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Nano-Green revolution: Harnessing phytoengineered nanoparticles for sustainable tomato production

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Article Info

Abstract

Nanotechnology is revolutionizing modern agriculture, offering innovative solutions to enhance crop productivity while promoting sustainability. Among various crops, tomato (*Solanum lycopersicum* L.) has emerged as a model system for studying nanotechnological interventions due to its global economic and nutritional importance. However, tomato cultivation faces significant challenges from both biotic stressorsincluding fungal, bacterial, and viral pathogensand abiotic factors such as drought, salinity, and temperature extremes. Conventional agrochemicals, though effective, often pose environmental and health concerns due to their non-biodegradable nature and off-target effects. As a response to these limitations, the development of green nanotechnology particularly the use of phytoengineered nanoparticles (phyto-NPs) is gaining momentum. Phyto-NPs are synthesized using plant extracts that serve as natural reducing and stabilizing agents. This eco-friendly approach avoids the use of toxic chemicals typically associated with physical and chemical synthesis methods, making it more sustainable and compatible with agricultural applications. These nanoparticles not only inherit beneficial properties from the plant phytochemicals involved in their synthesis but also exhibit enhanced biocompatibility, stability, and multifunctionality. Their small size and large surface area allow for efficient uptake by plants and targeted delivery of active ingredients, leading to improved disease management, stress tolerance, and nutrient use efficiency. In tomato crop management, phyto-NPs have demonstrated promising results in enhancing plant growth, suppressing pathogen infections, and alleviating environmental stress through mechanisms such as defence induction, antioxidant modulation, and improved metabolic activity. Despite these advantages, challenges related to scalability, standardization, long-term safety, and regulatory oversight remain barriers to widespread adoption.This review aims to provide a comprehensive overview of phytoengineered nanoparticles in tomato cultivation, covering synthesis techniques, key phytochemicals involved, modes of action at physiological and molecular levels, and practical applications. It also discusses the limitations and future directions necessary for integrating phyto-NPs into mainstream agricultural practices. By bridging current knowledge gaps, this review highlights the potential of plant-based nanotechnology as a sustainable tool for next-generation horticultural innovation.

1. Introduction

Nanotechnology has emerged as a transformative force across multiple scientific fields, and its integration into agriculture represents a significant leap toward sustainable and precision-based crop management. With increasing global demands for food and the need to minimize environmental impact, traditional agricultural practices are facing mounting pressure to innovate. Nanotechnology offers a suite of promising tools for enhancing productivity, improving nutrient use efficiency, and mitigating both biotic and abiotic stressors in crops (Saleem *et al*., 2024; Abdelsalam *et al*., 2023). In agricultural applications, nanomaterials typically sized between 1 and 100 nanometers are being increasingly deployed as next-generation agro-inputs such as nano-fertilizers, nano-pesticides, nano-herbicides, and smart delivery systems (Freitas *et al*., 2021). These materials possess unique physicochemical properties due to their high surface area and reactivity, enabling them to interact with plant systems more effectively than conventional inputs. Their small size allows for efficient penetration into plant tissues, targeted delivery of bioactive compounds, and controlled release mechanisms that reduce wastage and environmental contamination (Verma *et al*., 2021; Wang *et al*., 2024). Among the various crops grown globally, tomato (*Solanum lycopersicum* L.) has been widely adopted as a model

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horticultural species for studying the effects and applications of nanotechnology in agriculture. Tomato is not only of high economic importance but also contributes significantly to nutritional security worldwide. As per data from the food and agriculture organization (FAO), tomato ranks among the top vegetables in terms of global production, with over 186 million tonnes harvested annually. Major producers include China, India, the United States and Turkey. The widespread cultivation and consumption of tomatoes are attributable to their high yield potential, diverse culinary uses, and rich nutritional profile. Tomatoes are an excellent source of vitamins such as vitamin C, vitamin K and folate, and they also provide important minerals like potassium and magnesium. Additionally, they are rich in lycopene, a potent antioxidant with documented health benefits including cardioprotective and anticancer effects (El-Saadony *et al.*, 2022).

However, the production of tomato is frequently hindered by various stress factors. Biotic stressors such as fungal diseases (early blight, late blight), bacterial wilts, viral infections (like Tomato Yellow Leaf Curl Virus) and insect pests (whiteflies, aphids) significantly reduce yield and crop quality. Abiotic stresses such as drought, heat, salinity, and nutrient imbalances further threaten productivity and pose a challenge to global food security (Abdelsalam *et al.*, 2023; Wang *et al.*, 2024). To address these multifaceted challenges, researchers have increasingly turned to nanotechnology, particularly focusing on the use of nanoparticles in disease management, stress mitigation, and growth promotion (Pratap *et al.*, 2024). Despite the proven utility of nanoparticles, conventional methods of synthesiswhether chemical or physicaloften involve toxic solvents, energy-intensive processes, and environmentally hazardous byproducts. These limitations raise significant concerns regarding safety, cost, and sustainability, thereby restricting their widespread adoption in eco-sensitive domains such as agriculture (Freitas *et al.*, 2021).In recent years, green synthesis approaches have garnered considerable attention as viable alternatives. One of the most promising green approaches is the use of plant extracts in nanoparticle synthesis, also known as phytoengineering. This technique utilizes the natural reducing and stabilizing agents present in plantssuch as alkaloids, flavonoids, terpenoids, phenolics and proteinsto facilitate the formation of nanoparticles under mild conditions, without the use of toxic chemicals (Munir *et al.*, 2023).The nanoparticles synthesized *via* plant-based methods, termed phytoengineered nanoparticles (phyto-NPs), offer several advantages over conventionally synthesized counterparts. They are typically more biocompatible, exhibit improved stability, and are less toxic to non-target organisms. Moreover, the phytochemical residues from the plant extracts can endow the nanoparticles with unique biological properties, including antimicrobial, antioxidant, and plant growth-promoting activities (Haq *et al.*, 2024; Munir *et al.*, 2023). These characteristics make phyto-NPs especially suitable for applications in tomato crop management. Studies have demonstrated their potential in controlling pathogens, enhancing tolerance to abiotic stresses, and improving nutrient uptake and utilization (Saleem *et al.*, 2024; Wang *et al.*, 2024; El-Saadony *et al.*, 2022).

