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A review on plant metabolite-mediated nanoparticle synthesis: sustainable applications in horticultural crops

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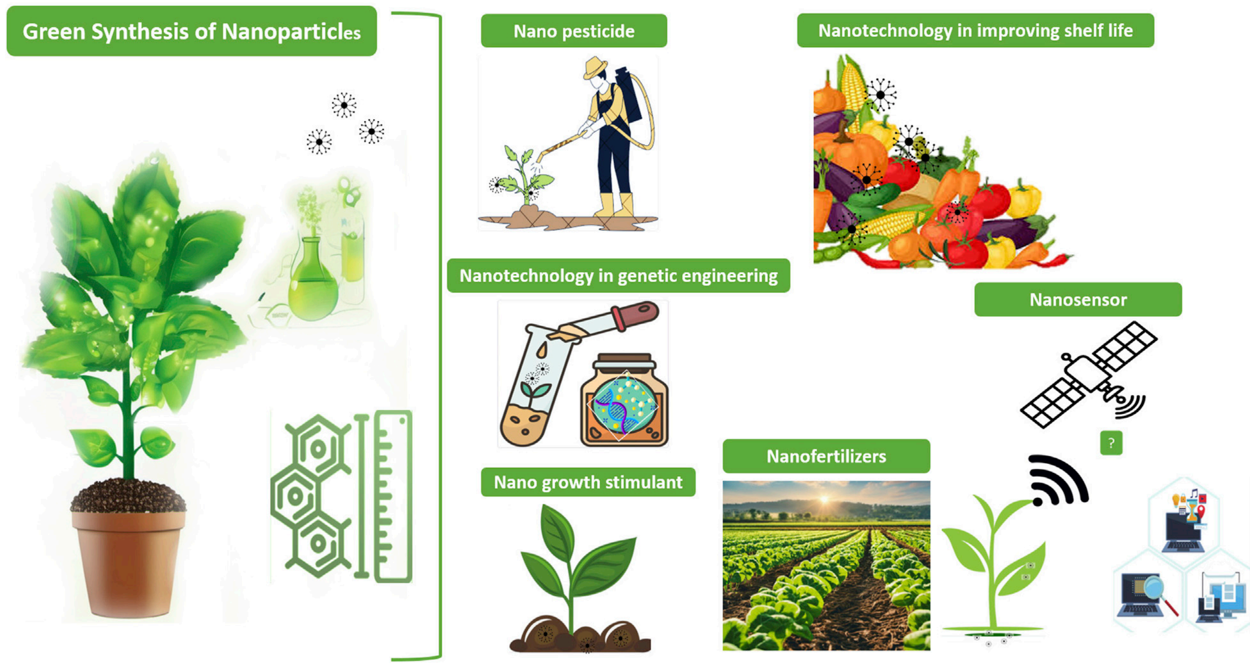
Global food security is increasingly threatened by climate change and population growth. This particularly affects horticultural crops, which often do not receive sufficient attention despite their significant nutritional and economic value. These crops pose a major challenge for breeding due to their high genetic diversity, long generation cycles, and complex reproductive biology, underlining the need for innovative approaches. The green synthesis of nanoparticles (NPs) using plant metabolites is proving to be a sustainable solution to these challenges. Biogenic nanoparticles, known for their improved biocompatibility and lower environmental impact compared to chemically synthesized (CS) counterparts, offer promising strategies to increase plant productivity, quality, and resilience. Applications of these nanoparticles include nanofertilizers for efficient nutrient delivery, nanopesticides for targeted pest control, and nano-packaging to reduce post-harvest losses. In addition, they function as nano(bio)sensors for the early detection of pathogens to ensure crop health and minimize losses. Recent studies suggest that biogenic nanoparticles can improve the efficiency of CRISPR/Cas9 transfer, which could promote the development of stress-resistant plants in precision agriculture. This review highlights the role of green nanotechnology in horticultural crop improvement, emphasizing the mechanisms by which plant metabolites mediate nanoparticle synthesis and exploring their diverse agricultural applications. By stimulating seed germination, mitigating biotic and abiotic stress, and improving nutrient quality with minimal environmental impact, biogenic nanoparticles hold great promise for revolutionizing horticulture. However, further research is required to optimize their scalability, standardization, and regulatory compliance so that they can be widely used in sustainable agriculture.

KEYWORDS

nanotechnology, biogenic nanoparticles, horticulture, crop yield, crop protection, nano-packaging, nanobiosensor, abiotic stress



GRAPHICAL ABSTRACT
Graphical representation for application of plant mediated nanoparticles.

1 Introduction

In the 21st century, the global challenge of food scarcity persists, exacerbated by the profound effects of climate change. The world faces a double burden of malnutrition, which can lead to disease and public health crises, as millions either consume insufficient food or diets deficient in essential nutrients, including minerals and vitamins (Masters et al., 2022). Addressing this challenge requires the advancement of the agricultural sector to enhance farmers' income, alleviate poverty in developing countries, and ensure the availability of nutritious food in adequate quantities. Agriculture contributes approximately 25% to GDP in emerging economies and 4% to global GDP, positioning it as a key driver of economic growth in these nations (Prokisch et al., 2024). The global population is expected to reach 10 billion by 2025, intensifying food security concerns (Sharma et al., 2020). In response to rising global food demand, agriculture has adopted advanced and innovative technologies aimed at enhancing productivity and reducing hunger worldwide. While some approaches have primarily focused on enhancing crop production, others, such as precision farming, gene editing, and advanced irrigation systems, have simultaneously improved agricultural productivity by increasing resource-use efficiency and yield potential (Tadele et al., 2024). Fruits and vegetables serve as primary sources of nutrients, minerals, and vitamins for humans, playing essential roles in both direct human nutrition and livestock feed. However, the rapid growth of the world's population currently outpaces the expansion of food production capacity. To meet the escalating demand for food, fruit and vegetable production, along with the availability of nutrient-fortified foods, must increase by a further 50% by 2050 (Tripathi et al., 2019). Alarmingly, approximately 20%–30% of horticultural crops are lost after harvesting due to factors such as perishability, susceptibility to pathogens, and improper handling. The efforts to meet the world's food demand are hampered primarily by certain conditions like climate change (Lowry et al., 2019). Environmental stress factors such as soil conditions, climate variability, salinity, soil composition, and pest infestation exacerbate these challenges and significantly affect the production and quality of fruits and vegetables (Kumar et al., 2024). To increase crop production and counteract the negative effects of global warming, farmers have over-applied pesticides and fertilizers to reduce biotic and abiotic stress. This resulted in harmful gases such as nitrogen oxides being released into the environment, polluting water supplies, farmland, and the ecosystem (Ndaba et al., 2024). The widespread dependence on synthetic chemical fertilizers particularly macronutrients is largely driven by the escalating pressure on farmers to boost crop yields, compounded by generous government subsidies that encourage their continued use. When macronutrient fertilizers are applied to crops, this can have detrimental effects as it leads to micronutrient deficiencies (Singh A. et al., 2024). Moreover, micronutrient deficiencies pose significant challenges to plant growth, development, and fruit production. Although synthetic fertilizers supply essential macronutrients such as nitrogen, phosphorus, and potassium (NPK), their imbalanced or excessive application can disrupt soil nutrient dynamics. This disruption may lead to secondary deficiencies of critical micronutrients such as boron, manganese, zinc, copper, and iron, which are required in trace amounts for optimal physiological functioning in plants (Tripathi et al., 2015). Deficiencies in these micronutrients can lead to various plant diseases and adversely affect plant growth, exacerbating concerns about food scarcity. Addressing these challenges necessitates managing post-harvest losses and enhancing the nutritional quality of horticultural commodities, particularly under stress conditions. This endeavor is critical not only for meeting future food and nutrient demands but also for improving the income of farmers. However, conventional chemicals often used to mitigate these issues can lead to toxicity in fruits and vegetables, posing risks to human health and contributing to environmental pollution (Kim et al., 2018).

Nanoparticles (NPs) have emerged as a promising tool to address these challenges and enhance agricultural productivity (Manzoor et al., 2024). Nanotechnology, an emerging field of scientific research, offers transformative applications in biotechnology and agriculture, emphasizing precision, environmental sustainability, and reduced toxicity. It encompasses the study, design, manufacture, synthesis, manipulation, and utilization of materials less than 100 nm in size (Lee and Moon, 2020). Nanoparticles possess a suite of unique physicochemical properties, including an exceptionally high surface area-to-mass ratio, regulated uptake by plant systems, and remarkable electrical and catalytic functionalities (Rajput et al., 2024). This advancement has propelled nanotechnology as a pivotal tool across various scientific domains, including chemistry, physics, medicine, materials science, aeronautics, pharmaceuticals, agriculture, and horticulture (Andrews and Lipson, 2019). In the face of a growing global population and shifting climate patterns, ensuring food and nutritional security has become an increasingly formidable challenge. Therefore, leveraging frontier technological approaches such as nanotechnology and biotechnology to enhance productivity and mitigate post-harvest losses has emerged as a key strategy.

In horticulture, the application of nanomaterials holds significant promise for bolstering productivity, improving product quality, and reducing post-harvest losses of fruits and vegetables. In developing countries, up to 30% of horticultural crop products are lost due to microbiological spoilage and physiological processes. Employing nanofilm and nano-packaging infused with antimicrobial nanomaterials can substantially reduce these losses to 5%–10%, thereby preserving substantial quantities of nutritious food (de Sousa et al., 2023). By minimizing losses, farmers can not only improve their incomes but also enhance the quality and nutritional value of food products. In contrast to conventional synthetic fertilizers and pesticides, which pose environmental and health hazards while being prohibitively expensive, innovative formulations of nanopesticides and nanofertilizers offer heightened efficiency, target specificity, and safety (Yadav et al., 2023; Porwal et al., 2023). To boost plant growth and combat abiotic and biotic stresses, minute-sized nanoparticles are applied to plants either through soil amendment or foliar spray, accelerating fertilization with reduced environmental impact compared to traditional fertilizers. However, further research is needed on their long-term effects and to enhance the rate of nutrient delivery to the plant system (El-Saadony et al., 2022). Furthermore, these nanoparticles also act as phytoremediation agents to remove pollutants and harmful toxic chemical agents from contaminated soil and water (Singh A. et al., 2024).

Nanotechnology has been closely linked with agriculture for the past 15 years and has gained increasing prominence over the last decade (Usman et al., 2020). However, there is growing global concern about the potential entry of engineered nanomaterials into the human food chain and their possible implications for human health. Although preliminary studies have indicated potential toxic effects, the current evidence remains inconclusive. Therefore, comprehensive and long-term toxicological assessments are warranted to better understand their safety and guide regulatory frameworks (Balusamy et al., 2023; Wahab et al., 2024). These concerns intersect with broader issues in sustainable agriculture, agri-food waste valorization (Preethi et al., 2024), agri-food industry practices (Shah et al., 2024), and the rapidly evolving agrotechnology sector (Ridhi et al., 2024). Due to this harmful effect of nanomaterials, researchers have focused on synthesizing plant-based biogenic nanomaterials that are less harmful to humans and do not pollute the soil and water as they contain fewer synthetic substances (Saraswat et al., 2023). In addition, plant-based nanomaterials mitigate the negative effects of abiotic and biotic stress due to their metabolites. Plant-based nanomaterials have diverse applications in horticulture and the food industry, including their use as biosensors for detecting diseases and pest infestations, and as nanofertilizers, nanopesticides, and seed-priming agents to enhance germination. They are also incorporated into packaging films and edible coatings on fruits and vegetables to extend shelf life and preserve quality during storage and handling (Rana et al., 2021; Manzoor et al., 2024; Thakur et al., 2022).

Plant improvement efforts in the horticultural sector are generally less industrialized than those in staple field crops due to a combination of economic, biological, and logistical constraints. Although breeding programs for horticultural crops do exist, their scale and investment vary widely across regions, often reflecting local market demands and resource availability. Moreover, many horticultural species present intrinsic breeding challenges such as polyploidy, extended juvenile phases, complex reproductive systems, and limited genetic resources, which collectively slow the pace of genetic advancement (Tarakeshwari and Pavan). These factors underscore the need for innovative approaches such as nanotechnology and molecular breeding to complement traditional horticultural improvement strategies. Nanotechnology is paving the way for horticultural crop improvement programs that increase the production and quality of plants. Nanotechnology plays a significant role in agriculture, and extensive literature highlights the effects of nanomaterials on improving yield, quality, and reducing post-harvest losses in various fruit and vegetable crops. However, a comprehensive review specifically addressing the application of nanomaterials to enhance horticultural crop outcomes is still lacking (Rana et al., 2021). Specifically, there is limited understanding of how plant-mediated nanoparticles can be systematically utilized to address post-harvest losses, enhance stress tolerance, and improve nutrient delivery in horticultural systems. Furthermore, the physiological responses, transport mechanisms, and environmental interactions of these nanoparticles remain underexplored. Addressing this gap is essential to unlocking the full potential of biogenic nanoparticles in sustainable agriculture. This review aims to (i) examine the current state of research on plant-mediated nanoparticle synthesis, (ii) explore their applications in enhancing horticultural crop productivity and reducing post-harvest losses, and (iii) propose future research directions to integrate these technologies into sustainable agricultural practices. By bridging the existing knowledge gap, this review provides a comprehensive understanding of how green nanotechnology can revolutionize horticultural crop management while maintaining ecological balance.

2 Importance of green synthesis

Nanotechnology encompasses the creation, analysis, and utilization of NPs, with various materials like gold, silver, silica, zinc, iron, boron, copper, and platinum commonly employed in their synthesis through a plethora of chemical and physical procedures (Burlec et al., 2023). However, the conventional chemical approach to NP synthesis poses significant environmental and health hazards, relying on harsh and toxic compounds such as reducing agents, organic solvents, and stabilizers. These chemicals not only contribute to environmental pollution but also pose risks like toxicity and carcinogenicity (Hua et al., 2018). Moreover, the use of such chemicals limits the applicability of nanoparticles in clinical and biological settings due to contamination concerns.

In contrast, the concept of "green synthesis" offers a compelling alternative. Green synthesis involves the production of NPs through methods that are secure, biocompatible, and environmentally friendly, facilitating a wider range of applications, including those in biological systems (Hano and Abbasi, 2021). This innovative, environmentally friendly approach is gaining popularity worldwide and has spurred the development of safe, economical, and scalable methods for NP synthesis without the use of toxic chemical substances, thereby minimizing potential health risks compared to chemically synthesized (CS) NPs (Chandra et al., 2020). By harnessing biological organisms such as yeast, fungi, bacteria, and plant extracts, researchers have unlocked the potential for creating NPs in a sustainable manner (Baig et al., 2021). Notably, various plant parts, including leaves, fruits, roots, stems, and seeds, have been utilized for NP synthesis, highlighting the versatility and abundance of natural resources available for green synthesis (Narayanan and Sakthivel, 2011). Compared to microorganism-based nanoparticle synthesis, plant-based approaches are less labor-intensive as they do not require steps such as the isolation, cultivation, or maintenance of microbial cultures (Bahrulolum et al., 2021). Additional advantages of plant extract-mediated NP synthesis include minimal energy consumption, operation under ambient pressure and temperature, and the presence of bioactive compounds that facilitate rapid metal ion reduction. This process results in stable products while promoting environmental protection, waste minimization, and a cleaner production atmosphere (Sharma et al., 2022; Abuzeid et al., 2023; Álvarez-Chimal and Arenas-Alatorre, 2023).

There are instances where green synthesis can produce NPs with enhanced properties under optimized conditions (Gokila et al., 2021; Ying et al., 2022). For example, green-synthesized iron nanoparticles were found to be smaller in size than those produced using conventional wet chemical methods. Embracing green synthesis not only aligns with principles of environmental stewardship but also facilitates the development of novel nanomaterials with enhanced biocompatibility and applicability across diverse fields.

