ti & Au incorporated in polyimide                    | (69)       |
|               | VOCs              | Chemo resistive nano sensor  | SWCNTs & Cu                                          | (70)       |
| Metal ions    | -                 | Bio resistor                 | Polyethylene dioxythiophene & polystyrene sulfonate  | (71)       |
| Phytohormones | Strigolactone     | Strigolactone receptor       | Yoshimulactone Green                                 | (72)       |
|               | Ethylene          | Chemo resistive sensors      | Tungsten oxide or Tin oxide                          | (73)       |
|               | Auxin             | Nano sensor                  | surface-modified carbon nanotubes and platinum black | (74)       |
|               | Gibberellins      | FRET-based nano-sensor       | -                                                    | (75)       |
|               | Salicylic acid    | Thin film sensor             | Structure switching nanopores                        | (76)       |
| Oxygen        | -                 | Electrochemical nano-sensors | Carbon filled quarts with platinum                   | (77)       |
| Soil moisture | -                 | Optical sensor               | Nanoporous aluminium oxide                           | (78)       |
| ATP           | -                 | Venus                        | Renilla luciferase & fluorescent protein             | (79)       |
| Pest          | Brown stink bug   | Ag Cantilever nano sensor    | Polyaniline-silver & sodium polystyrene sulfonate    | (80)       |

## 7. Challenges and concerns

Although nanoparticles offer superior efficiency and versatility relative to traditional inputs, their potential constraints and risks warrant critical evaluation. These risks include phytotoxicity, as well as environmental and health risks.

### 7.1. Phytotoxicity

Phytotoxicity is the toxic effect of chemical / physical agent or biological substance that disrupts plant growth and development or causes mortality. Concentration-dependent toxicity is a major concern in NPs. While low concentrations often show beneficial effects, higher concentrations can cause oxidative stress and cellular damage, disruption of normal physiological processes inhibition of growth, genotoxic effects which causes mutation (81–84).

### 7.2. Environmental and health risks

Nanoparticles released into the environment accumulate in soil systems, subsequently migrate to water bodies and plants, and enter the human food chain leading to bioaccumulation and biomagnification. Soil is the primary sink for nanoparticles where it is collected. These nanoparticles affect the physicochemical properties of soil like pH, humic acid, organic carbon, nutrient cycling, dehydrogenase enzymes and the microbial communities (85). Nanoparticles cause bacterial cell death due to their inherent toxicity (86). NPs enter the plants through roots, stomata or open wounds and damages the cell wall. Higher concentrations of nanoparticles reduce the bioavailability of plant nutrients causing phytotoxicity that leads to germination impairment of seeds (81–87). They increase ROS production, lipid peroxidation, protein denaturation, DNA damage affecting the photosynthetic efficiency (88). Runoff and leaching of Nano fertilisers and Nano pesticides leads to contamination of water. Some novel nano-pesticides like chlorophyllin has been reported to increase Biological Oxygen Demand (BOD) of water and affect the health of aquatic animals like cat fishes (89). There is a potential exposure risk for

workers and consumers through engineering of these products and others through plants, soil and water contamination. It enters human body through air, water or skin and translocated to other sensitive organs causing denaturation of proteins, ROS production and neurological dysfunction (87). However, the development and application of this technology should be guided by rigorous risk assessment and responsible management, with particular emphasis on its potential environmental and human health implications.

## 8. Future perspectives

### 8.1. Emerging technologies

Emerging technologies like smart delivery systems, nano sensors and monitoring platforms are extensively used in medicine and holds significant potential for ornamental plant production. Ma et al. (90) discussed smart delivery systems which is the development of stimulus-responsive nanocarriers that release active ingredients in response to specific environmental or external factors like sunlight, temperature, pH, enzymes or the combination of the above based on the principal effect expressed by the affected plants. Rhaman et al. (91) discussed on seed priming using nanoparticles and its advantages on increasing seed germination, nutrient use efficiency, improving tolerance to both biotic and abiotic stress through strong antioxidant defense system. Patil et al. (19) discussed on its role in genetic enhancement and the effect of nanoparticles on plants under stress and their manipulation of genetic expression to overcome the abiotic stress. Kwak et al. (92) conducted research on *Nasturtium officinale* in which luciferase loaded on to Si NP, luciferin and coenzyme A carried by Chitosan have shown luminescence and are termed nanobionic plants.

### 8.2. Sustainable approaches

Traditional inputs lack sustainability, a limitation which can be addressed by nanotechnology. The production and utilisation of nanoparticles without residue is the prime motive of sustainable ornamental plant production. Green Synthesis is the production of nanoparticles in eco-friendly manner. Nanoparticles are synthesised using vitamins, enzymes, microwave assisted technology and bio-agents like bacteria (*Pseudomonas* spp.), actinomycetes, fungi (*Fusarium oxysporum*), yeast and algae (*Cyanobacteria*) to reduce toxicity caused by them (93). The traditional nanocarriers, though achieve their role, they cause huge harm to the environment. This is a novel approach for synthesising natural nanopolymers like chitin, cellulose, collagen and Polyhydroxyalkanoates to replace the traditional nanocarriers that disrupts the ecology. Green synthesis of the former has been carried out to enhance its biodegradability reducing the residual effect to environment (94). Precision agriculture enables site-specific input application at precise rate and quantity which can remotely controlled thereby improving the system efficiency. Nanotechnology helps achieve precise application of pesticides and fertilisers by controlled release system. Plant monitoring and disease diagnosis are aided by nano sensors (95).

## 9. CONCLUSION

Nanotechnology offers promising solutions for enhancing ornamental plant production, quality and sustainability. Applications range from improving growth and stress tolerance to extending post-harvest life and developing precision management tools. Future advancements are likely to expand their scope of application resulting in a wider range of products with improved efficiency. However, the technology must be developed and deployed responsibly with careful consideration of potential environmental and health risks.

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