The use of phyto-NPs not only supports environmentally responsible farming but also aligns with the broader goals of sustainable agriculture and climate-smart crop production. Given the increasing interest in eco-friendly nanotechnology and the urgent need for sustainable interventions in tomato cultivation, a comprehensive review of the current state of phytoengineered nanoparticles is both timely and necessary.The rationale for this review stems from the growing evidence supporting the role of phyto-NPs in improving plant health and productivity, particularly in high-value vegetable crops such as tomato (Haq *et al.*, 2024). Despite this, research is still fragmented, and a consolidated understanding of their synthesis mechanisms, modes of action, application strategies, and potential limitations is lacking. This review aims to bridge that gap by systematically evaluating the role of phyto-NPs in tomato management. Specifically, it seeks to elucidate the various plant-based methods used for nanoparticle synthesis, identify key phytochemicals involved, and explore how these nanoparticles interact with plant physiological and molecular processes (Munir *et al.*, 2023; Pratap *et al.*, 2024). Furthermore, this review will highlight the practical benefits of phyto-NPs in terms of disease suppression, stress tolerance, and yield enhancement, drawing on recent experimental findings (Haq *et al.*, 2024; Saleem *et al.*, 2024). At the same time, it will critically assess the limitations, including scalability issues, potential toxicity, regulatory hurdles, and gaps in long-term environmental impact assessments. The ultimate aim is to provide a holistic understanding of how phytonanotechnology can be harnessed to enhance tomato production systems in a sustainable and environmentally responsible manner. By exploring the mechanisms, benefits, challenges, and future prospects of phytoengineered nanoparticles, this review aspires to inform future research directions and promote the adoption of green nanotechnological solutions in horticulture.

2. Phytoengineered nanoparticles

2.1 Conceptual basis of phytonanotechnology

Phyto-nanotechnology is an emerging interdisciplinary field that involves the use of plant-based materials to engineer nanoparticles (NPs) for agricultural and biomedical applications (Li and Yan, 2020). These nanoparticles, often referred to as phytoengineered nanoparticles (phyto-NPs), are typically synthesized using plant extracts to reduce metal ions or organic compounds to their nanoparticulate form. The primary advantage of phyto-NPs over conventionally synthesized nanoparticles lies in their eco-friendly synthesis processes, which avoid toxic chemicals and excessive energy consumption associated with traditional physical or chemical methods (Wahab *et al.*, 2023). Phyto-NPs are generally classified based on their material composition. Metallic nanoparticles, such as silver (Ag), gold (Au), and copper (Cu) nanoparticles, are the most widely studied due to their antimicrobial properties, catalytic activity, and potential for enhancing plant growth. Metal oxide nanoparticles, including zinc oxide (ZnO), titanium dioxide (TiO_2) and iron oxide (Fe_2O_3), are also commonly synthesized and used in agriculture. These nanoparticles are particularly valued for their photocatalytic properties and ability to stimulate plant defence mechanisms. Additionally, hybrid nanoparticles combine elements from both metallic and non-metallic materials or organic and inorganic substances, offering a range of tailored properties. The versatility of these nanoparticles, such as their ability to carry both hydrophobic and hydrophilic agents, makes them highly effective in plant health management (Bhattacharya *et al.*, 2022).

2.2 Role of plant metabolites in nanoparticle biosynthesis

The synthesis of phytoengineered nanoparticles relies heavily on the phytochemicals present in plant extracts. Plants offer a diverse

array of bioactive compounds that play crucial roles in nanoparticle biosynthesis. These phytochemicals act as reducing agents, stabilizing agents, and capping agents, which enable the formation of nanoparticles and impart various functional properties. Reducing agents in plant extracts, such as flavonoids, terpenoids, alkaloids, and polyphenols, are key to the reduction of metal ions into nanoparticles (Faraz *et al*., 2019). Flavonoids, for instance, are known for their antioxidant properties, which allow them to efficiently reduce metal ions. Terpenoids, with their aromatic and hydrophobic nature, are often used in the synthesis of nanoparticles, providing both reduction and stabilization. Alkaloids and polyphenols are similarly effective due to their ability to interact with metal ions and reduce them to their nanoparticulate form. These plant metabolites not only drive the synthesis but also influence the size, shape, and surface charge of the nanoparticles. In addition to their role as reducing agents, plant metabolites also serve as stabilizing agents, preventing the aggregation of nanoparticles and ensuring their stability in solution (Mustapha *et al*., 2022). Some metabolites form a protective layer around the nanoparticles, contributing to surface functionalization. This functionalization can enhance the compatibility of nanoparticles with plant tissues, improve their bioavailability, and increase their interaction with cellular components. Stabilizing agents derived from plants thus significantly impact the biological and physicochemical properties of phyto-NPs, making them suitable for agricultural applications such as pest control, stress mitigation, and nutrient delivery (Lala, 2021).

2.3 Key synthesis parameters influencing np characteristics

Several synthesis parameters are crucial in determining the characteristics of phytoengineered nanoparticles, including their size, shape, surface charge, and stability. These parameters must be carefully controlled to achieve the desired nanoparticle properties for specific agricultural applications (Silva *et al*., 2024).Temperature plays a significant role in the rate of nanoparticle synthesis. Higher temperatures generally accelerate the reduction process but can also lead to the formation of larger nanoparticles. Conversely, lower temperatures may result in smaller nanoparticles but can slow the reaction time. pH is another critical factor that influences the surface charge and stability of nanoparticles. For instance, acidic or alkaline conditions may affect the ionic state of the metal precursor and the functional groups on the plant metabolites, influencing nanoparticle size and stability (Altammar, 2023). The pH also impacts the solubility of metal ions and their interaction with plant phytochemicals. Precursor concentration determines the availability of metal ions for reduction and thus influences the size and morphology of the resulting nanoparticles. A higher precursor concentration often leads to larger nanoparticles, while a lower concentration favors the formation of smaller nanoparticles. Extract ratio of plant extract to metal precursor also significantly impacts the outcome of the synthesis. A higher concentration of plant extract can increase the availability of reducing agents, leading to faster nanoparticle formation, while a lower ratio may result in slower but more controlled nanoparticle synthesis (Pang *et al*., 2021). These parameters must be optimized to obtain nanoparticles with specific characteristics suited for their intended application, whether for enhancing plant growth, controlling pests, or improving resistance to abiotic stress.