Ensuring global food and nutrition security remains a huge challenge in the 21st century, exacerbated by climate change, environmental degradation, and population growth. While fruits and vegetables are essential sources of vitamins, minerals, and antioxidants, the production of horticultural crops is increasingly affected by abiotic stress, disease pressure, and post-harvest perishability—factors that threaten both yield stability and food quality (Toscano et al., 2019). Overcoming these challenges requires the integration of advanced technologies such as green nanotechnology and genetic engineering. Plant-mediated nanoparticles offer multiple benefits, including improved nutrient uptake, targeted pest and disease control, and reduced post-harvest losses. At the same time, genetic engineering tools such as CRISPR/Cas9 enable the development of stress-resistant plant varieties tailored for compatibility with nanomaterials, improving delivery efficiency and overall efficacy (Rani et al., 2025).

Despite their immense potential, the implementation of these technologies faces considerable obstacles. These include limited farmer awareness, a lack of standardized synthesis protocols, reproducibility challenges, and an insufficient understanding of the interactions between nanoparticles and plant systems. Achieving batch-to-batch consistency, standardizing reaction kinetics, biochemical consistency of extracts, scaling up green synthesis, and ensuring regulatory compliance remain urgent research priorities. This review critically analyzes (i) the molecular mechanisms by which phytochemicals mediate nanoparticle biosynthesis; (ii) applications of plant-derived nanoparticles in horticultural productivity, including their role in nanosensors for disease diagnostics, mitigation of environmental stress, and targeted pest control; (iii) their integration into sustainable packaging materials and edible coatings for post-harvest preservation; and (iv) future directions to enable the scalable, safe, and climate-friendly use of green nanotechnology in horticulture. By harmonizing these advances with genetic engineering, the field is moving closer to highly efficient, sustainable cropping systems that maintain the integrity of the agroecosystem and ecological balance.

2.1 Plant-mediated synthesis of nanoparticles

Plants serve as natural reservoirs of secondary metabolites, including phenols, alkaloids, flavonoids, saponins, tannins, and carbohydrates. These phytochemicals play a central role in the traditional synthesis of nanoparticles as they serve as both reducing and stabilizing agents, replacing hazardous organic and inorganic compounds (Table 1). Flavonoid–metal complexes, for example, exhibit strong antioxidant properties, enhancing the stability of nanoparticles and preventing oxidative damage during synthesis. The hydroxyl and carbonyl groups in flavonoids facilitate metal ion chelation, leading to efficient reduction and stabilization of nanoparticles. This not only ensures smaller and more uniform nanoparticle formation but also enhances their bioactivity in agricultural applications (Walencik et al., 2024). By carefully controlling various parameters such as pH, temperature, exposure time, and mixing ratios, it is possible to synthesize stable and monodisperse

TABLE 1 Green synthesis of nanoparticles using aqueous plant extract.

Plant species	Type of nanoparticles and plant part	Plant part used for nanoparticle synthesis	Precursor	Size and shape of nanoparticles	Metabolites involved in nanoparticle synthesis	Reference
Mentha arvensis (mint)	Titanium nanoparticles (TiNPs)	Leaf	Titanium tetraisopropoxide	20–70 nm Spherical	Saponins, alkaloids, flavonoids, phenol, terpenoids, steroids, carbohydrate, and proteins	Ahmad et al. (2020)
Hagenia abyssinica (African redwood)	Copper nanoparticles (CuNPs)	Leaf	Copper nitrate tetrahydrate	34.76 nm; mix of spherical, hexagonal, triangular, cylindrical, and irregularly shaped Cu particle	Phenolics, tannins, and proteins	Murthy et al. (2020)
Raphanus sativus (radish)	Zinc oxide nanoparticles (ZnONPs)	Leaf	Zinc acetate	209 nm; partial crystal spherical shape and wurtzite crystal nature	Flavonoids and terpenoids	Umamaheswari et al. (2021)
Capsicum chinense (Habanero pepper)	Gold nanoparticles *(AuNPs)*	*Leaf*	*Tetrachloroauric(III) acid trihydrate*	*16.76 ± 0.32* nm *Spherical*	*Polyphenols, reducing sugars, and amino acids*	Lomelí-Rosales et al. (2022)
Clitoria ternatea (butterfly pea)	Nickel oxide nanoparticles (NiONPs)	Flower	Nickel acetate	9–13 nm; hexagonal shape	Phenols, tannins, and glycosides	Prabhu et al. (2022)
Cocus nucifera (coconut)	Nickel oxide nanoparticles (NiONPs) Zinc oxide nanoparticles (ZnONPs)	Seed	Nickel nitrate Zinc nitrate	NiONPs: 19–28 nm ZnONPs: 28 nm–59 nm; rock-shaped and spheroid-like particles	Flavonoids and tocopherols	Ramesh et al. (2022)
Ocimum americanum (American basil) *Ocimum gratissimum* (clove basil) and *Ocimum tenuiflorum* (holy basil)	Silver nanoparticles (AgNPs)	Leaf	Silver nitrate ($AgNO_3$)	**American basil-synthesized AgNPs:** 58.5 ± 18.7 nm and spherical shape **Clove basil-synthesized AgNPs** 46.9 ± 9.0 nm and flake-surfaced spherical shape **Holy basil-synthesized AgNPs:** 69.0 ± 5.4 nm and rocky-surfaced spherical	Proteins	Alex et al. (2024)
Bauhinia tomentosa (Yellow Bauhinia)	Iron oxide Nanoparticles (FeONPs)	Leaf	Ferric chloride ($FeCl_3$)	70 nm	Phenols	Lakshminarayanan et al. (2021)
Fragaria ananassa Duchesne (strawberry)	Iron nanoparticles (FeNPs)	Leaf Waste	Ferric chloride hexahydrate ($FeCl_3$. $6H_2O$); ferric sulfate trihydrate ($Fe_2(SO_4)_3$. H_2O); ferrous chloride tetrahydrate ($FeCl_2$. $4H_2O$), and $FeCl_3$ anhydrous	**$FeCl_3$. $6H_2O$** 60 nm oblong or polygonal shape **$FeCl_2$. $4H_2O$** 70–145 nm **$Fe_2(SO_4)_3$. H_2O** 50–78 nm triangle, nanospheres and nanocubes with irregular edges **$FeCl_3$ anhydrous** 29–52 nm and oblong shape	Organic compounds	Góral-Kowalczyk et al. (2024)
Azadirachta indica (neem)	Nickel nanoparticles (NiNPs)	Leaf	Nickel nitrate (AR)	7–18 nm with triangular shape	Flavonoids, terpenoids, and phenolic	Kumar et al. (2025)
Cassia fistula (Golden shower tree)	Nano boron nitride	Leaf	Boron nitride	69.4 nm Hexagonal	-------	Pruthviraj et al. (2025)

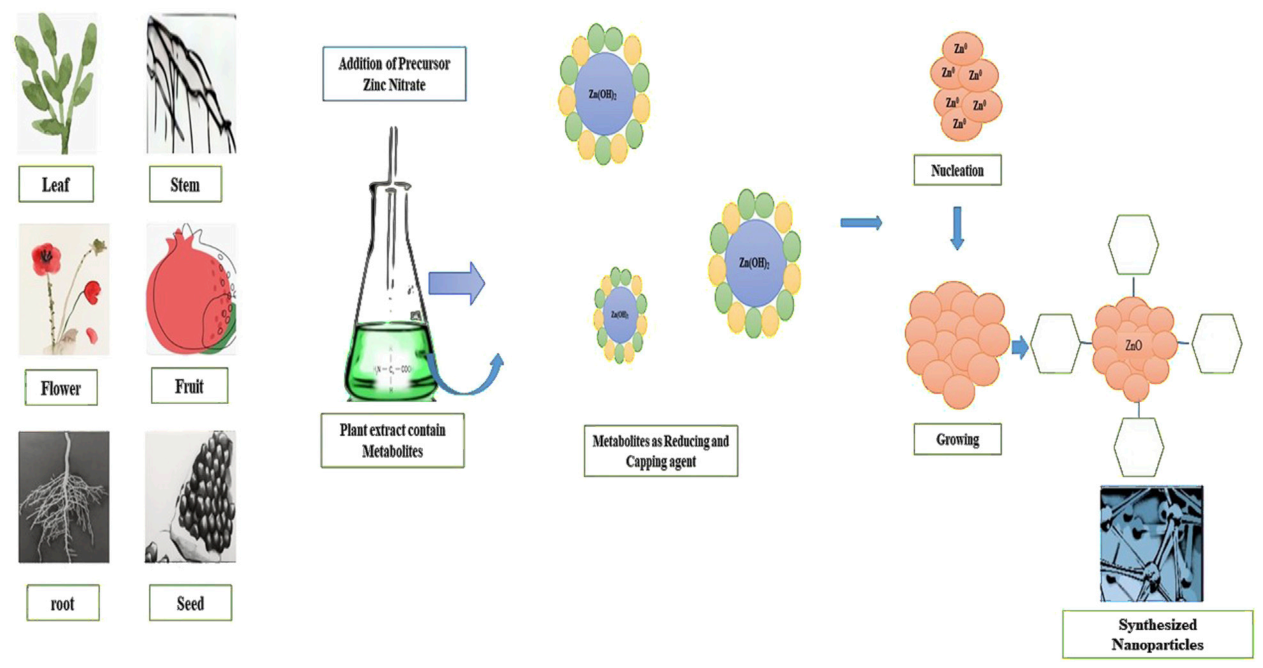


FIGURE 1
Schematic representation of plant-mediated biogenic nanoparticle synthesis using plant metabolites as capping and reducing agents, producing non-hazardous and environmentally safe stable nanoparticles.

nanoparticles with plant extracts (Chopra et al., 2022; Santhosh et al., 2022). In addition, the type of plant, the plant species, the growth stage, and the parts used in the synthesis of nanoparticles also affect the size and stability of the nanoparticles (Figure 1). Different plant species contain varying concentrations of bioactive compounds, which significantly influence the morphology and stability of the nanoparticles (Salayová et al., 2021). The presence of specific secondary metabolites, such as terpenoids and alkaloids, can dictate whether the resulting nanoparticles adopt a spherical, triangular, or irregular shape.

Two main approaches are used to synthesize nanoparticles from plant extracts: 1) solid-state methods and 2) solution-phase methods. Among them, the solid-state route approach has received less attention from the scientific community. The synthesis process involves the interaction of metal precursors with biomolecules present in the plant extracts. Generally, the synthesis of metal nanoparticles in plants and plant extracts occurs in three stages (Azad et al., 2023):

1. Activation phase: Metal ions are reduced, leading to the nucleation of reduced metal atoms. In this phase, secondary metabolites such as phenolic acids initiate the reduction of metal ions by donating electrons, which helps control the nucleation process, resulting in the formation of small, stable nanoparticles.
2. Growth phase (Ostwald ripening): Small nanoparticles spontaneously coalesce into larger particles, accompanied by an increase in thermodynamic stability. The availability of stabilizing compounds like flavonoids and tannins during this phase helps prevent excessive agglomeration, ensuring the formation of uniformly sized nanoparticles.
3. Termination phase: This critical phase governs the ultimate morphology of nanoparticles, largely shaped by the plant extract's intrinsic stabilizing properties and its interaction with metal precursors (Makarov et al., 2014). For example, phenols and alkaloids present in the extract can form surface-active layers around nanoparticles, enhancing their structural stability and functional properties.

For instance, nanotriangles are less stable owing to their high surface energy. To minimize Gibbs free energy, these nanotriangles tend to adopt a more stable morphology, such as a truncated triangle, in extracts where nanoparticle stability is not adequately maintained. This transformation is possible but depends heavily on reaction kinetics and solvent effects, rather than only on stability.

2.1.1 Advantages

The green synthesis of nanoparticles using plant extracts represents a transformative step toward sustainable agriculture, offering a broad spectrum of applications that extend from the sowing stage to the consumer's table. These eco-friendly nanoparticles have the potential to revolutionize agricultural practices by serving as biodegradable packaging films or edible coatings, enhancing food preservation and safety. They function as priming agents to boost seed germination and crop resilience, nanofertilizers to improve nutrient efficiency, and nanopesticides to provide targeted pest control with minimal environmental impact.

1. Plant-derived nanoparticles synthesized from bioactive phytochemicals offer practical handling advantages and represent a sustainable, cost-efficient synthesis strategy, inherently endowed with potent antimicrobial properties.

They help reduce environmental impact, minimizing harmful effects on both ecosystems and human health (Mohammadzadeh et al., 2022).
2. Green-synthesized nanoparticles (GSNPs) can be produced from commonly available, inexpensive raw materials made from plant extracts or agricultural waste, which drastically lowers production costs.
3. Unlike chemical synthesis, plant-based nanoparticles do not require toxic chemicals as reducing agents, making the process environmentally benign and more biocompatible. This approach eliminates harmful byproducts, ensuring safety for both ecosystems and human health. Although generally considered more biocompatible, GSNPs still require detailed toxicological assessments depending on their intended use (Hosseingholian et al., 2023).
4. For nanoparticle production, the waste generated by green-synthesized nanoparticles is significantly lower than that produced by conventional methods, making it a more sustainable option (Ying et al., 2022).
5. Additionally, their integration into pathogen detection systems enables early and precise identification of infections, safeguarding crop health and yield. This green approach not only aligns with the principles of sustainability but also bridges the gap between advanced nanotechnology and practical agricultural solutions. By leveraging these advantages, green-synthesized nanoparticles address existing limitations related to reproducibility, scalability, and standardization (Abegunde et al., 2024).

2.1.2 Disadvantages

1. The plant extract contains a diverse range of metabolites such as terpenoids, phenolics, alkaloids, flavonoids, and other compounds that act as reducing or capping agents. However, the composition and concentration of these bioactive compounds are highly variable and are influenced by multiple factors, including plant species or variety, plant part used, developmental stage, seasonal variation, and geographical origin. This intrinsic variability poses significant challenges as it directly impacts the size, stability, and shape of the synthesized nanoparticles (Singh et al., 2016). The lack of a uniform phytochemical profile often leads to inconsistencies in the synthesis process, thereby affecting nanoparticle morphology, reproducibility, stability, and functional performance. To improve the reproducibility of nanoparticle synthesis, it is essential to standardize extraction protocols for plant metabolites to ensure a consistent bioactive profile. Moreover, selecting robust plant species with stable and high concentrations of target metabolites can further enhance the efficiency and reliability of nanoparticle production.
2. Producing nanoparticles from plant extracts in large quantities remains a significant challenge due to multiple variables affecting the size, shape, and stability of nanoparticles (Zanbili and Poursattar Marjani, 2025). At the industrial scale, biogenic synthesis is further complicated by batch-to-batch variability caused by inconsistencies in the metabolite composition of plant extracts. To address these challenges, the use of bioreactors with controlled environmental conditions, including precise regulation of pH, temperature, precursor concentration, extract volume, and agitation speed, has shown potential in improving synthesis efficiency, product yield, and nanoparticle uniformity. Additionally, emerging microfluidic technologies offer a promising platform for achieving better control over synthesis parameters.
3. Several protocols for synthesizing nanoparticles from plant extracts require high temperatures and prolonged reaction times, which can have harmful environmental consequences. To mitigate this impact, standardizing extraction and synthesis conditions to minimize energy inputs and optimize yield is necessary. Ensuring reproducible nanoparticle synthesis under milder conditions is critical for aligning green nanotechnology with sustainability goals.
4. Despite their eco-friendly appeal, the synthesis of plant-based nanoparticles faces several limitations. The process can be highly variable, depending on the plant species, extraction method, and consistency of phytochemical content. Reproducibility remains a challenge due to natural variability in plant extracts. Additionally, controlling nanoparticle characteristics such as size, shape, and uniformity is often more difficult in green synthesis than in conventional chemical methods. However, it is inaccurate to generalize that green synthesis always results in low nanoparticle yield or requires multiple synthesis cycles. These outcomes depend significantly on the plant species used, the specific protocol applied, and the degree of process optimization. Recent advancements in modern techniques, such as microwave-assisted synthesis, have demonstrated the potential to drastically reduce reaction time and improve nanoparticle yield, enhancing the feasibility of green synthesis for practical applications. Therefore, continuous refinement of methodologies and integration of advanced technologies are essential for achieving high efficiency and reproducibility in plant-based nanoparticle production.
5. Plant-based nanoparticles are often significantly less stable due to aggregation. This instability may occur when metabolites in the plant extract fail to form strong interactions with the nanoparticle surfaces, thereby reducing their efficacy. Enhancing stability typically requires careful optimization of reaction conditions or the addition of stronger external stabilizing agents, which may complicate the simplicity and sustainability of the green synthesis approach.
6. Several challenges hinder the large-scale production of GSNPs at the industrial level, primarily due to variability in plant extract composition and the difficulty of consistently replicating optimal synthesis conditions. Metabolomics-guided profiling can be employed to identify dominant reducing and stabilizing agents within plant extracts, thereby supporting reproducibility and standardization in green nanoparticle synthesis. Such approaches provide a scientific basis for optimizing extraction protocols and selecting plant species or genotypes enriched in key functional metabolites.
7. Genetically engineered plants offer a promising strategy to overcome the variability and inconsistency associated with plant-based nanoparticle synthesis. These engineered plants

can be modified to biosynthesize targeted secondary metabolites such as flavonoids, terpenoids, or alkaloids in stable and uniform concentrations, thereby facilitating the reproducible and efficient synthesis of nanoparticles. This approach not only improves batch-to-batch consistency but also supports the scalability of green nanomaterial production at the industrial level. Recent studies, including those by Abegunde et al. (2024), have highlighted the potential of metabolomic profiling and genetic engineering to identify and enhance the expression of key bioactive compounds that act as potent reducing and capping agents. Such precision strategies can significantly enhance protocol standardization, streamline synthesis pathways, and reduce the variability introduced by plant-based raw materials. Although this remains a largely speculative avenue, it aligns with the emerging trend toward integrating molecular biology tools into green nanotechnology for improved reproducibility and functional optimization.

