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Phytosynthesized nanoparticles in fruit crops: Roles in nutrition, stress tolerance and disease control

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Abstract

Phytosynthesized nanoparticles have emerged as a promising green nanotechnological approach for enhancing sustainability, productivity and resilience in fruit crop systems. Unlike conventionally synthesized nanomaterials, phytosynthesized nanoparticles are produced using plant-derived biomolecules that act as natural reducing and stabilizing agents, offering an eco-friendly, cost-effective and biologically compatible alternative. Fruit crops, which play a vital role in global nutrition, food security and agricultural economies, face increasing challenges from inefficient nutrient management, abiotic stresses, plant diseases and postharvest losses, particularly under changing climatic conditions. In this context, phytonanotechnology provides innovative solutions by improving nutrient availability and use efficiency, enhancing tolerance to drought, salinity and temperature stress and offering effective disease control through both antimicrobial activity and induction of plant defense responses. Additionally, phytosynthesized nanoparticles contribute to postharvest quality management by reducing microbial spoilage, regulating physiological processes and extending fruit shelf life through nanocoatings and active packaging systems. This review comprehensively examines the synthesis, physicochemical characterization, uptake and translocation mechanisms and functional roles of phytosynthesized nanoparticles in fruit crops, with emphasis on nutrition, stress tolerance, disease management and postharvest applications. Environmental safety, biosafety considerations and future research directions are also discussed. Overall, phytosynthesized nanoparticles represent a sustainable and multifunctional tool with significant potential to support climate-resilient fruit production, reduce agrochemical dependence and enhance fruit quality and nutritional security. Continued interdisciplinary research and responsible implementation are essential to facilitate their successful integration into modern fruit crop management systems.

1. Introduction

Nanotechnology has emerged as a transformative scientific domain with wide-ranging implications in agriculture, horticulture and food systems. In recent years, phytosynthesized or green nanoparticles have attracted considerable attention due to their environmentally benign synthesis, biological compatibility and multifunctional properties. Phytosynthesized nanoparticles are produced using plant-derived materials such as leaves, fruits, peels, seeds, bark and agro-industrial residues, wherein plant secondary metabolites act as natural reducing, stabilizing and capping agents (Iravani and Varma, 2020; Ahmed *et al.*, 2021). Unlike conventional chemical and physical methods that often involve toxic reagents and high energy consumption, phytosynthesis follows green chemistry principles and offers a sustainable alternative for nanoparticle production (Singh

et al., 2021). These nanoparticles, typically ranging from 1 to 100 nm, possess unique physicochemical properties including high surface area, enhanced reactivity and improved bioavailability, which facilitate efficient interactions with plant biological systems (Khan *et al.*, 2022). The presence of phytochemicals such as phenolics, flavonoids, terpenoids and alkaloids not only governs nanoparticle formation but also imparts additional biological functionality, making phytosynthesized nanoparticles particularly suitable for agricultural applications (Rai *et al.*, 2021). Fruit crops play a crucial role in global nutrition, agricultural economies and food security. Fruits are rich sources of essential vitamins, minerals, dietary fiber, antioxidants and health-promoting bioactive compounds that contribute significantly to human well-being and disease prevention (Slavin and Lloyd, 2021). Increased fruit consumption has been consistently associated with reduced risks of cardiovascular diseases, diabetes, obesity and certain cancers (Wang *et al.*, 2022). From an economic perspective, fruit crops are highvalue commodities that support millions of smallholder farmers and contribute substantially to export earnings and rural employment, particularly in tropical and subtropical regions (FAO, 2023). As global population growth, urbanization and dietary transitions intensify demand for fruits, ensuring sustainable and resilient fruit production systems has become

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a critical priority for global food and nutritional security (Godfray *et al.*, 2021).