2.4 Advantages over conventional nanoparticles

Phytoengineered nanoparticles offer numerous advantages over conventionally synthesized nanoparticles, making them highly attractive for agricultural applications. The most notable advantages include biocompatibility, sustainability, cost-effectiveness, and enhanced biological activity. One of the main benefits of phyto-NPs is their biocompatibility, as they are synthesized from natural plant extracts. This minimizes the risk of toxicity to non-target organisms, including beneficial insects, animals, and humans (Alavi and Hamidi, 2019). The use of plant-derived stabilizing agents further enhances the compatibility of the nanoparticles with plant systems, ensuring their safe integration into agricultural practices.The green synthesis of phyto-NPs offers a sustainable alternative to traditional chemical methods. By utilizing plant extracts, which are renewable resources, this approach reduces the need for toxic chemicals and harmful solvents. Moreover, the eco-friendly nature of the synthesis process aligns with the principles of green chemistry and environmentally responsible agriculture (Hamada *et al*., 2024). Phytoengineered nanoparticles are often less expensive to produce compared to those synthesized through conventional methods. Plant extracts are abundant, widely available, and inexpensive, making the overall process more cost-effective. Additionally, the green synthesis process typically requires fewer resources and less energy, further reducing production costs (Sur *et al*., 2019). The unique properties of phyto-NPs, including their size, surface charge, and functionalization with plant metabolites, often result in enhanced biological activity. For example, phyto-NPs have demonstrated improved antimicrobial properties, higher nutrient uptake efficiency, and better stress tolerance in plants compared to conventional nanoparticles. This enhanced activity makes them particularly useful for improving crop health and productivity.

3. Characterization techniques for phytoengineered nanoparticles (Phyto-NPs)

The characterization of phytoengineered nanoparticles (phyto-NPs) is a critical component in understanding their morphology, composition, stability, and biological functionality. As phyto-NPs are synthesized using plant extracts, their properties are influenced by various phytochemicals, synthesis conditions, and the type of metal precursor used. Comprehensive characterization not only confirms successful nanoparticle formation but also helps in evaluating their suitability for specific agricultural applications. Several sophisticated techniques are employed to examine the morphological, structural, optical, surface, and chemical properties of phyto-NPs. This section discusses the major characterization methods commonly utilized in the study of phytoengineered nanoparticles, including morphological and structural tools, optical and surface analyses, and phytochemical profiling of plant extracts (Ambele *et al*., 2024).

3.1 Morphological and structural characterization

Understanding the morphology and crystal structure of nanoparticles is fundamental, as these properties greatly influence their reactivity, stability, and interaction with biological systems. Among the most commonly employed techniques are scanning electron microscopy (SEM), transmission electron microscopy (TEM), atomic force microscopy (AFM) and x-ray diffraction (XRD) scanning electron microscopy (SEM) is widely used to analyze the surface topography and shape of nanoparticles. It provides high-resolution images by

scanning a focused beam of electrons across the sample surface. SEM helps in determining the size distribution, degree of agglomeration, and surface roughness of phyto-NPs. It is particularly useful in identifying spherical, rod-like, or irregular particle morphologies resulting from different plant-mediated synthesis conditions (Jain and Tailang, 2023; Hamdy et al., 2024). Transmission electron microscopy (TEM) offers even greater resolution than SEM and is ideal for determining the internal structure and precise dimensions of nanoparticles. By transmitting electrons through a thin sample, TEM provides detailed two-dimensional images of nanoparticle size and morphology at the nanoscale level. It also allows the observation of the nanoparticle's core-shell structures, which can occur due to phytochemical coatings during synthesis. TEM is especially valuable for visualizing the dispersion and homogeneity of the nanoparticles (Sencan et al., 2024). Atomic force microscopy (AFM) is a surface-sensitive technique that enables three-dimensional imaging of nanoparticles without requiring vacuum conditions, unlike SEM and TEM. It uses a mechanical probe that scans the surface of the sample to measure topographical features at nanometer-scale resolution. AFM is useful in analyzing the surface roughness, height, and aggregation behavior of phyto-NPs, and can provide information in both air and liquid environments, making it suitable for biological and environmental studies (Sakthivel et al., 2025). X-ray diffraction (XRD) is an essential technique for determining the crystalline nature and phase purity of nanoparticles. When X-rays are directed at a sample, they are diffracted according to the atomic arrangement in the crystalline material. The resulting diffraction patterns reveal the presence of specific crystal planes, which can be compared with standard reference data to confirm the identity of the metal or metal oxide. In the case of phyto-NPs, XRD is particularly useful in confirming the successful synthesis of nanoparticles and estimating the average crystallite size using the Debye–Scherrer equation (Hamdy et al., 2024).

3.2 Optical and surface characterization

Optical and surface-related properties of nanoparticles provide critical insights into their stability, reactivity, and potential interactions with biological systems. Several techniques such as UV-visible (UV-Vis) spectroscopy, fouriertransform infrared spectroscopy (FTIR), dynamic light scattering (DLS) and zeta potential analysis are commonly employed for this purpose. UV-Visible spectroscopy is often the first and simplest method used to confirm the formation of nanoparticles. During the synthesis of metallic nanoparticles using plant extracts, a distinct color change is usually observed due to the excitation of surface plasmon resonance (SPR), which can be quantitatively monitored using UV-Vis spectroscopy. For example, silver nanoparticles typically exhibit SPR bands around 400-450 nm, while gold nanoparticles show absorption peaks near 520-550 nm. The peak position and intensity provide information about particle size, concentration, and aggregation state (Jafari et al., 2024). Moreover, a shift in the SPR peak can indicate changes in particle surface characteristics or interactions with capping agents from plant extracts.Fourier transform infrared spectroscopy (FTIR) is used to identify the functional groups present on the surface of the nanoparticles, originating from plant-derived biomolecules that act as reducing and stabilizing agents. FTIR spectra reveal the presence of characteristic bands corresponding to hydroxyl, carbonyl, amine, or carboxylic groups. These functional groups are typically involved in metal ion reduction or stabilization processes (Hamdy et al., 2024).