2.2 Role of green synthesis of nanoparticles in promoting a sustainable green economy

Nanotechnology plays a crucial role in advancing a green economy by contributing to sustainable agriculture, the food industry, and green energy. In the agricultural sector, the application of fertilizers remains a pivotal strategy to enhance crop productivity. Globally, countries such as India, the European Union, the United States, and China are among the leading producers of fertilizers, accounting for approximately 20% of phosphorus and potassium production and 60% of nitrogen production (Xu et al., 2023). Global food security has been increasingly threatened by the ongoing Ukraine–Russia war, which has severely disrupted fertilizer production as elevated natural gas prices constrain manufacturing capacity. For instance, in 2021, undernourishment affected 10% of the global population (828 million), compared to 8% (678 million) in 2019, despite initial efforts to mitigate hunger through responses to climate change, the COVID-19 pandemic, and conflicts (Głodniok et al., 2021; Piersa et al., 2021). To achieve the United Nations' Sustainable Development Goal of eradicating hunger, novel and innovative solutions are urgently required.

In this context, green-synthesized nanofertilizers have emerged as a groundbreaking innovation in driving the transition toward a sustainable and resilient green economy. Green synthesis is in perfect harmony with these principles because it uses renewable, non-toxic materials and lessens dependency on finite resources. The biosynthesis of nanoparticles using plant extracts as raw materials represents a highly sustainable and eco-conscious approach. This approach effectively valorizes agricultural waste, offering a sustainable alternative to conventional input materials. It significantly reduces reliance on hazardous synthetic chemicals and mitigates both ecological degradation and the substantial energy demands inherent in traditional chemical synthesis processes. This method not only mitigates environmental pollution but also enhances resource efficiency, paving the way for a more circular and responsible agricultural paradigm (Kirchherr et al., 2023). Osman et al. (2024) reported that leveraging green chemistry in nanoparticle synthesis could lead to a 50% surge in industrial output, coupled with a 40% reduction in costs and a 30% decrease in energy consumption compared to conventional synthesis methods.

These nanofertilizers enhance crop yields while requiring smaller quantities, ensuring slow nutrient release, reduced leaching, and a diminished environmental impact, all of which contribute to long-term economic sustainability (Sah et al., 2024). Furthermore, the secondary metabolites inherent in biogenically synthesized nanofertilizers, such as phenols, flavonoids, and alkaloids, provide additional benefits by protecting plants from environmental stresses and insect attacks through the enhancement of reactive oxygen species (ROS) production (Adetuyi et al., 2024). The nutrient uptake efficiency of these nanoscale macro- and micronutrients surpasses that of conventional fertilizers, maintaining the rhizosphere's nutritional accessibility.

In addition to fertilizers, the pesticide industry is a significant contributor to environmental pollution, with demand increasing daily. For example, the European Union alone recorded pesticide sales of approximately 333,000 tons (Veiga-Del-Baño et al., 2023). This trend raises serious concerns regarding environmental health. In response, researchers have shifted their focus toward nanopesticides, which are being promoted to farming communities as innovative, cost-effective solutions for protecting crops against insect pests. These nanopesticides not only mitigate insect–pest infestations but also reduce environmental harm, aligning with the principles of a sustainable green economy (Chen Z. et al., 2023). Moreover, these advanced technologies generate revenue through the development and commercialization of eco-friendly pest control solutions (Intisar et al., 2022; Hassan et al., 2024). For instance, nanopesticides with high surface area-to-volume ratios have demonstrated enhanced efficacy, with studies reporting significant reductions in lepidopteran insect attacks within 1 day of application (Dwivedi et al., 2016).

Biogenic, plant-mediated nanoparticles such as silver nanoparticles (AgNPs) and zinc nanoparticles (ZnNPs) are also used in the food industry to minimize post-harvest losses and extend the shelf life of fruits and vegetables through applications such as packaging films and edible coatings (Lieu et al., 2024; Zafar and Iqbal, 2024). Conventional wax coatings, though cost-effective, often contain harmful chemicals, offer limited antimicrobial properties, and lack multi-functionality, making them unsuitable for a sustainable green economy (Zhu et al., 2022). In contrast, nanomaterials represent a significant advancement in this domain, offering budget-friendly, biodegradable, and highly effective solutions with antibacterial and antioxidant properties.

The biogenic approach for nanoparticle synthesis has garnered considerable attention due to its alignment with sustainability principles. Nanoparticles synthesized using plant extracts offer numerous advantages, including small size, well-defined shape, environmental compatibility, minimal resource requirements, and the absence of hazardous by-products (Ahluwalia et al., 2014; Kalyani et al., 2019). Additionally, the metabolites present in plant extracts enhance the stability of these nanoparticles, making them highly effective for applications such as pest control and targeted nutrient delivery in crops. Compared to conventional synthesis methods, plant-based nanoparticle synthesis reduces reliance on synthetic stabilizers through the intrinsic capping ability of plant derived compounds (Bachheti and Bachheti, 2023).

Plant metabolites are broadly classified into primary and secondary metabolites. Primary metabolites, including amino acids, carbohydrates, and chlorophyll, are essential for fundamental plant functions, while secondary metabolites exhibit diverse physiological activities and play a crucial role in nanoparticle synthesis (Ovais et al., 2018). Secondary metabolites, such as flavonoids, act as natural reducing and stabilizing agents, preventing nanoparticle aggregation by chelating metal ions and releasing reactive hydrogen atoms (Nobahar et al., 2021). The composition of these metabolites varies among plant species, directly influencing the size, morphology, and reactivity of the synthesized nanoparticles (El-Seedi et al., 2019).

2.2.1 Flavonoids

Flavonoids comprise a diverse group of secondary metabolites, including anthocyanins, isoflavonoids, flavonols, chalcones, flavones, and flavanones, which are characterized by their oxygen-containing heterocycle ring C linking two phenyl rings (A and B) hydroxylated at different positions (Kachlicki et al., 2016). These compounds exhibit strong antioxidant properties and play a crucial role in combating biotic and abiotic stress factors. Studies have shown that flavonoid–metal complexes have higher antioxidant activity than free ligands (Kostyuk et al., 2007; Samsonowicz et al., 2017).

The chelation and reduction capabilities of flavonoids are largely attributed to their functional groups, particularly carbonyl and hydroxyl moieties, which facilitate metal ion binding at multiple sites. Notable coordination occurs at the C3′ and C5′ hydroxyl groups and the C3′ and C4′ catechol group positions (Raghavan et al., 2015). These sites enable the conversion of metal ions into nanoparticles through adhesion, chelation, reduction, and stabilization processes. In addition, tautomeric shifts from enol to keto forms can release reactive hydrogen atoms, which facilitate the reduction of metal ions (Makarov et al., 2014).

The quantity and spatial arrangement of hydroxyl and carbonyl groups on the A, B, and C rings determine the efficiency of nanoparticle synthesis. For example, Ahmad et al. (2010) synthesized AgNPs (~10 nm) from sweet basil extract via the conversion of luteolin and rosmarinic acid into keto-forms. Similarly, Sahu et al. (2016) used hesperidin and naringin—both containing saturated pyran rings—to synthesize AgNPs, while diosmin's unsaturated pyran ring influenced its electron-donating behavior and nanoparticle formation efficiency.

Quercetin, a potent flavonoid, exhibits strong metal chelation through its multiple reactive sites, including hydroxyl and catechol groups on rings A and B. These enable interaction with a range of metal ions such as Fe^{2+}, Fe^{3+}, Cu^{2+}, Zn^{2+}, Al^{3+}, Cr^{3+}, Pb^{2+}, and Co^{2+}, facilitating nanoparticle formation through chelation, aggregation, and bio-reduction (Makarov et al., 2014). Genistein similarly reduces Au^{3+} to Au^0 and forms a genistein–AuNP complex by electron transfer, creating a negatively charged surface layer that stabilizes the nanoparticles (Stolarczyk et al., 2017).

2.2.2 Phenols

Phenolic acids, derivatives containing at least one functional carboxyl group, are frequently employed in the green synthesis of metal nanoparticles due to their dual role as reducing and stabilizing agents. These compounds are effective in thermodynamically driven synthesis pathways, where phenolic acids introduced at concentrations sufficient to induce supersaturation gradually reduce metal ions and promote nanoparticle nucleation, particularly under alkaline conditions that enhance oxidative activity (Cao, 2004; Wang et al., 2007). Nanoparticles synthesized using phenolic compounds often exhibit greater stability compared to those produced via traditional reducing agents. In contrast, protonated reducing agents such as citrate—although also capable of stabilizing nanoparticles—function primarily through surface adsorption via intermolecular interactions between their carboxylate groups and the metal surface (Park and Shumaker-Parry, 2014). To improve clarity, it is important to distinguish between the chelation-driven mechanism of phenolic acids and the surface-coating behavior of citrate.

The reductive capacity of phenolic acids is influenced by both the number and position of hydroxyl groups on the aromatic ring. Although it was previously assumed that a higher number of hydroxyl groups might decrease reactivity due to steric hindrance, more recent evidence suggests that additional hydroxyl groups can enhance redox potential, particularly in the absence of aggregation or spatial obstruction (Hwang et al., 2015). Oxidized phenolic compounds can adhere to nanoparticle surfaces and serve as growth mediators. For instance, caffeic acid contains a carboxyl group that forms adsorptive bonds with metal atoms, enabling it to act as both a reducing and capping agent (Schliebe et al., 2013).

Moghadas et al. (2020) reported that compounds present in the *Mentha piperita* leaf extract, particularly caffeic acid, effectively facilitated AgNP synthesis. The mechanism involves initial chelation between Ag^+ ions and hydroxyl groups of caffeic acid, followed by electron donation leading to the reduction and nucleation of Ag^0. The antioxidant property of caffeic acid stabilizes the resulting phenoxy radicals. Subsequent tautomeric shifts enable the formation of stable o-quinone intermediates through the release of additional electrons and hydrogen ions. Further oxidative dimerization of semiquinone radicals leads to the formation of a caffeic acid dimer, which can also release multiple electrons and protons to enhance the reduction process. Additionally, the aromatic ring's high nucleophilicity facilitates the chelation of silver ions via carbonyl and hydroxyl coordination.

In a separate study, Mohammadzadeh et al. (2022) demonstrated that phenolic compounds present in the walnut husk extract acted as both reducing and capping agents in the synthesis of AgNPs. Wang et al. (2022) synthesized biogenic ZnO nanoparticles (~8.29 nm) using the coffee leaf extract. The identified phenolics, 5-caffeoylquinic acid, rutin, and mangiferin, participated in the following sequential steps: (i) chelation of Zn^{2+} ions, (ii) reduction to metallic Zn^0, and (iii) subsequent oxidation to form ZnO nanoparticles. The presence and function of these compounds were confirmed using spectroscopic methods such as HPLC, FT-IR, and TEM, which validated their incorporation into the final nanostructure.

2.2.3 Alkaloids

Plants can produce a variety of secondary metabolites when exposed to stress-inducing conditions. Among these, alkaloids and certain organic acids have been widely recognized as effective bioreductants in the synthesis of nanoparticles. For example, pedicellamide, an alkaloid found in the extract of *Piper pedicellatum*, has been shown to reduce metal ions through the release of reactive hydrogen atoms, thereby facilitating the synthesis of silver nanoparticles (Tamuly et al., 2014).

Subha et al. (2015) demonstrated that root extracts of *Ipomoea pes-caprae* contain a diverse array of metabolites, including ergoline alkaloids, indolizidine alkaloids, benzoids, and phenolic compounds, which collectively enable the reduction, synthesis, and stabilization of AgNPs. Steroidal alkaloids such as α-solanine and α-chaconine, extracted from potato leaves, have also been used to synthesize silver nanoparticles with sizes of 47 nm and 39.5 nm, respectively. These nanoparticles exhibited antifungal properties against plant pathogens (Almadiy and Nenaah, 2018).

Tekin et al. (2019) synthesized Ag nanoparticles using the eugenol extract derived from clove and found that eugenol served as an effective reducing agent, enabling the production of stable nanoparticles. The mechanism involves the deprotonation of the hydroxyl group in eugenol, which generates an anionic species. This anion is then oxidized by metal ions, leading to their reduction and the subsequent formation of metallic nanoparticles.

2.2.4 Terpenoids

Plant terpenoids are secondary metabolites derived from essential oils, which are complex mixtures of volatile compounds synthesized from five-carbon isoprene units and possess antibacterial and antiviral properties. These terpenoids can bind to the surface of nanoparticles by interacting with carbonyl groups or electron-rich sites. Although the precise mechanism by which plant-derived terpenoids facilitate nanoparticle synthesis remains unclear, they are believed to function as surface-active substances that contribute to nanoparticle stabilization and size reduction. A previous study reported that citronellol and geraniol—two terpenoids with hydroxyl functional groups—were capable of reducing Ag^+ ions in the leaf extract of *Pelargonium graveolens*, thereby promoting the formation of silver nanoparticles (Shankar et al., 2003). Similarly, Sathishkumar et al. (2009) found that the bark extract of *Cinnamomum zeylanicum* contains linalool, eugenol, and methyl chavicol, all of which exhibit metal-reducing activity.

Sharma et al. (2022) also utilized the *Syzygium aromaticum* (clove) extract to produce gold and silver nanoparticles, identifying eugenol as the primary bio-reducing agent. The hydroxyl group in eugenol plays a central role by forming a resonance-stabilized structure upon proton dissociation, which facilitates electron transfer to metal ions and their subsequent reduction into nanoparticles (Singh et al., 2018). The deprotonated hydroxyl group forms an anion, which is then oxidized by metal ions, initiating nanoparticle formation. Additionally, the methoxy and allyl groups acting as electron-withdrawing substituents enhance the reduction potential of eugenol. Functional groups positioned at the para and ortho locations further facilitate this process through the simultaneous release of two electrons.