Despite their importance, fruit crops are highly sensitive to both biotic and abiotic stresses. Diseases caused by fungi, bacteria and viruses significantly reduce fruit yield and quality, while abiotic stresses such as drought, salinity, heat and nutrient deficiencies further exacerbate production losses (Savary *et al.*, 2022). To address these challenges, modern fruit production systems rely heavily on synthetic fertilizers and pesticides. However, excessive and indiscriminate use of agrochemicals has led to soil degradation, environmental pollution, disruption of beneficial soil microbiota and the emergence of resistant pathogen strains (Carvalho, 2021). Moreover, chemical residues in fruits pose serious risks to food safety, consumer health and international trade, as global markets increasingly enforce strict maximum residue limits (MRLs) (Handford *et al.*, 2021). Another major limitation of conventional agrochemicals in fruit crops lies in their low use efficiency. A significant proportion of applied fertilizers and pesticides is lost through leaching, runoff, volatilization and degradation, resulting in poor nutrient uptake and reduced efficacy (Dimkpa and Bindraban, 2020). Foliar sprays often suffer from wash-off and limited penetration, while soil-applied inputs may become immobilized or inaccessible to plant roots. These inefficiencies increase production costs and intensify environmental burdens, particularly in perennial fruit crops characterized by complex canopy structures and long growth cycles (Zhang *et al.*, 2021). Under changing climatic conditions, such limitations further challenge the sustainability of conventional fruit crop management practices. In this context, phytonanotechnology has emerged as a promising alternative to overcome the constraints associated with traditional agrochemical-based systems. Phytosynthesized nanoparticles offer enhanced delivery efficiency, controlled release and targeted action, thereby reducing application rates and minimizing environmental losses (Raliya *et al.*, 2021). Due to their nanoscale size, these particles can enter plants through stomata, cuticular pores and root epidermal cells, facilitating improved uptake and translocation within plant tissues (Lv *et al.*, 2022). The biogenic origin of phytosynthesized nanoparticles enhances their compatibility with plant systems and reduces the risk of phytotoxicity compared to chemically synthesized nanomaterials (Tripathi *et al.*, 2023).

Phytosynthesized nanoparticles exhibit multifunctional roles in fruit crops, acting as nano-fertilizers, stress modulators and antimicrobial agents. Nano-formulations of essential micronutrients such as zinc, iron, copper and manganese have been reported to improve nutrient use efficiency, photosynthetic performance and fruit quality attributes, including sugar content, vitamin levels and antioxidant capacity (Kah *et al.*, 2020; Seleiman *et al.*, 2022). Under abiotic stress conditions, phytosynthesized nanoparticles enhance plant tolerance by regulating antioxidant enzyme activity, reducing oxidative damage, maintaining membrane integrity and improving water-use efficiency (Latef *et al.*, 2021). Their ability to modulate reactive oxygen species homeostasis plays a pivotal role in mitigating stress-induced cellular damage in fruit crops (Hasan *et al.*, 2023). Disease control is another key area where phytosynthesized nanoparticles demonstrate significant potential. Many plant-based nanoparticles possess intrinsic antimicrobial properties due to synergistic interactions between metal ions and phytochemical coatings (Khan *et al.*, 2021). These nanoparticles can inhibit pathogen growth by disrupting cell membranes, interfering with enzymatic

activity and suppressing spore germination. Additionally, phytosynthesized nanoparticles can induce plant defense responses by activating defense-related enzymes, phenylpropanoid pathways and systemic resistance mechanisms, thereby providing durable and broad-spectrum protection against fruit crop diseases (Elmer and White, 2022).

The adoption of phytonanotechnology also aligns closely with sustainability and circular economy principles. Utilizing plant extracts and fruit processing wastes for nanoparticle synthesis reduces dependence on hazardous chemicals while adding value to agricultural residues such as fruit peels, pomace and pruning waste (Patel *et al.*, 2021). This approach not only minimizes waste generation but also promotes resource efficiency and environmental stewardship, particularly in fruit-based agro-industrial systems (Varma, 2023). Such sustainable synthesis routes enhance the socio-environmental acceptability of nanotechnology in horticulture. Despite promising advancements, the application of phytosynthesized nanoparticles in fruit crops remains at an early stage. Variability in synthesis protocols, limited field-scale validation, insufficient understanding of long-term environmental fate and regulatory uncertainties continue to hinder large-scale adoption (Kookana *et al.*, 2020; Kah *et al.*, 2022). Furthermore, fruit crops exhibit species-specific physiological traits that influence nanoparticle behavior, necessitating crop and context-specific optimization strategies. A comprehensive synthesis of existing research is therefore essential to identify knowledge gaps and guide responsible innovation.

The primary objective of this review is to critically evaluate the role of phytosynthesized nanoparticles in enhancing nutrition, improving stress tolerance and controlling diseases in fruit crops. The review aims to integrate current knowledge on synthesis approaches, physicochemical properties, plant uptake mechanisms and biological interactions of phytoderived nanoparticles. Additionally, it addresses biosafety concerns, environmental implications and future research priorities to facilitate the sustainable integration of phytonanotechnology into fruit crop management. By consolidating recent advances and identifying future directions, this review seeks to support the development of eco-friendly, efficient and resilient fruit production systems capable of meeting global food and nutritional security challenges.