Dynamic light scattering (DLS) is used to determine the hydrodynamic diameter of nanoparticles in colloidal suspensions. DLS measures the fluctuation in light intensity scattered by particles undergoing Brownian motion, which is then used to calculate the average particle size and size distribution. Unlike SEM or TEM, which provide dry-state measurements, DLS offers size information in aqueous environments, making it particularly relevant for biological applications (Bapi et al., 2018). Zeta potential analysis is another critical technique used to evaluate the surface charge and colloidal stability of nanoparticles. A high absolute zeta potential value (positive or negative) generally indicates strong electrostatic repulsion between particles, preventing aggregation and enhancing dispersion stability. Phyto-NPs with zeta potentials beyond ±30 mV is typically considered stable in aqueous suspensions. This analysis is essential for predicting the behavior of nanoparticles in plant systems and soil environments (Bapi et al., 2018).

3.3 Phytochemical screening of plant extracts

The green synthesis of nanoparticles using plant extracts relies heavily on the presence and activity of specific bioactive compounds. Therefore, phytochemical screening of the plant material used is crucial in understanding the synthesis mechanism and the resultant properties of the nanoparticles. Preliminary qualitative analysis is often conducted to identify major classes of phytochemicals, including flavonoids, terpenoids, alkaloids, phenolics, saponins, tannins, and glycosides. These compounds serve as natural reducing and stabilizing agents (Javed et al., 2020). For example, flavonoids and phenolic acids possess strong antioxidant activity, which facilitates the reduction of metal ions. Terpenoids and alkaloids also contribute to both reduction and stabilization, often influencing the size and morphology of the resulting nanoparticles.Various biochemical assays are employed for the identification of these compounds. The ferric chloride test is commonly used for detecting phenols, while the Shinoda Test is employed for flavonoids. Drage dorff's reagent is utilized to confirm the presence of alkaloids, and the foam test is indicative of saponins. These tests help in the rapid screening of bioactive constituents in the plant extract (Chen et al., 2024). For more detailed analysis, high-performance liquid chromatography (HPLC), gas chromatography-mass spectrometry (GC-MS), and liquid chromatography-mass spectrometry (LC-MS) are used to identify and quantify individual phytochemicals. These methods allow for the determination of specific compounds responsible for reduction and stabilization, such as quercetin, kaempferol, gallic acid, and eugenol (Nagar et al., 2020). In addition to identifying phytochemicals, total phenolic content (TPC) and total flavonoid content (TFC) assays are used to estimate the overall concentration of reducing agents in the extract. These quantitative assays help correlate the biochemical composition of the extract with the efficiency of nanoparticle synthesis and the characteristics of the final product (Chen et al., 2024). Phytochemical profiling is, therefore, an essential step in the green synthesis process. It provides insight into the underlying chemical mechanisms driving nanoparticle formation and helps tailor the synthesis conditions for optimal results. Furthermore, the bioactive coatings imparted by plant metabolites often enhance the biological activity of the nanoparticles, making them more effective as antimicrobial agents, stress mitigators, or growth promoters in agricultural systems.

4. Applications of phytoengineered nanoparticles in tomato crop management

Phytoengineered nanoparticles (phyto-NPs), synthesized via eco-friendly green methods using plant extracts, offer a promising avenue for sustainable management of horticultural crops like tomato (*S. lycopersicum*) (Hussain *et al*., 2024). As a globally significant crop both nutritionally and economically, tomato is vulnerable to various biotic and abiotic stressors, which often constrain its yield and quality. Traditional agrochemicals, though effective, pose environmental and health concerns. Phyto-NPs present a viable alternative, combining the advantages of nanotechnology with the inherent bioactivity of plant metabolites. This section explores the multiple roles of phyto-NPs in tomato cultivation, including their application as nanofertilizers, biocontrol agents, elicitors of plant defense mechanisms, stress alleviators, and tools for seed priming (Khan *et al*., 2024).

4.1 Nanofertilizers and growth stimulants

Nanofertilizers represent a breakthrough in plant nutrition, offering precise and sustained delivery of nutrients at the nanoscale. When engineered through green synthesis, phyto-NPs such as zinc oxide (ZnO), iron oxide (Fe_2O_2), and silicon dioxide (SiO_2) not only supply essential elements but also improve plant physiological processes through their nano-size advantages (Helal *et al*., 2023). The primary mechanism by which nanofertilizers enhance nutrient uptake lies in their increased surface area and reactivity. These properties allow for better root absorption and translocation within the plant. ZnO NPs, for instance, have been shown to facilitate zinc uptake, enhancing chlorophyll synthesis and auxin metabolism (Saffan *et al*., 2022). Fe_2O_2 NPs support photosynthetic electron transport and vegetative development. SiO_2 NPs are linked to increased water-use efficiency by enhancing cell wall rigidity and reducing transpiration. Foliar applications of these nanofertilizers have demonstrated significant improvements in tomato biomass, leaf area, and fruit yield (Ahmed *et al*., 2021).

4.2 Biocontrol agents against phytopathogens

The use of phytoengineered nanoparticles as antimicrobial agents has gained significant attention due to their broad-spectrum activity against plant pathogens (Karthika *et al*., 2020; Awan *et al*., 2022). In tomato, green-synthesized nanoparticles such as silver (AgNPs), copper (CuNPs) and titanium dioxide (TiO_2 NPs) have demonstrated potent antifungal and antibacterial activities. These NPs function through membrane disruption, ROS generation, and enzymatic inhibition. AgNPs synthesized using *Ocimum sanctum* extract inhibited *Alternaria solani*, reducing lesion development by over 70% (Hussain *et al*., 2024). Neem-derived CuNPs have suppressed *Fusarium oxysporum*, and TiO_2 NPs, *via* photocatalytic activity, have shown broad antifungal potential. Their biocompatibility, combined with plant-extract-mediated synthesis, provides a stable and environmentally benign solution for pathogen control (Borzykh *et al*., 2022).

4.3 Induction of plant defense responses

Phyto-NPs can stimulate systemic defense responses such as systemic acquired resistance (SAR) and jasmonic acid (JA) signaling pathways, enhancing immunity against a broad range of pathogens (Abd-Ellatif *et al*., 2022). ZnO and AgNPs upregulate salicylic acidresponsive PR genes, increasing lignin deposition and cell wall strength. CuNPs boost JA levels and activate defensins and flavonoid biosynthesis (Narasimhamurthy *et al*., 2022). These responses are further amplified by secondary metabolite production, including phenolics and alkaloids, providing both direct and systemic protection. This dual role in direct toxicity and defence elicitation positions phyto-NPs as a sustainable and energy-efficient alternative in disease management (Ashraf *et al*., 2021).