Pungle et al. (2022) reported that terpenoids such as tiamulin and lupanyl acid, present in the leaf extract of *Tridax procumbens*, acted as major reducing agents in the synthesis of AgNPs. The resulting nanoparticles ranged in size from 11.1 to 45.4 nm and exhibited moderate stability, with a zeta potential value of −20.7 mV.

2.2.5 Sugars

Sugars such as monosaccharides and disaccharides are environmentally friendly compounds whose reducing properties enable the green synthesis of metal nanoparticles. To modulate the physical characteristics of plant-mediated nanoparticles (PMNPs) during synthesis, polysaccharides also act as effective reducing and stabilizing agents (Makarov et al., 2014). Studies have demonstrated that plant-derived sugar extracts enhance nanoparticle stability through capping mechanisms. For example, Filippo et al. (2010) and Pattnaik et al. (2023) reported that non-soluble carbohydrates, such as starch, significantly contribute to nanoparticle stabilization. Monosaccharides containing an aldehyde group—such as glucose—are well-known reducing agents, while those with a ketone group—such as fructose—can only exhibit antioxidant activity after undergoing tautomeric conversion from a ketone to an aldehyde. This redox capacity is influenced by the monosaccharide's ability to adopt an open-chain structure, which exposes the reactive aldehyde group required for metal ion reduction. In disaccharides like maltose and lactose, at least one monosaccharide unit may transiently assume an open-chain conformation, allowing it to participate in nanoparticle formation.

In nanoparticle synthesis, polysaccharides (including soluble and non-soluble forms) facilitate both reduction and stabilization. They form non-covalent interactions with metal ions, enabling controlled nucleation and growth of nanoparticles. Although some studies have specifically focused on magnetic nanoparticles (MNPs), this stabilization mechanism also broadly applies to metal nanoparticles in general (Wang et al., 2017). Such interactions influence the morphology and kinetic growth profile of nanoparticles by modifying the free energy landscape.

Unlike reducing monosaccharides, sucrose—a non-reducing disaccharide composed of glucose and fructose—is unable to adopt an open-chain form due to its glycosidic linkage. As a result, it lacks the capability to reduce metal ions. Fructose, despite being a reducing sugar, has a lower reduction potential than glucose because its conversion from ketone to aldehyde form is kinetically slower. This slower tautomeric shift limits the availability of reactive aldehyde species, thereby reducing its overall capacity to act as a reductant in nanoparticle synthesis (Panigrahi et al., 2004).

2.2.6 Amino acids

Amino acids, the fundamental building blocks of proteins, play critical roles in cellular metabolism and interact readily with various oxidizing agents. Their reducing capabilities have been widely investigated for NP synthesis by numerous research groups worldwide. All amino acids contain a central carbon bonded to an amino group (NH_2), a carboxyl group (COOH), a hydrogen atom, and a variable side chain (R group). Typically, the amino and carboxyl groups are the most chemically reactive moieties in NP synthesis.

The presence of amino acids during synthesis not only facilitates the reduction of metal ions but also significantly influences nanoparticle morphology as they often function as effective capping agents (Mandal et al., 2002; Courrol and de Matos, 2016). Specific side chains—such as thiol groups in cysteine, thioether in methionine, hydroxyl groups in serine, threonine, and tyrosine, and carbonyl groups in asparagine and glutamine demonstrate strong affinities for metal ions (Ramrakhiani and Ghosh, 2018).

Experimental studies have shown that hydroxyl groups (e.g., from tyrosine) and carbonyl groups (e.g., from glutamine and asparagine) contribute to the reduction of silver ions. Similarly, amino and thiol side chains, such as those found in cysteine, also play a role in the reduction process. Due to their zwitterionic nature and ability to alter charge in response to pH changes, amino acids such as tyrosine and tryptophan are especially suitable as reducing and capping agents. This pH-responsive behavior enhances their interaction with metal ions and supports nanoparticle stabilization (Shankar and Rhim, 2015).

Furthermore, the integration of amino acids with biocompatible polymers known for their mechanical strength and thermal stability has been explored to improve nanoparticle functionality (Fan et al., 2003). Maruyama et al. (2015) synthesized gold nanoparticles (AuNPs) using 20 amino acids and reported that histidine is the best reducing and capping agent.

2.2.7 Protein and peptides

Peptides have emerged as promising biomolecules in the biomedical field, owing to their ability to mimic protein-like functions and their high modularity in molecular design. Due to their modular structure and functional groups (thiols and disulfides), peptides are also of growing importance in nanotechnology. These functional groups serve as non-enzymatic reducers and stabilizers during NP synthesis. For nanoparticle synthesis, disulfide bonds and thiol groups present in proteins and amino acids function as intrinsic reducing and stabilizing agents, mediating the bioreduction of metal ions and ensuring nanoparticle stability throughout the biosynthetic process. Bhattacharjee et al. (2005) synthesized AuNPs using a tripeptide sequence containing "C-terminal tyrosine residues," which acted as reductants. The integration of amino acids into a peptide chain can alter their ability to bind and reduce metal ions, as the formation of the peptide backbone changes the functional roles of the amino and carboxyl groups. Compared to polymers and surfactants, capping proteins offer significant advantages in nanoparticle production (AbdelRahim et al., 2017). Recent developments in peptide-based nanomaterials have been described in detail in several reviews from different perspectives. Currently, there are two main approaches to discovering artificial bioactive peptides: (i) the construction and screening of peptide libraries from random amino acid assemblies within a given macromolecular topology (peptide-library screening, a bottom-up approach) and (ii) the isolation of bioactive sequences from natural proteins based on their three-dimensional (3D) structures (structure-based design, a top-down approach) (Marasco et al., 2008; van der Sloot et al., 2011; Ryvkin et al., 2018).

Effective binders against a variety of targets, including tiny chemical compounds, peptides, DNAs, RNAs, cells, and inorganic materials, can be easily developed using peptide libraries. However, the top–down method has an advantage over the bottom–up strategy as it allows the discovery of peptide sequences that target a specific binding site on bio-macromolecules based on the structural features of these molecules.

A dissolved peptide can adopt a specific shape, which often determines whether self-assembly occurs or not. Multivalence is a key feature that PNCs can offer. Non-covalent interactions such as hydrogen bonds, ionic bonds, van der Waals forces, stacking forces, and hydrophobic interactions account for the majority of interactions in biological systems. Peptides adopt specific conformations in solvents, such as α-helices, β-sheets, and β-hairpins, which determine self-assembly. Stabilization of the α-helix is critical for triggering self-assembly. Methods include cross-coupling of side chains, hydrogen bond surrogates, metal coordination, and salt bridge formation. Short α-helix peptides are easy to synthesize and modify but lack stability in solution. Kanchi et al. (2018) reported the synthesis of gold nanoparticles using the Jatropha extract. The result of FTIR analysis revealed characteristic absorption bands at 1450 and 1631 cm^{-1}, corresponding to amide linkages, indicating the involvement of proteins in the bioreduction and stabilization of silver ions. SEM analysis showed spherical nanoparticles with an average size of 22 nm.

An experiment by Pungle et al. (2022) confirmed that high-resolution LC-MS identified peptides such as 12-methoxy-4,4-bisnor-5 alpha-8,11,13-podocarpatrien-3-ol and Asp-Tyr dipeptide, which acted as capping agents in AgNP synthesis. Proteins and peptides derived from plant extracts have been reported to facilitate the reduction of metal ions to lower oxidation states while concurrently acting as capping agents. This biologically driven process is influenced by variables such as pH, temperature, reaction duration, ambient conditions, and extract concentration, offering a sustainable alternative to traditional chemical methods (Ying et al., 2022). In one such study, silver nanoparticles were synthesized using the seed extract of *Tribulus terrestris*. FT-IR analysis showed peaks at 1450 and 1631 nm, which indicate the presence of proteins responsible for reducing silver ions and capping the nanoparticles to provide stability. SEM analysis demonstrated that the synthesized nanoparticles exhibited uniform spherical morphology, with an average particle size measuring approximately 22 nm (Rahman et al., 2023).

3 Application of nanotechnology in horticultural crops

Global challenges facing the farming sector include rapid climate change, industrialization, resource constraints, and environmental concerns. These factors, along with others such as carbon absorption, photosynthesis, biochemical reactions, and membrane permeability, have varying effects on the crop's productivity and metabolism. Nanotechnology presents transformative prospects for horticulture by enabling site-specific delivery of nutrients and bioactive molecules, driving genetic enhancement, and fostering a suite of nano-enabled innovations including seed encapsulation, nano-packaging and coatings, nanobiosensors, nanofertilizers, and nanopesticides. Together, these advances stimulate seed germination, boost yield, and elevate the nutritional quality of horticultural produce (Figure 2).

3.1 Seed germination

Seed germination is widely regarded as the most delicate stage in a plant's life cycle, serving as the foundation for crop yield and

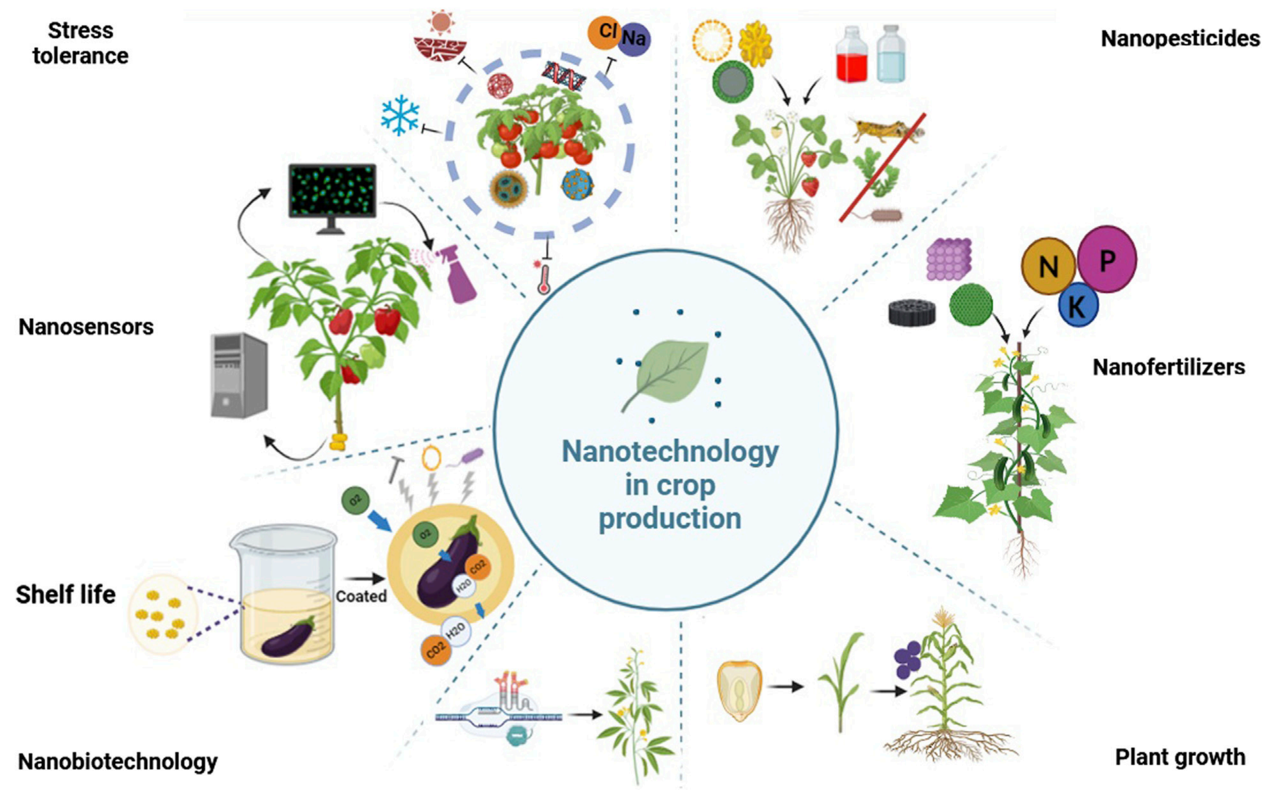


FIGURE 2
Promising applications of plant-mediated nanoparticles as a novel innovation in horticultural crop improvement. Effective applications include slow-release fertilizers, plant health monitoring sensors, and plant protection agents; their incorporation in edible coatings for enhanced shelf life; and their role as carriers for CRISPR technology.

productivity. Approximately 90% of agricultural crops rely on seeds to meet global food demands (Shang et al., 2019; Shelar et al., 2023). Seed dormancy presents a pivotal challenge in flowering and small-seeded vegetable species, often hindering germination and reducing production rates.

In the context of global climate change, environmental stressors including drought, soil salinity, temperature extremes, heavy metal accumulation, and seed-borne pathogens adversely affect seed quality. Exposure to such stressors can impair physiological seed functions, including viability and water uptake efficiency, leading to suboptimal germination, stunted seedling growth, and reduced yield potential (He et al., 2018; Das and Biswas, 2022).

Priming seeds with nanoparticles has emerged as an innovative and sustainable approach. This technique involves coating seeds with nanomaterials such as nanofertilizers, nanopesticides, and nanofungicides to enhance seed quality and resilience to environmental stress and pest infestation. These effects are largely attributed to biochemical mechanisms including the upregulation of aquaporin genes and enhanced activity of hydrolytic enzymes responsible for starch degradation, ROS modulation, and improved stress signaling pathways (Manjaiah et al., 2019; Shelar et al., 2021; Shelar et al., 2022). Although some studies suggest the possibility of nanopore formation in seed coats, particularly in research involving carbon nanotubes (CNTs)—most reported benefits of nano-priming are biochemical rather than physical, involving increased ROS activity and enzyme induction (Pachchigar et al., 2022; Shelar et al., 2024). Seeds treated with nanoparticles—particularly metal oxides such as silver, zinc, iron, titanium, and copper and multi-walled carbon nanotubes—function as sustained-release agrochemical carriers. These nanoformulations outperform conventional fertilizers by slowly delivering active ingredients from plant extracts, thereby enhancing germination and offering protection against seed-borne pests and pathogens (Haydar et al., 2024). Moreover, the enhanced uptake and intracellular movement of nanoparticles improve nutrient absorption, leading to increased biomass and plant productivity (Table 2). It has been demonstrated that exposure to green-synthesized nanoparticles enhances photosynthetic pigment content, nutrient availability, and the accumulation of beneficial secondary metabolites in developing seeds (Begum and Jayawardana, 2023).

In a previous study, exposure to carbon nanotubes was reported to enhance seed germination and plant growth by physically penetrating the seed coat of tomatoes (Srinivasan and Saraswathi, 2010). Kole et al. (2013) found that seed dressing of bitter gourd with carbon-based nanomaterials not only increased fruit yield by 128% but also enhanced the levels of nutritionally valuable compounds such as lycopene, inulin, cucurbitacin-B, and charantin compared to untreated controls. However, such enhancements in phytochemical composition are highly dependent on both crop species and the type of nanomaterial used and may not be broadly generalizable across plant systems.

TABLE 2 Impact of nano-priming and their impacts on germination, growth, and development of different horticultural plant species.