4.4 Abiotic stress alleviation

Tomato crops face numerous abiotic stresses, including drought, salinity, and extreme temperatures. Phytoengineered nanoparticles alleviate these stresses by modulating antioxidant enzyme activity, osmolyte accumulation, and hormone signaling (El-Saadony *et al*., 2022). ZnO, SiO_2, and Fe_2O_2 NPs enhance the activity of SOD, CAT and POD enzymes, mitigating oxidative damage. SiO_2 NPs elevate proline levels and improve drought resilience. These NPs also regulate hormonal balance AgNPs and Fe_2O_2 NPs reduce ABA while increasing IAA, promoting root growth and water uptake. Lower MDA content and reduced electrolyte leakage in treated plants signify improved membrane integrity, suggesting enhanced tolerance under stress conditions (Guerriero *et al*., 2023).

4.5 Seed nano-priming and germination enhancement

Seed nano-priming, involving nanoparticle treatment before sowing, improves tomato germination and early seedling vigor (Sonawane *et al*., 2021). ZnO NPs, for instance, activate enzymes like amylase and protease, enhancing seed reserve mobilization. Fenugreek-synthesized ZnO NPs promote radicle emergence and balanced shoot-root development. Imbibition-based priming allows for deeper nanoparticle penetration, offering uniform germination even under saline or drought stress. AgNP-primed seeds exhibit stress resilience and metabolic activation, aided by the bioactivity of plant-derived capping agents (Mazhar *et al*., 2024). This nano-priming can induce a 'primed state' that prepares the seedling for enhanced performance in fluctuating field conditions (Imtiaz *et al*., 2023).

5. Molecular and cellular mechanisms of action

5.1 Uptake, translocation and accumulation in tomato plants

The effectiveness of phytoengineered nanoparticles (NPs) in tomato crop management hinges significantly on their ability to be absorbed by the plant, move through its tissues, and accumulate in specific organs. These processes are influenced by the route of application whether foliar or root-based as well as the physicochemical characteristics of the nanoparticles themselves, such as size, shape, surface charge, and functionalization (Lv *et al*., 2019). When applied to the aerial parts of tomato plants, nanoparticles can be absorbed through several entry points. Stomatal openings, which are natural pores on the leaf surface involved in gas exchange, serve as one of the main gateways for nanoparticle entry, especially for particles smaller than 100 nm. Nanoparticles may also penetrate through microscopic cracks in the cuticle or diffuse directly across it, particularly if they are ultra-small or functionalized with hydrophilic or lipophilic groups that enhance permeability (Rani *et al*., 2022). Once internalized, these particles can translocate *via* the phloem to reach other plant tissues, such as stems, roots, and fruits. This systemic movement depends on the size and solubility of the nanoparticles as well as their interaction with phloem sap constituents (Tripathi *et al*., 2017).

In contrast, soil-applied nanoparticles are absorbed predominantly by roots, and this uptake occurs through both apoplastic and symplastic pathways (Zhang *et al.*, 2013). In the apoplastic route, nanoparticles move along the cell walls and intercellular spaces, traveling until they encounter the Casparian strip in the root endodermis, a barrier that redirects particles into the symplast. The symplastic pathway involves passage through living cells *via* plasmodesmata, requiring entry across the plasma membrane, which is often mediated by active transport mechanisms such as endocytosis. Root uptake is strongly influenced by the composition of root exudates, which include organic acids, amino acids, sugars, and secondary metabolites. These exudates can alter the chemical stability, solubility, and aggregation behavior of nanoparticles in the rhizosphere (Tripathi *et al.*, 2017). Moreover, the architecture of the root system, including the density of root hairs and lateral roots, plays a vital role in determining the total surface area available for interaction with nanoparticles (Lv *et al.*, 2019).

On a cellular level, aquaporins and endocytosis are crucial components in nanoparticle uptake. Aquaporins are transmembrane proteins that facilitate the transport of water and small neutral molecules. Some specific aquaporin isoforms, particularly nodulin 26-like intrinsic proteins (NIPs), are known to transport metalloids and may be involved in nanoparticle uptake as well. The expression of aquaporins in tomato plants can be modulated by environmental factors and stress conditions, potentially influencing the permeability of membranes to nanoparticles (Zhang *et al.*, 2013). Meanwhile, endocytosis serves as a key mechanism for the internalization of larger or surface-modified nanoparticles. This energy dependent process involves the invagination of the plasma membrane to engulf external particles into vesicles, leading to their internalization and subsequent transport through the endomembrane system (Rani *et al.*, 2022). Different types of endocytosis may be involved in nanoparticle uptake, including clathrin-mediated endocytosis and clathrin-independent mechanisms (Lv *et al.*, 2019). Nanoparticles may either trigger or exploit these endocytic pathways depending on their surface chemistry and interaction with specific membrane receptors (Eichert *et al.*, 2008). The intracellular trafficking of nanoparticles post-endocytosis determines their final fate within the plant cells. Some may be directed toward the Golgi apparatus or endoplasmic reticulum, while others may be sequestered in vacuoles or exocytosis (Zhang *et al.*, 2013). These processes are often accompanied by physiological responses, such as reactive oxygen species (ROS) generation and changes in calcium signalling, which in turn can influence membrane fluidity and endocytic activity (Rani *et al.*, 2022). Overall, the movement and accumulation of nanoparticles within tomato plants are shaped by a combination of biological transport mechanisms and the engineered properties of the nanoparticles (Lv *et al.*, 2019).

5.2 Cellular and subcellular interactions

The internalization of phytoengineered nanoparticles (NPs) in tomato plants can lead to a variety of interactions at the cellular and subcellular levels, significantly influencing organelle structure and function. Among the primary organelles affected are chloroplasts, mitochondria, and vacuoles (Dai *et al.*, 2018). Chloroplasts, being the sites of photosynthesis, are particularly vulnerable to nanoparticle exposure. Several studies have indicated that NPs can alter chloroplast morphology, disrupt thylakoid membranes, and modify pigment composition (Wang *et al.*, 2021). These structural changes can impair light harvesting and carbon assimilation processes, ultimately reducing photosynthetic efficiency. Mitochondria, central to energy metabolism, are also sensitive to nanoparticle-induced stress. Exposure to certain NPs can disrupt the mitochondrial membrane potential, impairing ATP synthesis and increasing ROS generation (Missaoui *et al.*, 2018). Mitochondrial dysfunction can cascade into reduced respiration, impaired metabolic activity, and growth retardation (Dai *et al.*, 2018). Vacuoles, which sequester and detoxify foreign substances, may compartmentalize NPs to minimize cytoplasmic interference. However, their accumulation may affect vascular roles in ion storage and cellular turgor (Zhao *et al.*, 2012). Alterations in vascular function can disrupt nutrient homeostasis and stress signalling (Wang *et al.*, 2021). Nanoparticles induce reactive oxygen species (ROS), including superoxide anions, hydrogen peroxide, and hydroxyl radicals, arising from disruptions in electron transport chains (Dai *et al.*, 2018). While low ROS levels act as signalling molecules, excessive ROS causes oxidative damage to biomolecules (Missaoui *et al.*, 2018). To counteract this, antioxidant defences such as superoxide dismutase (SOD), catalase (CAT), and peroxidases (PODs) are activated (Zhao *et al.*, 2012). Non-enzymatic antioxidants like ascorbic acid, glutathione, and flavonoids also play roles (Eichert *et al.*, 2008). The balance between ROS generation and scavenging determines redox homeostasis and cellular outcomes (Wang *et al.*, 2021).

5.3 Omics-based insights

High-throughput omics technologies have deepened our understanding of molecular responses to nanoparticle exposure in tomato plants. Transcriptomic analyses reveal broad gene expression changes, particularly in stress-related pathways, hormone signalling, and metabolism (Sun *et al.*, 2020).Transcription factor families such as WRKY, MYB, NAC and bZIP are upregulated, orchestrating defence mechanisms. Genes for antioxidant enzymes like SOD, CAT, and GST are also activated (Majumdar and Keller, 2021). Proteomic studies reveal alterations in proteins linked to photosynthesis, redox regulation, and stress responses. Changes in Rubisco, ATP synthase, heat shock proteins and pathogenesis-related proteins are observed (Athar *et al.*, 2022). Post-translational modifications, such as phosphorylation and ubiquitination, modulate protein activity and enable rapid stress responses (Sun *et al.*, 2020). Metabolomic analyses show increased accumulation of Osmo protectants like proline and betaine, and secondary metabolites like flavonoids, phenolics, and alkaloids. These play protective and signalling roles (Sharma *et al.*, 2021). Changes in sugar and amino acid profiles suggest shifts in carbon and nitrogen metabolism, reflecting stress adaptation strategies (Majumdar and Keller, 2021). Epigenetic regulation, including DNA methylation, histone modification, and non-coding RNAs, also mediates plant-nanoparticle interactions (Athar *et al.*, 2022). Methylation changes and non-coding RNAs modulate gene expression, with some effects potentially heritable (Sharma *et al.*, 2021). These multi-omics insights underscore the complexity of plant responses to phytoengineered NPs, emphasizing the need for integrated strategies for sustainable nanoparticle application in tomato crop management.

6. Benefits and strategic advantages in tomato production

6.1 Enhanced crop yield and quality

The application of phytoengineered nanoparticles (phyto-NPs) has demonstrated significant potential in improving both the yield and

quality of tomato crops. Studies have shown that treatments with specific nanoparticles, such as zinc oxide (ZnO) and silicon (Si), can lead to increased fruit set, larger fruit size, and elevated concentrations of essential phytochemicals. For instance, ZnO nanoparticle treatments have been associated with higher levels of lycopene, flavonoids, and vitamin C in tomato fruits, contributing to enhanced nutritional value and antioxidant properties (Liu et al., 2023). Moreover, the integration of nano-fertilizers, like nano-NPK formulations, has been linked to improved phytochemical profiles in tomatoes. These formulations can enhance the accumulation of vitamins A and C, β-carotene, polyphenols, and anthocyanins, thereby boosting the overall antioxidant capacity of the fruits. Such enhancements not only improve the health benefits of tomatoes for consumers but also increase the market value of the produce (W³odarczyk et al., 2024).

6.2 Reduction in agrochemical dependency

Phyto-NPs offer a promising avenue for reducing reliance on conventional agrochemicals. Their unique properties enable targeted delivery and controlled release of nutrients and pesticides, thereby minimizing the quantities required and reducing environmental contamination. For example, nano-formulations of pesticides can achieve effective pest control at lower dosages compared to traditional formulations, decreasing the overall chemical load on the environment (Zhao et al., 2022). Additionally, the use of nano-fertilizers enhances nutrient use efficiency, ensuring that plants absorb a higher proportion of applied nutrients. This efficiency reduces the need for excessive fertilizer applications, thereby lowering the risk of nutrient runoff into water bodies and mitigating associated ecological issues. By decreasing the dependency on conventional agrochemicals, phyto-NPs contribute to more sustainable and environmentally friendly agricultural practices (Gonçalves et al., 2021).

6.3 Suitability for precision and climate-smart agriculture

The integration of phyto-NPs into precision agriculture systems aligns with the goals of climate-smart agriculture by enhancing resource use efficiency and resilience to environmental stresses. Nanoparticles can be engineered to respond to specific environmental cues, enabling site-specific applications that optimize inputs based on real-time plant needs (Duhan et al., 2017). For instance, nano-enabled delivery systems can release nutrients or pesticides in response to changes in soil moisture or pH, ensuring timely and efficient resource utilization. Furthermore, phyto-NPs can bolster plant tolerance to abiotic stresses such as drought, salinity, and extreme temperatures. By modulating stress-responsive pathways and enhancing antioxidant defenses, nanoparticles help maintain plant productivity under challenging climatic conditions (Singh and Singh, 2023). This adaptability is crucial for sustaining tomato production in the face of climate variability and supports the broader objectives of climate-smart agriculture.

6.4 Integration into organic and low-input farming systems

The compatibility of phyto-NPs with organic and low-input farming systems offers opportunities to enhance productivity while adhering to sustainable agricultural principles. Green synthesis methods for nanoparticles, utilizing plant extracts or other biological materials, align with organic farming standards by avoiding synthetic chemicals in the production process. Incorporating phyto-NPs into organic systems can improve nutrient availability and pest management without compromising the ecological balance (Edoti et al., 2024). For example, the use of nano-formulated bio-pesticides can effectively control pests while minimizing harm to beneficial organisms. Additionally, nano-fertilizers derived from natural sources can enhance soil fertility and plant nutrition, supporting the goals of low-input agriculture. By integrating phyto-NPs, organic and low-input farming systems can achieve higher yields and better crop quality, contributing to food security and sustainability (Srivastava and Singh, 2021).