Crop	Priming NPs	NP concentration	NP size	Physiological/biochemical/ molecular changes	Reference
Moringa oleifera (moringa)	Zinc oxide nanoparticles (ZnONPs)	0.5, 2.5, 5, 7.5, and 10 mg L^{-1}	16.49 nm	Nano zinc priming enhances seed sprouting and promotes the synthesis of beta-carotene and chlorophyll. Furthermore, primed seeds produce plants with a significantly higher quantity of flavonoids, phenols, and vitamin C	Garza-Alonso et al. (2021)
Lycopersicum esculentum (tomato)	Zinc oxide nanoparticles (ZnONPs)	21.35–99.07 ppm	30 nm	Priming with zinc oxide nanoparticles promotes the translocation of zinc through roots and stems, significantly enhancing seed germination	Asmat-Campos et al. (2022)
Stevia rebaudiana Bertoni (Stevia)	Silica nanoparticles (SiNPs)	1, 5, 10, 25, 50, and 100 ppm for 20 h soaking duration	50–100 nm	Among various concentrations of silica nanoparticles, 10 ppm was most effective, accelerating seed germination and enhancing seedling growth. Treated seedlings exhibited significantly higher shoot dry weight, root dry weight, and total seedling dry weight than control seedlings	Hasanaklou et al. (2023)
Vigna unguiculata (cowpea)	Nano calcium borate (NCB)	0.1%, 0.25%, and 0.5%	117.7 nm	Soaking cowpea seeds in nano calcium borate at 0.025% concentration enhances the germination rate by 16.5%. All concentrations tested show significant improvements in growth parameters, including seedling vigor index and root growth	Smitha et al. (2024)
Abelmoschus esculentus (okra)	Zinc oxide nanoparticles (ZnONPs)	20 and 40 ppm (soaking 18 h and 24 h)	------	Nano zinc priming at a 20 ppm concentration with an 18-h soaking duration significantly reduces the time to seed germination, increasing germination rates by 24.62% and 58.22%, respectively. This treatment also improves growth parameters, including root and shoot growth and fresh and dry weights	Ramzan et al. (2024)
Capsicum annuum (capsicum)	Silver nanoparticles (AgNPs)	10, 30, and 50 ppm	25–45 nm	Priming with nano silver synthesized from *Moringa oleifera* and *Azadirachta indica* (AgMo and AgAI) at 50 ppm concentration notably increases germination rates and achieves maximum seedling length	Mawale and Giridhar (2024)

Several other studies have demonstrated that certain nanomaterials can be incorporated into the seed coat, potentially increasing the seed's capacity for water absorption (Banerjee and Kole, 2016). This improved water uptake may stimulate enzymatic activity during germination, contributing to enhanced seedling vigor.

Nanoparticle effects on early plant development are governed by a combination of physicochemical properties and plant-specific factors. Nanomaterial characteristics such as composition, size, morphology, surface charge, stabilizing agents, concentration, and exposure duration influence bioavailability and interaction with plant tissues. Simultaneously, plant-related variables such as species, genotype, seed coat traits, developmental stage, and environmental stressors modulate uptake and physiological response. Together, these factors affect germination rate, seedling vigor index (SVI), and early growth, determining whether the outcomes are promotive or inhibitory (Hossain et al., 2019). Plant growth is positively affected by an increase in the concentration of nanoparticles, but at high concentrations, toxic substances may accumulate in the plant, which can retard plant growth. Uddin et al. (2021) evaluated the toxicological effects of plant-mediated NiO NPs at different concentrations ranging from 31.25 to 1000 μg/m on the seed germination indices of radish. The experimental observations indicated that biogenic NiO NPs act as growth-promoting agents, improving the rate of germination by approximately 3%–8% by breaking seed dormancy. At higher concentrations ranging from 250 to 1000 μg/mL, the rate of germination was observed to increase to approximately 33.17%–39.60%.

In addition, both the type of nanoparticles and the crop species influence seedling growth. In the previous study, researchers evaluated the role of biogenic copper nanoparticles (CuNPs) as promising growth stimulants (Khaldari et al., 2021) in two different crops, lettuce and tomatoes, in contrast to chemically synthesized copper nanoparticles. The study revealed that lettuce and tomato seeds treated with biogenic NPs at concentrations ranging from 4 to 400 μg/mL did not exhibit any phyto-toxicological effects. However, at a concentration of 4000 μg/mL, biogenic NPs were found to retard germination indices and cause a significant increase in the percentage of abnormal seedlings—up to 30% in tomatoes and 52.93% in lettuce. In this context, tomato and lettuce seeds treated with synthetic nanoparticles triggered germination at a lower concentration (40 μg mL^{-1}), but at the highest concentration of CS NPs, germination percentages were reduced to 65.33% in tomatoes and 78.67% in lettuce. Overall, green synthesis-based CuNPs appeared to be less toxic and more effective, possibly due to the presence of bioactive compounds. However, at highest concentrations, both type of NPs were more toxic to lettuce than to tomatoes, possibly due to differences in seed coat hardness and permeability.

The different characteristics, such as chemical composition, shape, size, and surface area alone or in combination, played significant roles in enhancing the germination and growth of seedlings. Zinc and copper nanoparticles synthesized from onion leaf extract were examined by Hussain et al. (2019) for their effects on nucellus tissue germination and the biochemical attributes of Kinnow mandarin. The effect of NP suspension (40 μg mL^{-1}) on nucleus tissue germination was recorded after 14 days, each at 7-day intervals. Plant-mediated ZnNPs suspended in MS medium exhibited significantly greater bioefficacy than green CuNPs, as evidenced by enhanced germination rates of nucellus tissues, increased seedling vigor index (SVI), and superior shoot and root elongation over time. Furthermore, the production of antioxidant enzymes is elevated by CuNPs, which act as stress inducers due to their toxic, bulky texture. A similar study conducted by Acharya et al. (2019) evaluated that seed priming with silver and gold nanoparticles synthesized using plant extracts improved yield and growth parameters, increased chlorophyll and sugar content, and reduced the pungency level of onion bulbs. The pathway of nanoparticle synthesis also has an impact on plant germination and growth performance.

Seed priming with nanoparticles is considered a promising strategy to overcome seed dormancy and enhance plant growth performance. However, several studies have reported that excessive nanoparticle application during seed priming can negatively affect seed coat integrity, interfering with embryo hydration, gas exchange, and nutrient diffusion, ultimately reducing germination rates.

High concentrations of nanoparticles may induce phytotoxicity by disrupting cellular ultrastructure, impairing membrane integrity, interfering with cellular function, and causing cytoplasmic contraction. Additionally, they can stimulate the overproduction of ROS, limit water uptake, and reduce nutrient translocation, thereby inhibiting seedling growth and development (Gao et al., 2023). Some studies have also shown that nanoparticle exposure can affect hormonal balance and alter metabolic pathways. For instance, certain nanoparticles may influence the ratio of biosynthetic precursors for gibberellin and potentially downregulate gene expression linked to germination. However, these effects are not uniform and depend significantly on the type of nanoparticle, plant species, dosage, and mode of application.

Toxic effects are also associated with the inhibition of key enzymatic activities, including α-amylase, peptidase, malate dehydrogenase, protease, and pyruvate kinase, all of which are essential for starch hydrolysis, energy metabolism, and protein mobilization. Their inhibition leads to delayed germination and impaired seedling development.

Nasiri et al. (2018) conducted an experiment to evaluate the phytotoxic effects of green and chemically synthesized silver nanoparticles on basil and chamomile seeds. Treatments at concentrations of 100, 200, 400, and 600 ppm revealed that higher levels of AgNPs inhibited germination in both species. Notably, chemically synthesized nanoparticles exhibited stronger toxic effects than green nanoparticles, with concentrations above 200 ppm nearly completely inhibiting germination.

Despite substantial research, the mechanisms by which nanomaterials affect seed germination remain incompletely understood. Although their role in enhancing water uptake has been proposed, this process is yet to be clearly defined. To minimize phytotoxic risks, it is essential to optimize nanoparticle concentration and delivery systems to ensure gradual release. Establishing species-specific safe thresholds will help promote beneficial outcomes, enhancing germination and early growth while preventing oxidative stress and metabolic disruption. Implementing these strategies will not only reduce toxicity risks for plants and the surrounding environment but also improve the responsible application of nanoparticles in horticultural systems.

3.2 Improve shelf life

Fruits and vegetables are rich in nutrients and bioactive compounds essential for human health. However, after harvest, these crops are highly perishable, leading to significant post-harvest losses. It is estimated that 20%–40% of fresh produce is wasted due to improper handling, enzymatic browning, microbial contamination, moisture loss, and the absence of adequate post-harvest infrastructure (Lakhani et al., 2025). To reduce spoilage, it is critical to manage ethylene production, prevent microbial growth, and slow respiration rates (Kumar et al., 2021; Mariah et al., 2022). During storage, fruits and vegetables undergo changes in their physicochemical attributes, including flesh softening, weight loss, shrinkage, and decreases in sugar, acidity, ascorbic acid, and resistance to microbial attack, all of which contribute to reduced marketability (Odetayo et al., 2022). Nanotechnology provides an emerging solution to these challenges by preserving the freshness and quality of produce through advanced packaging and coating systems (Sagar et al., 2022).

Nanotechnology is an innovative approach in the horticultural sector with demonstrated potential to extend the shelf life of fruits and vegetables. By incorporating nanoparticles into edible coatings or packaging films, these systems can help preserve post-harvest quality. Edible nano-coatings improve barrier properties against oxygen and moisture, reduce ethylene production, and inhibit microbial infections, often outperforming conventional preservation strategies. Although traditional methods such as cold storage and chemical preservation have long been used, they may pose limitations, including chilling injury, high operational costs, or potential chemical residues. Nanotechnology-based solutions offer promising alternatives using bioactive, eco-friendly materials in coatings and packaging. However, despite these advantages, safety concerns surrounding the ingestion of nanoparticles remain. Regulatory agencies such as the European Food Safety Authority (EFSA) and the U.S. Food and Drug Administration (FDA) are currently evaluating the long-term implications of nanomaterials in food systems, highlighting the need for continued toxicological studies and risk assessments (Sagar et al., 2018; Dubey et al., 2023).

TABLE 3 Application of metal-based oxide nanoparticles in extending shelf life by delaying ripening, inhibiting microbial infections, and preserving the nutritional quality of fruits and vegetables.

Crop	Priming NPs	NP concentration	NP size	Physiological/biochemical/ molecular changes	Reference
Musa paradisiaca (banana)	Silver nanoparticles (AgNPs)	0.01%–0.05%	50–100 nm	Shelf life of banana improved by reducing ethylene biosynthesis, which delays the process of fruit ripening No recorded penetration of nano silver in banana pulp	Nayab and Akhtar (2023)
Mangifera indica (mango)	Silver nanoparticles (AgNPs)	5, 20,40, 60, and 100 mM	50–60 nm	Delay process of fruit maturation due to lower production of ethylene and decreased hydrolysis of carbohydrates	Ounkaew et al. (2021)
Lycopersicum esculentum (tomato)	Zinc oxide nanoparticles (ZnONPs) along with chitosan	100 ppm	36 nm	Enhanced storage period of tomato fruits by reducing weight loss	Iqbal et al. (2022)
Vitis vinifera (grape)	Magnesium oxide nanoparticles (MgONPs)	20, 30, and 40 mM	28.60 nm	Under storage at room temperature and cold temperature, the supplementation of nano magnesium enhances the shelf life of grape berries by inhibiting the attack of microorganisms, improving nutritional quality, and maintaining firmness	Mushtaq et al. (2024)

Nanoparticles enhance shelf life through their unique physicochemical properties, including high reactivity, small size, customizable shape, tunable optical features, and large surface area. In the field of nanotechnology, metal and metal oxide nanoparticles such as those composed of copper, iron, silver, zinc, and titanium are widely recognized for their antifungal and antimicrobial properties, which contribute to the inhibition of molds, fungi, and bacteria (Qu et al., 2025). Incorporating nanoparticles into packaging films or edible coatings can effectively prevent oxidative degradation, helping preserve the nutritional quality, color, and flavor of fruits and vegetables due to their intrinsic antioxidant activity. Through their biocatalytic properties, nanoparticles play a vital role in prolonging produce freshness by minimizing moisture loss and suppressing respiration (Ding et al., 2024). Although nanoparticles often demonstrate enhanced interaction with microbial biofilms, largely attributed to their high surface area-to-volume ratio, the strength and nature of this interaction are not uniform. They are influenced by nanoparticle characteristics such as core composition, surface chemistry, and specific surface modifications, all of which modulate their reactivity and antimicrobial potential. This surface reactivity can, in turn, facilitate more efficient contact with microbial cells, thereby enhancing antimicrobial efficacy in appropriately tailored systems.

Nanoparticles possess the ability to disrupt microbial integrity by infiltrating biofilm matrices, destabilizing cell membranes, and inducing oxidative stress. These interactions can impair enzymatic pathways and compromise cellular structure, ultimately leading to microbial inactivation (Mondal et al., 2024). In addition, the integration of nanomaterials into packaging films has been shown to suppress the activity of key pro-oxidative enzymes such as lipoxygenase (LOX) and phenylalanine ammonia-lyase (PAL), thereby reducing enzymatic browning in fruits and vegetables. At the same time, nanoparticles can enhance the activity of endogenous antioxidant systems such as catalase (CAT), ascorbic acid (AA), and glutathione reductase (GR), contributing to oxidative stress regulation and delayed senescence (Manzoor et al., 2024).

To enhance the shelf life of fruits and vegetables, the effectiveness of nanoparticles depends on factors such as application method, storage duration, and environmental conditions. Common delivery formats include edible coatings, spraying, and active nano-packaging films, all of which aim to reduce spoilage and preserve freshness (Table 3). For instance, nanoparticles such as AgNPs and ZnONPs have been incorporated into coatings and packaging materials, demonstrating notable antimicrobial and antioxidant properties that actively maintain produce quality during storage (Baraketi and Khwaldia, 2024). Their antimicrobial effects are primarily mediated through mechanisms such as the generation of ROS, disruption of microbial cell membranes, and the controlled release of metal ions, each contributing to the inhibition of spoilage and pathogenic microorganisms. However, although these nanoparticles are effective, particularly at lower concentrations, the use of AgNPs at higher doses may raise concerns regarding residual toxicity and potential environmental accumulation. This underscores the importance of optimizing nanoparticle concentrations and conducting rigorous toxicological assessments before broader agricultural or commercial deployment.

In a previous study, edible coatings developed with ZnO nanocomposites demonstrated the ability to retard banana ripening, maintain sensory qualities, and reduce fungal infections during storage by up to 1.25-fold compared to uncoated fruits (Li et al., 2019).

A comparative evaluation of green and chemically synthesized AgNPs for the storage of bell peppers revealed that green-synthesized nanoparticles performed better at inhibiting microbial growth while maintaining fruit firmness and quality without causing cytotoxic effects. This highlights the enhanced performance of bio-based nanoparticles in food preservation (Lieu et al., 2024).

The incorporation of biogenic nanoparticles into packaging films offers an even safer and more efficient method to minimize post-harvest losses. These nanocomposite materials are often engineered to function without coming into direct contact with the food surface, thereby significantly reducing the risk of nanoparticle leaching or migration into the edible portion of the product. This design approach not only enhances food safety but also ensures compliance with regulatory standards governing food-grade materials. In parallel, such films retain antimicrobial efficacy, extending shelf life and preserving product quality.

These active films improve gas barrier properties, enhance resistance to microbial spoilage, and maintain the nutritional content and visual appeal of fresh produce. For example, mint-extract-mediated ZnO/chitosan nanocomposite films were found to significantly reduce microbial infection and maintain the texture and color of strawberries and red plums during storage, offering superior protection compared to conventional materials (Alamdari et al., 2022).

Nanotechnology can minimize post-harvest losses by enabling the development of functional packaging materials with enhanced mechanical strength, controlled gas permeability, and antimicrobial activity. According to Mohammad et al. (2022), the global market for nanotechnology-enabled food packaging was valued at approximately USD 15 billion in 2020, with projections suggesting continued growth. These packaging systems often incorporate engineered nanoparticles such as silver (Ag), titanium dioxide (TiO_2), copper oxide (CuO), and magnesium oxide (MgO), which are widely studied for their antimicrobial and antifungal activity. However, referring to these materials as “natural preservatives” may be misleading as they are synthetically engineered and not automatically granted GRAS (Generally Recognized as Safe) status. As such, their use in food packaging requires careful consideration of exposure thresholds, toxicological effects, and adherence to food safety regulations established by agencies such as the FDA and EFSA.