7. Challenges and limitations

7.1 Variability in synthesis and formulation

One of the foremost challenges associated with the application of phytoengineered nanoparticles (phyto-NPs) in agriculture is the variability in synthesis methods and the lack of scalability in formulation. Unlike conventional chemical synthesis, green synthesis using plant extracts involves a complex mixture of biomolecules whose concentrations can vary depending on species, cultivar, plant part used, growth stage, and extraction method. This inconsistency often leads to batch-to-batch variability in nanoparticle size, shape, stability, and bioactivity. For example, different extracts of the same plant may yield nanoparticles with distinct surface properties or functional group compositions, which in turn affects their biological interaction with tomato plants. Furthermore, the transition from laboratory-scale synthesis to industrial or agricultural-scale production remains a major bottleneck. The absence of standardized protocols for extract preparation, precursor selection, and reaction conditions hampers reproducibility and commercial viability. Many plant-based synthesis protocols are labor-intensive, time-consuming, or reliant on specific environmental conditions, making them unsuitable for mass production. As a result, despite promising experimental outcomes, many phyto-NP technologies are yet to be translated into scalable agricultural solutions.

7.2 Potential phytotoxicity and soil microbiome disruption

While phyto-NPs are generally considered safer than chemically synthesized counterparts, their application still raises concerns about phytotoxicity, particularly when used at higher concentrations or over extended periods. The dose-dependent nature of nanoparticle action means that while low concentrations may stimulate plant growth and metabolism, excessive exposure can impair physiological processes such as photosynthesis, nutrient uptake, and oxidative balance. Symptoms of phytotoxicity in tomato plants may include chlorosis, necrosis, reduced root elongation, and compromised fruit development. Another emerging concern is the potential disruption of the soil microbiome. Nanoparticles introduced into the rhizosphere can interact with a wide range of beneficial microorganisms, including nitrogen-fixing bacteria, mycorrhizal fungi, and plant growth-promoting rhizobacteria (PGPR). These interactions may be either stimulatory or inhibitory depending on nanoparticle type, concentration, and soil characteristics. For instance, silver and copper nanoparticles, known for their strong antimicrobial properties, could inadvertently suppress beneficial soil microbes, thereby altering nutrient cycling and soil health. Such unintended consequences highlight the need for detailed ecological risk assessments and the development of strategies to mitigate microbial imbalance.

7.3 Food safety and human health risks

The increasing application of phyto-NPs in crop production, including foliar sprays, seed treatments, and soil amendments, raises critical questions about their safety for human consumption. One major concern is the potential accumulation of nanoparticles in edible parts of tomato plants. Several studies have reported the translocation and retention of nanoparticles in leaves, stems, and fruits, depending on the mode of application and nanoparticle properties such as size, surface charge, and composition. Although, some phyto-NPs may degrade or be metabolized within the plant system, others may persist and enter the human food chain. The health risks associated with chronic dietary exposure to engineered nanoparticles remain largely uncharacterized. Concerns include oxidative stress, genotoxicity, inflammatory responses, and disruption of gastrointestinal microbiota. The lack of long-term toxicological studies, particularly those examining nanoparticle bioavailability, biotransformation, and excretion in humans, contributes to the uncertainty surrounding their safety profile. Moreover, the variability in nanoparticle synthesis methods adds another layer of complexity, as different batches may exhibit distinct toxicological behaviors. Ensuring food safety requires comprehensive studies on nanoparticle fate in planta, along with standardized toxicological evaluations across diverse human populations and dietary patterns.

7.4 Lack of field-level data and standardized protocols

Despite extensive laboratory and greenhouse research on phyto-NPs, their field-level application remains limited. Most current studies focus on controlled environments where variables such as light, temperature, humidity, and soil composition can be precisely managed. However, under open-field conditions, these factors are subject to fluctuation, potentially altering nanoparticle behavior and efficacy. Environmental variables such as UV radiation, rainfall, soil heterogeneity, and microbial interactions may affect the stability, dispersion, and bioactivity of nanoparticles, leading to inconsistent outcomes in crop productivity and health. The lack of standardized application protocols further impedes the adoption of phyto-NPs in horticultural practices. Parameters such as application timing, dosage, frequency, and delivery methods (*e.g.*, foliar spray, root drenching, or seed coating) are often optimized for specific experimental settings and may not be readily transferable to field conditions. Moreover, there is a lack of universally accepted guidelines for assessing the agronomic performance, environmental safety, and economic feasibility of nanoparticle-based inputs. This standardization gap hinders regulatory approvals and undermines farmer confidence in nanotechnology-based interventions.

7.5 Regulatory gaps and public perception

Regulatory oversight of nanotechnology applications in agriculture, particularly in the horticultural sector, remains fragmented and underdeveloped in many regions. While international bodies like the food and agriculture organization (FAO) and the organization for economic cooperation and development (OECD) have issued preliminary guidelines on nanomaterial use in food and agriculture, there is still no globally harmonized framework for evaluating phyto-NPs. National regulations vary widely, with some countries lacking any formal policies or risk assessment protocols for nano-enabled agro-inputs. This regulatory ambiguity extends to labelling requirements, permissible exposure limits, and monitoring of nanoparticle residues in food products. As a result, there is limited consumer transparency and oversight, increasing the likelihood of misuse or misbranding. Public perception is another critical factor that influences the adoption of nanotechnology in agriculture. Scepticism and fear related to "nano-foods," often fuelled by media misrepresentation and lack of accessible information, can lead to resistance among both consumers and producers. Transparent communication, stakeholder engagement, and public education are essential to build trust and promote informed decision-making regarding phyto-NPs.

8. Future directions and research perspectives

To fully unlock the potential of phytoengineered nanoparticles (phyto-NPs) in tomato crop management, large-scale field trials across diverse agroecological zones are essential. While most studies have been conducted in controlled environments such as laboratories and greenhouses, the performance of phyto-NPs in real-world conditions is still largely unexplored. These field trials must span different soil types, climates, and farming practices, as well as include a range of tomato genotypes to better understand how phyto-NPs affect plant growth, yield, and resilience to stressors. Additionally, agronomic optimization will play a pivotal role in improving the application protocols for phyto-NPs, such as determining the optimal doses, application methods, and timings for maximum efficacy. Understanding how these nanoparticles interact with various agricultural inputs like fertilizers, irrigation, and biological control agents will help integrate phyto-NPs into sustainable farming systems. This research will lead to the development of practical guidelines tailored to specific tomato production systems, ultimately encouraging broader adoption by farmers. A promising future direction for phyto-NPs in agriculture is the development of smart nano-delivery systems, which can offer controlled, targeted release of nutrients, pesticides, or growth regulators. Unlike conventional formulations that provide a uniform dose, these advanced systems can be designed to release active substances in response to specific environmental stimuli, such as pH changes, temperature fluctuations, or enzymatic activities. This technology could significantly reduce input wastage and environmental contamination by ensuring that agrochemicals are delivered only when and where they are needed. For instance, in tomato cultivation, nanoparticles could be engineered to release micronutrients precisely when the plant is deficient, or to target pathogens at the site of infection. Moreover, the use of biodegradable materials for encapsulating such active compounds would enhance the sustainability of such systems, reducing the environmental impact of their application. The future of nano-delivery systems lies in fine-tuning their design to make them more efficient, cost-effective, and eco-friendly, ensuring they can be seamlessly integrated into precision farming practices.

Nanotechnology also offers the potential to revolutionize plant health monitoring through the development of nanobiosensors. These sensors, which utilize the unique properties of nanoparticles, can provide real-time diagnostics of plant health by detecting specific biomarkers related to disease, nutrient deficiencies, or environmental stress. In tomato crops, for instance, nano sensors could be used to detect early signs of fungal or bacterial infections, enabling farmers to apply targeted treatments and prevent large-scale outbreaks. Similarly, sensors based on nanoparticles could monitor plant nutrient status, detecting imbalances in nitrogen, phosphorus, or potassium levels and allowing for more precise fertilizer application. By integrating nano biosensors with mobile or IoT-enabled platforms,

farmers could access real-time data and make informed decisions, enhancing the efficiency of pest and nutrient management. These precision diagnostic tools would not only improve crop productivity but also minimize the environmental impact of excessive chemical use, promoting sustainable agricultural practices.While the green synthesis of phyto-NPs is a promising approach, scaling up production to meet the demands of commercial agriculture remains a significant challenge. Large-scale production requires efficient, cost-effective, and environmentally sustainable technologies. One potential solution is the development of green reactors, automated systems that can optimize nanoparticle synthesis by controlling factors such as temperature, pressure, and reactant concentrations. These reactors could process larger volumes of plant extracts and metal precursors, ensuring consistent and high-quality nanoparticle production. Additionally, incorporating renewable energy sources, such as solar or wind power, into the synthesis process would reduce the carbon footprint of nanoparticle production. The use of agricultural by-products, such as tomato plant waste, for nanoparticle synthesis could further contribute to sustainability by turning waste into valuable resources. Advancing these sustainable scale-up technologies will be crucial for making phyto-NPs commercially viable and reducing their environmental impact. The successful integration of phyto-NPs into mainstream agricultural practices will require the establishment of comprehensive policy frameworks and regulatory guidelines. Currently, there is a lack of standardized protocols for assessing the safety, efficacy, and environmental impact of phyto-NPs, which has led to regulatory uncertainty in many regions. To address this, governments and international regulatory bodies must work together to create guidelines specific to nanotechnology applications in agriculture, covering aspects such as product testing, risk assessment, and environmental monitoring. The development of certification mechanisms, such as eco-labelling or third-party verification of nanoparticle-based products, will further promote their acceptance by consumers and ensure that they meet safety and environmental standards. Moreover, transparent risk assessments that take into account the potential long-term effects of nanoparticle accumulation in the soil, water, and food chain will help mitigate public concerns about their safety. Public engagement and education are also crucial to address misconceptions about nanotechnology and foster consumer confidence. As the regulatory landscape evolves, it will be important to ensure that policies balance innovation with safety, allowing phyto-NPs to contribute to sustainable agriculture while protecting human health and the environment.

9. Conclusion

Phytoengineered nanoparticles (phyto-NPs) have emerged as a promising and sustainable tool in the management of tomato crops, offering multiple benefits in terms of enhanced growth, stress resistance, and disease control. Their ability to provide precise, targeted solutions for nutrient delivery, pest management, and stress alleviation positions them as essential components of modern, sustainable agriculture. The green synthesis of nanoparticles using plant extracts, coupled with their biocompatibility and environmentally friendly nature, makes them an attractive alternative to traditional agrochemicals. As highlighted throughout the review, phyto-NPs offer numerous advantages, including the reduction of chemical inputs, increased crop yield, and enhanced quality, all while minimizing environmental contamination. Despite the significant potential, there are challenges that need to be addressed for widespread

adoption, such as variability in synthesis, potential phytotoxicity, and regulatory hurdles. The research presented also stresses the importance of large-scale field trials and the development of robust, sustainable production methods to overcome these challenges. Moreover, the integration of phyto-NPs into integrated pest management (IPM) systems and climate-smart agriculture practices presents an exciting avenue for future research. Smart nano-delivery systems, nano biosensors, and sustainable scale-up technologies are among the innovative strategies that can further enhance the effectiveness of phyto-NPs, making them more adaptable to diverse farming conditions and scalable for commercial use. The future of phyto-NPs in tomato cultivation relies on interdisciplinary collaboration between nanotechnologists, agronomists, plant biologists, and policymakers. There is a clear need for integrated approaches that combine scientific innovation with practical application to ensure that phyto-NPs are used effectively and sustainably. This collaboration will also be crucial in developing the necessary regulatory frameworks to ensure safety and public acceptance. By fostering these interdisciplinary efforts, phyto-NPs can become a cornerstone of sustainable tomato production systems, contributing not only to the productivity and resilience of the crop but also to the broader goal of advancing sustainable agricultural practices globally. In conclusion, phytoengineered nanoparticles represent a cutting-edge, eco-friendly technology with the potential to revolutionize tomato crop management. As research continues to uncover the full scope of their benefits and applications, it is clear that these nanoparticles will play a crucial role in shaping the future of agriculture. By addressing the current challenges and embracing the opportunities for innovation, we can ensure that phyto-NPs become a key tool in the pursuit of sustainable and climate-resilient tomato production systems.

Conflict of interest

The authors declare no conflicts of interest relevant to this article.

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