In addition to coatings and packaging, nanotechnology can play a crucial role in the development of sensor-based approaches. These systems can detect ethylene production and other biochemical markers that indicate the quality and freshness of the produce, allowing better control over storage conditions and reducing post-harvest losses. The incorporation of nanomaterials like nanoclays into coatings has shown great promise in extending the shelf life of orange fruits by reducing water loss and maintaining nutritional quality (Ashfaq et al., 2022).

3.3 Nanobiosensors

Plants infested by insects and pests pose a major risk to agriculture worldwide, resulting in food production losses and significant economic damage. Timely identification and monitoring of plant diseases are crucial for effective management and minimizing crop losses. Conventional diagnostic methods are often time-consuming and labor-intensive and require skilled personnel, limiting their application to a small number of samples. Nanobiosensors offer a promising alternative, enabling rapid, sensitive, and specific detection of plant pathogens.

Nanobiosensors are equipped with bioreceptors such as antibodies, nucleic acids, or enzymes that are designed to bind selectively to target analytes. These devices operate with high sensitivity and are capable of detecting analytes at molecular or nanoscale resolution; however, atomic-level resolution is rarely achieved in real-world agricultural applications. Nanobiosensors have been successfully applied to detect a wide range of compounds, including glucose, urea, herbicides, pesticides, metabolites, and plant pathogens (Rai and Ingle, 2012). Their high specificity, non-invasive nature, and real-time monitoring capabilities make them valuable tools for field diagnostics (Zamora-Sequeira et al., 2019). Recent advances in nanobiotechnology have enabled the development of cost-effective, highly sensitive, and application-specific nanobiosensors tailored to different agricultural scenarios (Kalyani et al., 2021).

The quality of fruits and vegetables is impaired by infestation with harmful pathogens. In order to maintain quality and increase yields, various pesticides are used to combat infestations of pests and diseases at different doses and intervals. However, due to the toxicity of these pesticides present in food over a long period of time, they are reported to be harmful to both human health and the food sector (Zhao et al., 2015). In addition, monitoring the pathogen infestation and pesticide concentration in fruits and vegetables using a nanobiosensor can help prevent the excessive use of pesticides and effectively control the application of pesticides in horticultural crops. Therefore, the detection of pesticide residues in fruit and vegetable crops is always an important part of the analysis of hazardous elements.

The marketable quality of fruits and vegetables depends on their nutritional composition and degree of ripeness. Research has found that fruits and vegetables produce various bioactive compounds at different stages of their growth, e.g., during fruit formation, immaturity, ripening, and storage, which can be detected using nanobiosensors. The volatile substances present in plants are detected using a glucose oxidase-based nanobiosensor. In addition, the evaluation of fruit quality and shelf life depends on phytoconstituents such as fructose, benzoic acid, phenols, and maleic acid (Della Pelle and Compagnone, 2018). The diagnosis of pest infestation, pesticide residues, and nutritional quality using nanobiosensors reduces time and labor, especially for asymptomatic crops, to increase production. In addition, the food industry uses nanobiosensors to detect allergens and pathogens very quickly and ensure food safety during production and packaging. There are other difficulties in the food sector, such as ensuring the availability, safety, and protection of food and optimizing its use (Calicioglu et al., 2019). Nanobiosensors, through the integration of nanobionics and advanced sensing technologies, facilitate accurate detection of complex and meaningful plant responses across extensive agricultural landscapes. According to Butnariu and Butu (2019), nanobionics refers to the integration of biological sensing with nanoscale signal processing, often enhanced by computational models.

In the field of nanobiosensors, green biosensors show great potential for the early detection of diseases in plants. In order to precisely identify certain pathogens or disease-related changes in plants, these biosensors use plant extracts, living organisms, or their components, such as enzymes or antibodies. Compared to conventional techniques, green biosensors offer a number of advantages in the agricultural era, such as rapid detection, high sensitivity, affordability, quick action, and minimization of significant damage to crops, making them suitable for wide application in agriculture. Due to their ability to quickly and accurately identify specific pathogens, green biosensors are now considered an important tool for plant disease detection. Different types of biosensors have been developed, such as DNA biosensors, electrochemical biosensors, and optical biosensors, all of which have their own unique mechanisms and advantages. The DNA-based nanobiosensor is used to detect infection based on DNA sequences, amplification patterns with disease markers, or changes in the expression patterns of genes. Biogenic copper nanoparticles (CuNPs) demonstrated superior efficacy in inhibiting Colletotrichum capsici compared to conventional fungicides such as carbendazim and copper oxychloride, thereby contributing to reduced yield losses in chili crops (Franco et al., 2019). A biosensor is an optical type that detects disease-related changes in plants by absorbing or emitting light. Another type is the electrochemical biosensor, which detects electrical signals caused by biochemical reactions associated with plant diseases.

Researchers have developed biosensors produced by fluorescent probes with silicon dioxide to identify pathogenic infections caused by the pathogen *Xanthomonas axonopodis* in tomatoes and peppers. Witches' broom disease in lemon plants caused by *Phytoplasma aurantifolia* was diagnosed using nanobiosensors that utilize the phenomenon of fluorescence resonance energy transfer with quantum dots (Duhan et al., 2017).

Nanomaterials such as graphene and carbon nanotubes are being used by scientists in the field of biosensors to improve signal transmission and increase the detection of minute amounts of substances. Previous researchers have reported that green biosensors are being used to detect pathogens in horticultural crops such as citrus canker and tomato blight to reduce severe crop losses due to pest infestations. In addition, farmers with limited resources can benefit from green biosensors because they are easy to use and require no specialized equipment or training. Despite their benefits, green biosensors have limitations such as reduced specificity among pathogen strains. The need for continuous monitoring is another limitation as plant diseases can evolve rapidly and new variants may emerge in the future. Overall, nanobiosensors play an important role in the field of "smart agriculture" in improving their ability to detect, process, and respond to changes (Mittal et al., 2020). To make accurate decisions that lead to higher yields with less use of chemicals, precision agriculture provides a comprehensive analysis of data collected in the field or soil (Alvarado et al., 2019; Thakur et al., 2022).

Nanomaterial-based biosensors are revolutionizing agriculture and food technology, yet several constraints hinder their broader adoption. Although some high-precision biosensors incur elevated costs due to intricate fabrication processes and the use of advanced materials such as graphene, CNTs, and certain engineered nanoparticles, this is not universally the case. Increasingly, biosensor technologies are incorporating low-cost, plant-derived, or naturally abundant nanomaterials, which significantly reduce manufacturing expenses without compromising functionality. This shift toward cost-effective materials is making biosensor platforms more accessible and scalable across diverse agricultural and environmental applications (Virk et al., 2024). These sophisticated materials, critical to the enhanced performance of nanobiosensors, substantially escalate production expenses, thereby restricting their widespread commercialization and accessibility. Another key risk associated with nanobiosensors arises from their intrinsic nanoscale characteristics, including exceptional surface area-to-volume ratio, precise structural morphology, and heightened stability (Prasad et al., 2017). Furthermore, another risk associated with nanobiosensors is variation in stability and reproducibility due to the development of nanobiosensors from nanoparticles, which can have inherent variability in their size, shape, surface charge, and surface functionalization. These factors can significantly influence the sensor's performance. Even slight differences in the synthesis process of nanoparticles can lead to inconsistent results, affecting the sensor's reliability, sensitivity, and reproducibility across different batches or over time. This variability is a major concern when scaling up production for widespread use, particularly in applications that demand high precision and consistency, such as environmental monitoring. The lack of uniformity in the properties of nanoparticles, such as surface chemistry or aggregation behavior, can result in fluctuations in the sensor's output, thus compromising its accuracy and reliability in real-world scenarios. Although these properties enhance their sensitivity and functionality, their interaction with biological and environmental systems raises concerns regarding nanotoxicity, bioaccumulation, and potential ecological imbalances. Advancing nanobiosensors from prototype development to commercial deployment presents significant challenges, primarily due to the necessity of comprehensive field-scale trials to rigorously assess their effectiveness in real-world applications (Thakur et al., 2022). These large-scale evaluations are critical for ensuring accuracy, reliability, and practical applicability across different industries. Furthermore, enhancing end-user awareness is crucial as successful adoption relies on informing stakeholders, addressing potential concerns, and demonstrating the superiority of nanobiosensors over conventional technologies. The analysis and transmission of data generated by nanobiosensors present a formidable challenge, necessitating highly sophisticated and complex computational processing. These systems require advanced signal processing algorithms to ensure precise interpretation and real-time data analysis. Furthermore, seamless integration with wireless communication technologies is imperative for efficient data sharing, remote accessibility, and real-time monitoring, thereby enhancing their practical applicability across diverse fields.

The development of green biosensors to detect plant diseases has enormous potential to transform agricultural practices. As scientists continue to develop this technology, numerous future possibilities are conceivable. First, the sensitivity and specificity of these biosensors must be increased to accurately identify a range of plant pathogens. In addition, there should be a focus on miniaturizing these devices so that they can be easily integrated into current agricultural systems. It would be easier to make immediate decisions about disease management if wireless communication capabilities were added as they would allow data to be monitored and analyzed in real time.

3.4 Nanofungicides/nanopesticides

Plant diseases and pest infestations are key challenges that have caused major financial losses in agricultural production worldwide in recent years. According to Flood 2010, plant pests and diseases

TABLE 4 Application of plant-extract-derived nano-formulated pesticides and their efficacy in enhancing crop protection through disease suppression in fruits and vegetables.

Target organism	Infested crop	Plant used for NP synthesis	Plant part used	Type of NP	Efficacy of NP	Reference
Anthracnose	Dendrobium sp. (orchid)	*Musa sapientum* (banana)	Peel extract	Zinc oxide nanoparticles (ZnONPs)	On Dendrobium orchid, Colletotrichum infection was controlled by the supplementation of nano zinc	T-Thienprasert et al. (2021)
Soft rot	*Brassica chinensis* (Chinese cabbage)	*Mahonia fortunei* (Chinese Mahonia)	----	Silver nanoparticles (AgNPs)	Supplementation of nano silver at a rate of 8 μg mL^{-1} provides protection to Chinese cabbage against *P. carotovorum* infection by decreasing colony formation	Wei et al. (2022)
Early blight	*Lycopersicum esculentum* (tomato)	*Azadirachta indica* (neem)	Leaf	Silver nanoparticles (AgNPs)	Silver nanoparticles (AgNPs) act as defensive agents against early blight in tomatoes, reducing disease incidence, enhancing growth and yield, and increasing the activity of defensive enzymes and bioactive compound biosynthesis	Ansari et al. (2023)
Malformation	*Mangifera indica* (mango)	*Melia azedarach* (Chinaberry)	Leaf	Selenium nanoparticles (SeNPs)	Selenium nanoparticles (SeNPs) at 300 μg/mL show the highest antifungal activity against mango malformation, creating a 14 mm inhibition zone, surpassing the efficacy of the standard antifungal drug arresten	Shahbaz et al. (2023)
Root knot Nematode	*Lycopersicum esculentum* (tomato)	Compost tea (rice (*Oryza sativa*)+ ground fertilizer)	Rice Straw	Iron oxide nanoparticles (FeONPs) and biochar nanoparticles	Iron oxide (FeONPs) and biochar nanoparticles reduce nematode infection in tomatoes by decreasing egg mass and root gall formation in the soil	Mohammad et al. (2022)
Fusarium Root rot	*Lycopersicum esculentum* (Tomato)	*Ziziphus spina* (Christ's thorn jujube)	Leaf	Copper oxide nanoparticles (CuONPs)	Copper oxide nanoparticles (CuONPs) at 250 mg/L are more effective than Trichoderma biocide and commercial fungicides in reducing root rot incidence and severity in tomatoes, achieving values of 9.17% and 4.17%, respectively	El-Abeid et al. (2024)

destroy 20%–40% of harvests worldwide every year. In modern agriculture, pesticides such as insecticides and fungicides are used to protect the harvest from pest infestation and increase crop yields (Kumar et al., 2019). Conventional chemical methods used globally for insect pest control often suffer from poor solubility and low efficiency. These chemicals tend to persist in the environment, accumulate through the food chain (biomagnification), and pose serious health risks to both humans and animals, potentially leading to numerous diseases (Savary et al., 2019). Apart from this, the decrease in pollinator populations, the facilitation of food adulteration, and the increase in antibiotic resistance are the main negative consequences (Annamalai and Namasivayam, 2015; Pilet-Nayel et al., 2017). Controlling pathogens that infect plants and cause yield losses is becoming increasingly difficult as the number of AMR cases with multiple causes increases and restrictions on harmful agrochemicals become more stringent (Kim et al., 2024). This has led scientists to seek new and innovative strategies that must, therefore, be developed to counter the infestation of insect pests to limit the financial damage and reduce food waste. These efforts are essential given the increasing discrepancy between the supply of food and global demand.

Compared to conventional pesticides, plant-extract-based nanopesticides have shown promise in enhancing efficiency and environmental compatibility, primarily due to the presence of bioactive compounds that confer pest and disease resistance. Their advantages, such as strong adsorption capacity, nanoscale size, high stability, and controlled release, can improve performance and reduce environmental impact. However, claims of superior efficiency and cost-effectiveness must be contextualized as these outcomes depend significantly on factors such as the synthesis method, formulation properties, application rate, and crop–pathogen interactions. Therefore, performance assessments should be tailored to specific agricultural systems (Table 4). By contributing to the targeted distribution of pesticides, nanoformulated pesticides can increase the efficiency of pesticides (Rana et al., 2024). Nanopesticides are typically categorized into two principal types: (1) metal-based formulations, such as copper nanoparticles, nanoclay, zein nanoparticles, and nanosilver; and (2) encapsulated insecticides, which are engineered for controlled release, enhanced stability, and improved efficacy. In addition, various metal oxide nanoparticles such as ZnO, TiO_2, and CuO act as nanocarriers (El-Ramady et al., 2024). Recently, plants have been protected from UV radiation and thunderstorms using polyethylene-mediated nano-based stretch films (Rajput et al., 2021). Although reports suggest that approximately 49 nano-enabled crop protection products have been developed by 12 countries, this figure should be interpreted cautiously unless substantiated by authoritative databases such as those maintained by FAO or OECD. In addition, to protect an active ingredient from

TABLE 5 Representative list of phyto-nanofertilizers synthesized from various plant parts and their effects on growth, biochemical attributes, and nutritional quality of fruits and vegetables.

Plant species used for the synthesis of different types of NPs	Plant part used	Type of nanoparticles	NP concentration	Studied plant spp.	Plant performance by the application of NPs	Reference
Cinnamomum zeylanicum (cinnamon)	Bark extract	Sulfur nanoparticles	0.01, 0.1, 1, and 10 mg/mL	*Lactuca sativa* (lettuce)	Among the different concentrations of sulfur nanoparticles, 1 mg/mL concentration of SNPs on lettuce plants show the best performance in terms of enhancing growth and improving nutritional composition	Najafi et al. (2020)
Punica granatum (pomegranate) and *Coffea* sp. (coffee)	Peel extract Seed extract	Phosphorous-containing hydroxyapatite nanoparticles (nHAP)	50, 100, 500, and 1000 mg/L	*Punica granatum* (pomegranate)	Supplementation of phosphorous-containing hydroxyapatite nanoparticles enhances the biosynthesis of carbohydrate and metabolic agents due to good photosynthetic performance	Abdelmigid et al. (2022)
Citrus sinensis (orange)	*Peel*	Copper oxide nanoparticles (CuONPs)	0.5, 1.0, 2.0, 4, and 6 mg mL^{-1}	*Lactuca sativa* (lettuce)	In orange plants, CuONP application improves nutritional status by improving the content of ascorbic acid (vitamin C), copper, and flavonoids of lettuce leaves due to the enhancement of the biosynthesis of photosynthetic pigment chlorophyll by approximately 135%	Gaucin-Delgado et al. (2022)
Vaccinium floribundum (Andean Blueberry)		Zinc oxide nanoparticles (ZnONPs) Iron oxide nanoparticles (FeONPs) Magnesium oxide nanoparticles (MgONPs)	270 and 540 ppm	*Brassica oleracea* var. *capitate* (cabbage) and *Lupinus mutabilis* (lupin)	Application of iron and zinc NPs at a rate of 270 ppm enhances plant height by up to 6% and chlorophyll content by 3.5% in lupin plants Application of 270 ppm concentration of MnO and FeO NPs enhances chlorophyll content, leaf area, and root length of cabbage by 7.1%, 25.6%, and 10.3% in contrast to untreated plants	Murgueitio-Herrera et al. (2022)
Mentha spp. (mint)	Leaf	Zinc oxide nanoparticles (ZnONPs)	5, 15, and 25 mg/L	*Brassica napus* (rapeseed)	Increases plant biomass, accumulation of chlorophyll, and carotenoid content and alters the expression of proteins related to stress response and glycolysis and photosynthesis of *Brassica napus* L	Sohail Sawati et al. (2022)
Spinacia oleracea (spinach)	Leaf	Iron oxide nanoparticles (FeONPs)	50 and 100 mg/L	*Rosmarinus officinalis* (rosemary)	Under the condition of drought stress, iron oxide nanoparticles act as stress defensing agents in rosemary plants, and highest compositions of sugars and other metabolic compounds, viz., camphene, 8-cineol, anthocyanin, and α-terpinene were recorded compared to plants without the application of FeONPs	(Afrouz et al., 2023)
Emblica officinalis (aonla)	Fruit	Iron oxide nanoparticles (FeONPs)	10, 50, and 100 mg/L	*Lycopersicum esculentum* (tomato)	Under oxidative stress, compared to the conventional fertilizer $FeSO_4$, iron NPs more efficiently enhance the growth	Singh et al. (2024b)

(Continued on following page)

TABLE 5 (*Continued*) Representative list of phyto-nanofertilizers synthesized from various plant parts and their effects on growth, biochemical attributes, and nutritional quality of fruits and vegetables.

Plant species used for the synthesis of different types of NPs	Plant part used	Type of nanoparticles	NP concentration	Studied plant spp.	Plant performance by the application of NPs	Reference
					of tomato plants and improve photosynthetic performance by increasing the activity of antioxidant enzymes, superoxide dismutase, and nitrate reductase activity	

degradation in the environment due to heat and UV radiation, nanocarriers can improve the chemical stability and water dispersibility of pesticides and, thus, increase their effectiveness (Athanassiou et al., 2018; Yin et al., 2023). Due to these advantages, scientists have developed a variety of nanocarriers with functional groups that are biocompatible. Through their active uptake by the cell, these carriers not only allow pesticides to be reduced to nano-size and provide protection, but they also facilitate and accelerate the transport of pesticides to certain crops and pests. For this reason, nanoparticles have a high antimicrobial activity through interactions with the surfaces of microorganisms.

The ability of biogenic nanoparticles to inhibit microbial activity of nanoparticles depends on the type of nanoparticles, concentration, functional group present in the plant, exposure time, type of pathogen, and resistance of spp. against disease. Among these factors, nanoparticle concentration plays a major role in inhibiting the activity of microorganisms. Previous studies reported that the highest percentage of inhibition against plants infected with diseases was recorded by the application of the highest dose of nanoparticles. Shahbaz et al. (2023) provided compelling evidence for this phenomenon by experimentally evaluating the antifungal efficacy of biogenic selenium nanoparticles (SeNPs) at five concentrations—150, 200, 250, 500, and 1000 ppm—administered both pre- and post-pathogen inoculation. Biogenic copper nanoparticles (CuNPs) demonstrated superior efficacy in inhibiting Colletotrichum capsici compared to conventional fungicides such as carbendazim and copper oxychloride, thereby contributing to reduced yield losses in chili crops (Iliger et al., 2021). In addition to these findings, application of mint-extract-synthesized copper nanoparticles (CuNPs) at 500 and 1000 ppm prior to inoculation with Colletotrichum capsici resulted in complete disease suppression, as reflected by reduced lesion size and number, along with a prolonged incubation period. Apart from these findings, *C. capsici* treated with CuNPs prepared from the mint extract, applied before inoculation at concentrations of 500 and 1000 ppm, resulted in complete disease inhibition, as indicated by lesion size, lesion number, and incubation period.

To enhance nanoparticle efficiency, researchers have increasingly focused on synthesizing nanocomposites by combining two or more types of nanoparticles. Previous studies have reported that such nanocomposites exhibit superior antimicrobial efficacy compared to individual nanoparticles (Begum and Jayawardana, 2023). For instance, citrus black rot, a major disease caused by *Alternaria citri*, can result in yield losses of up to 30%–35%. To counter this, ZnO, CuO, and CuZn hybrid nanoparticles were synthesized using the citrus peel extract and applied at concentrations ranging from 10 to 100 mg mL^{-1}. The antifungal efficacy of these treatments was evaluated using an *in vitro* agar well diffusion assay, in which zones of inhibition were measured in millimeters to assess pathogen suppression. The hybrid CuZn nanocomposite exhibited the highest fungicidal activity, producing a 53 mm zone of inhibition, compared to 51.5 mm and 50 mm for ZnONPs and CuONPs, respectively. Despite these promising findings, there is a paucity of research exploring the effects of biogenic hybrid nanoparticles on disease resistance in horticultural crops, particularly with regard to environmental safety.

Although nanopesticides represent a cutting-edge approach for improving pathogen control and reducing the overuse of conventional agrochemicals, their misapplication or accumulation in the environment poses significant ecological and toxicological concerns. Improper formulation or excessive exposure may lead to unintended interactions with key biological systems, potentially impairing pollination processes, disrupting soil nutrient cycling, and altering microbial equilibrium. Owing to their unique physicochemical properties, such as high surface area-to-volume ratio, enhanced reactivity, and improved mobility, nanoparticles can influence ecological stability and raise safety concerns for both environmental and human health. Although nanoparticles possess the capacity to penetrate biological tissues through inhalation, dermal absorption, or ingestion, the extent of cellular uptake and resulting toxicity is highly dependent on factors including particle size, surface charge, functionalization, concentration, and duration of exposure. At elevated doses or with chronic exposure, certain engineered nanoparticles have been reported to interfere with physiological functions and ecological interactions, adversely affecting non-target organisms such as pollinators (e.g., *Apis mellifera*), soil invertebrates (e.g., *Eisenia fetida*), and beneficial microbial communities—ultimately contributing to biodiversity loss and compromised ecosystem services. Their persistence and potential for bioaccumulation also allow for translocation into soil and aquatic systems, raising concerns over ecological contamination. In addition to bioaccumulation, emerging studies highlight associated risks such as phytotoxicity, soil leaching, and shifts in microbial population dynamics, which warrant further investigation (Thakur et al., 2022). In human systems, chronic ingestion of nanoparticles via contaminated food or water has been linked to cytotoxic outcomes including oxidative stress, hepatotoxicity, nephrotoxicity, and inflammatory responses, underscoring the need for comprehensive risk assessments and regulatory oversight.

To mitigate these risks, researchers must focus on developing biodegradable and eco-friendly nanopesticide formulations that degrade safely without accumulating in the environment. Comprehensive risk assessments and the establishment of robust regulatory frameworks are essential before large-scale deployment. Controlled-release technologies and nano-encapsulation methods offer promising solutions to reduce unintentional environmental exposure and enhance application precision. Equally important is the training of agricultural workers and farmers in the safe handling, application, and disposal of nanopesticides. Collaboration among researchers, policymakers, and industry stakeholders is critical to standardize safety protocols and promote responsible nanopesticide usage.

Concurrently, nanobiosensors—particularly those incorporating DNA-based and CRISPR-Cas systems—have demonstrated high specificity in detecting pesticide residues and identifying plant pathogens. However, the efficacy of these biosensors depends on factors such as sensor design, calibration standards, and environmental conditions. Although certain biosensor types may lack the precision to differentiate between closely related pathogens, advanced molecular-based sensors offer enhanced selectivity and sensitivity when appropriately optimized. Mathematical modeling contributes to biosensor optimization by simulating signal-transduction mechanisms and refining sensor responses. Nevertheless, the field-scale application of nanobionic systems for real-time phytohormone monitoring remains at a developmental stage and requires further empirical validation. By integrating advanced nanotechnologies with regulatory oversight, public awareness initiatives, and sustainable agricultural practices, it is possible to balance innovation with environmental and human safety.

3.5 Nanotechnology to enhance yield and nutritional quality

3.5.1 Nanofertilizers for yield and quality

The development of agriculture coincided with human evolution. Traditional farming methods in conventional agriculture require frequent use of fertilizers to promote plant growth and improve nutrient quality (Nongbet et al., 2022). Since the beginning of the Green Revolution, chemical fertilizers have played a pivotal role in boosting agricultural productivity. However, their long-term use has resulted in adverse environmental consequences such as soil contamination, greenhouse gas emissions, and water pollution (Shang et al., 2019). Due to processes like mineralization and leaching, a substantial portion of applied fertilizers remains unused, accumulating in soil and water bodies. With increasing demand for food and growing awareness of the risks associated with synthetic inputs, there is an urgent need for smart, eco-friendly fertilizers that are both efficient and less toxic (Verma et al., 2019).

Nanotechnology could pave the way for sustainable agriculture. By manipulating particles at the nanoscale and coating or encapsulating them to form "smart fertilizers," nutrients can be released gradually, improving nutrient use efficiency. For example, green-synthesized zinc oxide nanoparticles enhance nutrient bioavailability, resulting in improved chlorophyll production, plant growth, and overall crop yield (Singh et al., 2019). These nanoformulations reduce nutrient leaching and volatilization, thereby maintaining soil fertility and minimizing environmental degradation (Rautela et al., 2021). Nanofertilizers, with their high surface area-to-volume ratio and enhanced penetrability, outperform conventional fertilizers by improving nutrient uptake, stimulating photosynthesis, and restoring soil health (Wang et al., 2021; Tyagi et al., 2022).

Nanoparticles have been shown to enhance photosynthetic efficiency and crop yield via improved chlorophyll content and nutrient absorption (Table 5). For instance, the foliar application of zinc nanoparticles in garden peas significantly increased biomass and productivity. Likewise, iron oxide nanoparticles applied to *Brassica oleracea* under cadmium stress not only mitigated toxicity but also improved yield and nutrient density by increasing chlorophyll content by up to 40% (Francis et al., 2024). However, the utility of some nanomaterials, such as gold nanorods, cerium oxide, and quantum dots, remains limited due to high cost, toxicity, or regulatory concerns. Their deployment should, thus, be considered within specific experimental or high-value horticultural contexts.

3.5.2 Role in abiotic stress tolerance

Moreover, nanomaterials not only improve nutrient utilization under optimal conditions but also hold tremendous potential to alleviate environmental stresses. Emerging research highlights their capacity to influence biochemical, hormonal, and genetic pathways, enhancing plant resilience under extreme abiotic conditions.

Abiotic stresses such as drought, salinity, and heavy metal toxicity—adversely impact plant growth, development, and nutritional quality (Figure 3). Nanoparticles, owing to their small size and high reactivity, can activate various stress-response mechanisms in plants (Figures 4, 5). These include the upregulation of stress-responsive genes, modulation of phytohormone signaling, and stimulation of antioxidant enzyme activity (Saini et al., 2021). For example, spearmint-coated iron oxide nanoparticles applied to rosemary enhanced the activity of antioxidant enzymes, improving drought tolerance and promoting the synthesis of stress-related metabolites like phenols, anthocyanins, and camphene (Al-Khayri et al., 2023).

Soil salinity induces both osmotic and ionic stress, which impairs water uptake and causes ion toxicity. Nanoparticles help counter these effects by modulating ion transport, improving antioxidant defense, and enhancing osmolyte accumulation. In one study, sulfur nanoparticles increased salt tolerance in field beans by upregulating genes such as *ribulose bisphosphate carboxylase large chain-like (RbcL)*, *ethylene-responsive transcription factor 1 (ERF1)*, *chlorophyll a-b binding protein of LHCII type 1-like (Lhcb1)*, *and cell wall invertase I (CWINV1)*, while also boosting levels of glycine betaine, proline, and peroxidase enzymes (Khalifa et al., 2024). Similarly, biogenic silicon nanoparticles reduced cadmium uptake and improved photosynthetic pigment biosynthesis, leading to enhanced growth and lower toxicity in melon plants (Malik et al., 2025).

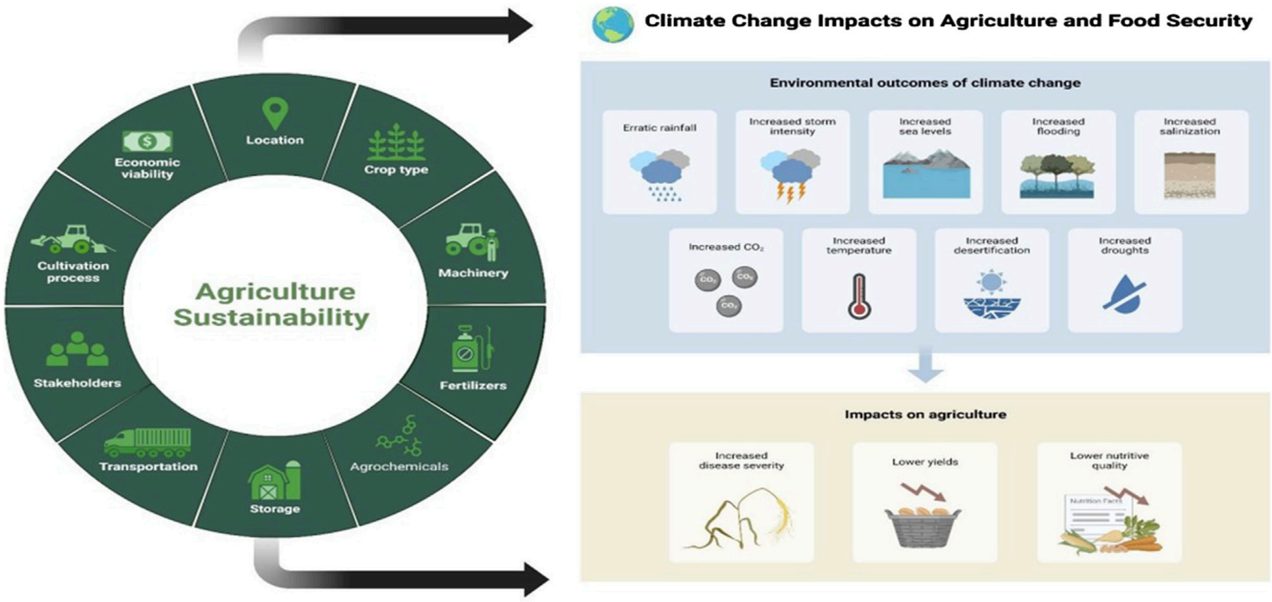


FIGURE 3
Sustainable agriculture and the impact of climate change on food security and quality through reduced crop yield and increased insect pest infestation. Source: Ghazaryan et al. (2024).

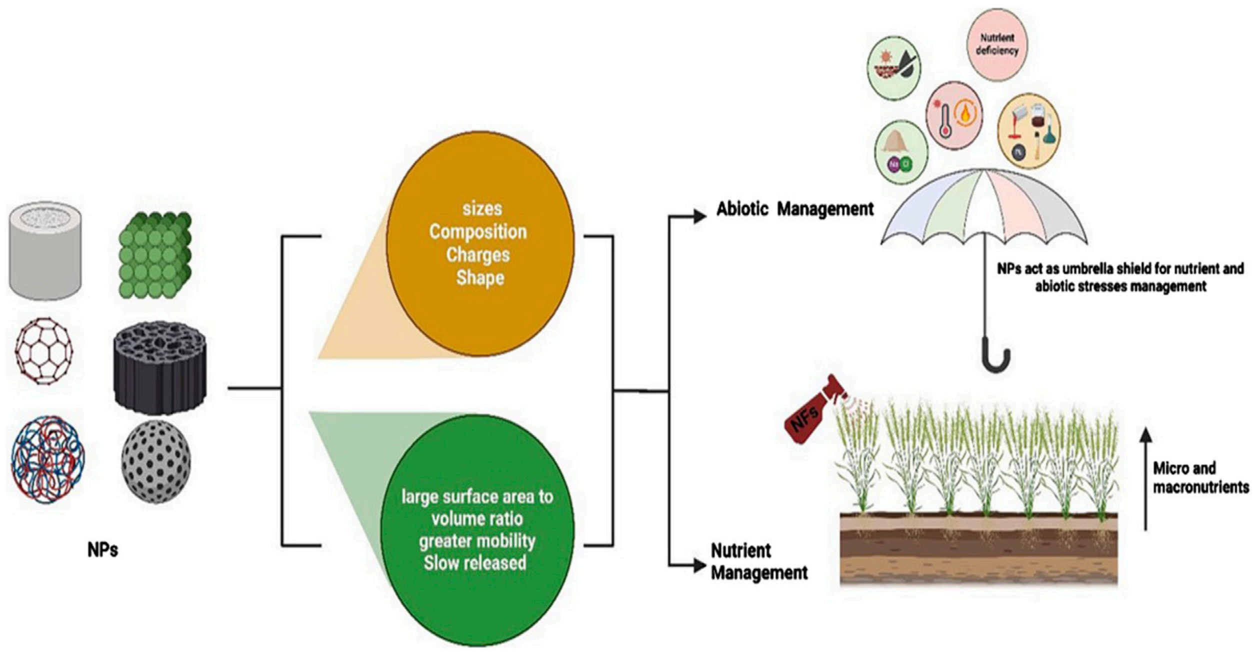


FIGURE 4
Application and characteristics for abiotic stress management and nutrient optimization in agriculture. NPs are nanoscale fertilizers with small and unique sizes, shape charges, composition, high reactivity, solubility, and controlled-release properties. They can mitigate drought, salinity, and temperature stress by directly delivering nutrients and bioactive compounds to plants. NPs also optimize nutrient utilization, protect against environmental losses, and enhance crop yield and quality. Source: Singh A. et al. (2024).

3.5.3 Nanotechnology and sustainable agriculture

Beyond yield and stress tolerance, nanotechnology contributes to sustainability goals by improving resource efficiency and minimizing environmental footprints. It supports the three pillars of sustainability: (i) environmental—through responsible resource management and reduced agrochemical dependency; (ii) economic—by increasing productivity per unit input; and (iii) social—by improving the quality of horticultural produce and

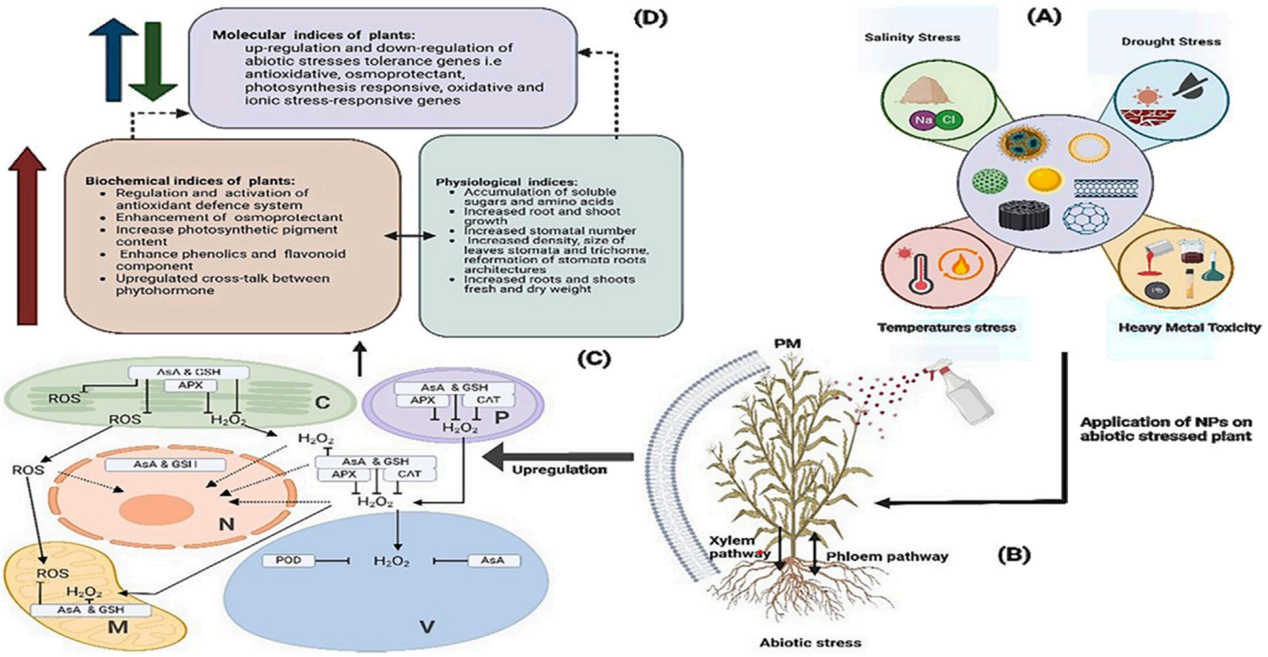


FIGURE 5
Effect of NPs on plant salinity stress. **(A)** Various types of abiotic stresses; **(B)** application of NFs/NPs on plants under abiotic stresses; **(C)** NFs/NPs upregulated antioxidant-responsive pathways; and **(D)** NPs mitigated abiotic stresses at physiochemical and molecular levels in plants. Possible signaling pathways: dotted arrows. AsA, ascorbate; APX, ascorbate peroxidase; C, chloroplast; CAT, catalase; GSH, glutathione; M, mitochondria; N, nucleus; P, peroxisome; POD, guaiacol-type peroxidase; V, vacuole. Source: Singh A. et al. (2024).

supporting rural livelihoods (El-Ramady et al., 2024). For instance, in regions affected by desertification, nano-clay-based fertilizers have been used to retain soil moisture and reduce water use by over 30%, showcasing nanotechnology's alignment with ecological resilience and climate adaptation.

However, these benefits are not universally realized and often depend on local regulations, socioeconomic conditions, and regional infrastructure.

3.5.4 Limitations and future directions

Although nanotechnology holds transformative potential, several challenges remain.

- Long-term field studies are needed to assess environmental safety, persistence, and efficacy under diverse conditions.
- Optimization of nanoparticle dose and delivery methods is essential to avoid phytotoxic effects.
- Regulatory oversight and clear guidelines are urgently required to ensure the responsible development and usage of nanotechnologies in agriculture.
- Socioeconomic feasibility and farmer acceptance must be addressed through participatory research and education programs.

Global initiatives such as the European Union's REACH (Registration, Evaluation, Authorisation, and Restriction of Chemicals) framework and India's National Nanotechnology Mission highlight the growing regulatory momentum. However, harmonized international guidelines and region-specific safety assessments remain a critical future need.

3.6 Role of nanotechnology in genetic engineering

Climate change poses a global challenge, leading to reduced crop yields and quality, thereby affecting the ability to meet food needs (Shaheen and Abed, 2018). With a projected population of 9.6 billion people by 2050, the demand for food will increase by 400 million metric tons (MT). Conventional breeding methods to increase crop yields are labor-intensive, costly, and time-consuming, often failing to achieve desired traits that are not naturally present in the gene pool. To overcome these limitations, the scientific community has turned to biotechnological approaches such as gene transformation. CRISPR/Cas9 has emerged as the preferred method for site-specific mutagenesis (Kumari et al., 2021). However, current delivery methods and regeneration protocols for genetic engineering are species-dependent and suffer from low throughput, hindering progress in plant biotechnology. Nanotechnology presents a promising avenue for enhancing gene delivery and regeneration processes in plants. Recent studies suggest that nanocarriers may enable the delivery of genetic material directly into reproductive tissues, potentially reducing the need for conventional regeneration steps. However, this strategy, particularly the direct modification of the germline, is still highly experimental. It represents a promising but emerging approach under active investigation, and its efficiency, reproducibility, and safety require further validation across a broad range of plant species (Squire et al., 2023).

3.6.1 Nanoparticles for DNA/RNA delivery in genetic engineering

The future developments of biogenic nanoparticles as delivery vehicles may revolutionize the field of genetic engineering. These nanoparticles not only enhance the stability and uptake of genetic materials but also minimize the damage associated with traditional methods of gene delivery, such as electroporation or viral vectors. For example, carbon nanotubes and mesoporous silica nanoparticles have been successfully used to deliver CRISPR/Cas9 components to plant cells, enabling high-efficiency gene editing with minimal off-target effects (Demirer et al., 2021). In genome editing approaches, the delivery of guide RNA and Cas9 protein is often inefficient and costly with existing technology (Duan et al., 2021). The use of nanoparticles as delivery vehicles solves these problems by improving the efficacy of genome editing while minimizing cell damage due to their small size. Nanoparticles such as lipid-based and polymeric nanoparticles have shown potential to improve the precision and delivery efficiency of gene-editing tools.

In addition to the aforementioned systems, AuNPs have garnered considerable attention due to their exceptional surface functionalization versatility, chemical inertness, and biocompatibility, which collectively facilitate efficient conjugation with nucleic acids and targeted intracellular delivery across both animal and plant models. Iron oxide nanoparticles, endowed with superparamagnetic properties, have been effectively utilized in magnetofection-based gene delivery, allowing spatially controlled transfection with improved localization and reduced systemic dispersion. Quantum dots (QDs), renowned for their tunable fluorescence and photostability, are not only employed for real-time tracking of gene delivery pathways but are also emerging as dual-function platforms for both bioimaging and nucleic acid delivery. Moreover, hybrid nanoparticles, engineered by integrating organic and inorganic constituents—such as silica-coated AuNPs or lipid-encapsulated magnetic nanoparticles—represent a novel class of multifunctional vectors offering synergistic advantages. These include enhanced colloidal stability, targeted and stimuli-responsive release, and the capability for simultaneous theranostic applications in gene engineering and molecular diagnostics.

3.6.2 CRISPR and RNAi facilitation via nanocarriers

In CRISPR-based gene editing, efficient delivery of guide RNA and Cas9 protein is a major challenge. Biogenic nanoparticles, synthesized using plant metabolites, provide a non-toxic and eco-friendly alternative to chemically synthesized nanoparticles, reducing the risk of phytotoxicity or unwanted DNA damage. This is particularly relevant for agricultural applications, where safety and environmental sustainability of paramount importance (Yang et al., 2022; Zhang et al., 2022). Different types of nanoparticles, including carbon-based, polymeric, mesoporous silica, lipid-based, carbon nanotubes, and inorganic nanoparticles, have shown positive results in genetic engineering in various plant species (Vats et al., 2022).

Nanoparticles offer a non-invasive delivery platform, non-invasive in the sense that they can bypass tissue culture or transformation methods involving physical force (e.g., biolistics) or pathogenic vectors (e.g., *Agrobacterium*), making them particularly advantageous in plant systems. This unique ability enables efficient cellular penetration, making nanoparticles highly effective vehicles for the delivery of RNA and DNA in modern gene-editing approaches, including CRISPR-based systems.

3.6.3 Spray-induced gene silencing as a non-GMO alternative

In addition, a new invention has emerged in the form of nanopesticides that utilize spray-induced gene silencing (SIGS). This approach protects host plants from microbial infection by delivering single-stranded RNA (ssRNA) or double-stranded RNA (dsRNA) molecules with nanoclays as carriers through foliar sprays. Importantly, this non-transgenic method is favored by consumers, especially in developing countries (Ghosh et al., 2023). Spray-induced gene silencing, in combination with nanoparticle delivery systems, opens a new frontier for crop protection without the need for genetic modification, addressing consumer concerns regarding GMOs while still providing enhanced resistance to pests and diseases (Chen A. et al., 2023; Ghosh et al., 2023).

Although SIGS is technically a non-GMO strategy, its classification under current regulatory frameworks remains under active debate in several regions. For example, the European Union has yet to establish a definitive regulatory stance on RNA-based technologies, including SIGS, which may influence future approval and adoption. This non-transgenic approach remains especially appealing in regions where GMO skepticism persists.

3.6.4 Biogenic nanoparticles: eco-friendly tools for gene delivery

In the field of genetic engineering, the use of biogenic nanoparticles opens up new possibilities for researchers to enhance crop yield, nutritional value, and climate adaptability, thereby ensuring the availability of high-quality food to feed the world's population. These nanoparticles can be used to directly modify plant genomes with high precision, accelerating the development of climate-resilient and nutrient-enhanced crops. While chemically synthesized nanoparticles have disadvantages such as phytotoxic effects and DNA damage, biogenic nanoparticles offer a promising alternative to overcome these limitations and advance efforts in the field of plant genetic engineering. By combining the precision of CRISPR technology with the biocompatibility of plant-derived nanoparticles, researchers can create safer and more efficient genetic modifications, enabling precise, scalable, and safer genetic interventions for sustainable agriculture (Mujtaba et al., 2021).

4 Conclusion

Green synthesis of nanoparticles using plant metabolites represents an environmentally friendly and sustainable approach with immense potential for horticulture. These biogenic nanoparticles address key challenges such as nutrient deficiencies, pest control, and post-harvest losses while contributing to sustainable agricultural practices. Their integration into fertilizers, pesticides, coatings, and packaging not only enhances crop productivity and quality but also ensures minimal environmental impact. Emerging applications, including nano-enabled genetic engineering tools, open new avenues for improving crop resilience to stress. However, further research is necessary to optimize the production scalability, standardization, and long-term safety of these materials. Advancing this field promises transformative contributions to achieving sustainable food systems and addressing global challenges in agriculture.

5 Future perspectives

The potential of biogenic nanoparticles in horticultural science remains largely untapped. Future research should focus on enhancing the scalability and reproducibility of green synthesis methods to meet industrial demands. Developing standardized protocols for nanoparticle synthesis and application is critical to ensure consistency in size, stability, and efficacy across diverse agricultural environments. Advancements in nanotechnology-driven tools, such as biosensors and genetic engineering platforms, hold promise for early pathogen detection and precise crop trait improvement. The effective advancement of BNP-based products hinges on collaborative efforts between academic institutions and industry. These partnerships are essential to overcoming challenges associated with large-scale production, the transfer of knowledge, the development of infrastructure, cost-effective manufacturing, market access, and overall economic viability. In addition to addressing any threats to the public and environmental health, policymakers must make sure regulatory frameworks promote responsible innovation and sustainable uses. Public–private partnerships, international cooperation, and joint funding programs could accelerate development by supporting translational research, facilitating pilot-scale testing, and offering financial support. Moreover, multidisciplinary collaborations integrating nanotechnology with bioinformatics, material science, and plant physiology could revolutionize sustainable agriculture. Long-term field studies are essential to assess the environmental and ecological impact of biogenic nanoparticles to ensure safety and compliance with regulatory standards. Expanding research into underutilized plants for nanoparticle synthesis may also uncover novel metabolites with superior stabilization properties. By addressing these challenges, the integration of biogenic nanoparticles into horticulture will not only enhance productivity but also contribute to global food security and sustainability goals.

Author contributions

KL: conceptualization, visualization, and writing – original draft. RH: conceptualization, visualization, and writing – review and editing. EM: writing – review and editing, conceptualization, and supervision. GM: supervision and writing – review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declare that no Generative AI was used in the creation of this manuscript.

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