2. Phytosynthesis of nanoparticles

Phytosynthesis of nanoparticles represents a biologically driven and environmentally sustainable approach to nanomaterial production that has gained substantial attention in agricultural and horticultural research. This green synthesis strategy utilizes plant-derived biomolecules to reduce metal salts into stable nanoparticles while simultaneously providing natural capping and stabilization. In contrast to conventional chemical and physical synthesis routes, which often involve hazardous reducing agents, extreme reaction conditions and significant energy inputs, phytosynthesis operates under mild temperatures, ambient pressure and aqueous conditions, making it a safer and more sustainable alternative (Iravani and Varma, 2020; Varma, 2023). The growing interest in phytosynthesized nanoparticles is largely attributed to their eco-friendly nature, cost-effectiveness, scalability and enhanced biological compatibility, particularly in plant-based systems such as fruit crops. The fundamental principle of phytosynthesis lies in the redox potential of plant secondary metabolites. Plant extracts contain a diverse array

of bioactive compounds, including phenolics, flavonoids, terpenoids, alkaloids, tannins, proteins, polysaccharides and organic acids, which collectively act as reducing and stabilizing agents during nanoparticle formation (Ahmed *et al.*, 2021). These phytochemicals donate electrons to metal ions such as Ag⁺, Au³⁺, Zn²⁺, Fe³⁺ and Cu²⁺, converting them into their respective zero-valent or oxide nanoparticle forms. Simultaneously, functional groups such as hydroxyl, carboxyl, amine and carbonyl groups bind to the nanoparticle surface, preventing aggregation and enhancing colloidal stability (Rai *et al.*, 2021). This dual functionality distinguishes phytosynthesis from microbial or chemically mediated nanoparticle synthesis methods.

Plant-based nanoparticle synthesis can be carried out using various plant parts, including leaves, fruits, peels, seeds, bark, roots, flowers and latex. In the context of fruit crops, both edible and non-edible tissues, as well as agro-industrial residues, have been successfully employed for nanoparticle production. Fruit peels and pomace from mango, banana, citrus, apple, pomegranate and grape processing industries are particularly rich in phenolic compounds and antioxidants, making them highly effective substrates for nanoparticle synthesis (Patel *et al.*, 2021; Varma, 2023). The utilization of such waste biomass not only enhances the sustainability of the synthesis process but also supports circular economy models by converting agricultural waste into high-value nanomaterials. The phytosynthesis process typically involves the preparation of an aqueous plant extract followed by its reaction with a metal salt solution under controlled conditions. Parameters such as extract concentration, metal ion concentration, pH, temperature, reaction time and light exposure significantly influence nanoparticle size, shape, yield and stability (Singh *et al.*, 2021). For instance, alkaline pH conditions often favor rapid reduction and the formation of smaller nanoparticles, while acidic environments may result in slower kinetics and larger particle sizes. Temperature also plays a crucial role, as elevated temperatures accelerate reaction rates but may degrade heat-sensitive phytochemicals. Optimization of these parameters is therefore essential to achieve reproducible and application-specific nanoparticle characteristics, particularly for use in fruit crop systems where dose and size-dependent effects are critical.

Phytosynthesized nanoparticles encompass a wide range of nanomaterial types, broadly categorized into metallic nanoparticles, metal oxide nanoparticles and nanoencapsulated phytochemicals. Metallic nanoparticles such as silver, gold, copper and iron have been extensively studied due to their antimicrobial properties and potential applications in disease management (Khan *et al.*, 2021). Among these, silver nanoparticles synthesized using plant extracts have demonstrated strong antifungal and antibacterial activity against several fruit crop pathogens. Metal oxide nanoparticles, including zinc oxide, titanium dioxide, iron oxide and copper oxide, are particularly relevant for nutritional enhancement and stress mitigation due to their role as micronutrient sources and redox-active agents (Kah *et al.*, 2020; Seleiman *et al.*, 2022). Nanoencapsulation of plant bioactives represents an emerging area in phytonanotechnology, enabling controlled delivery and enhanced stability of phytochemicals for plant protection and growth promotion. One of the defining advantages of phytosynthesized nanoparticles is their enhanced biological functionality derived from plant-based surface coatings. Unlike chemically synthesized nanoparticles that often require synthetic stabilizers, phyto-derived nanoparticles are naturally capped with bioactive compounds that improve their interaction

with plant tissues (Tripathi *et al.*, 2023). These surface-bound phytochemicals can modulate nanoparticle solubility, mobility and bioavailability, thereby influencing uptake, translocation and physiological responses in fruit crops. Additionally, the presence of natural capping agents reduces the risk of cytotoxicity and enhances environmental compatibility, making phytosynthesized nanoparticles more suitable for agricultural deployment.

In fruit crop systems, the physicochemical properties of phytosynthesized nanoparticles play a crucial role in determining their effectiveness. Particle size influences penetration through leaf cuticles, stomata and root epidermal cells, while shape and surface charge affect interaction with cellular membranes and transport pathways (Lvet *et al.*, 2022). Smaller nanoparticles with high surface area-to-volume ratios exhibit greater reactivity and bioavailability, allowing them to elicit physiological responses at lower concentrations. However, excessively small particles may pose phytotoxic risks if not properly optimized. Therefore, achieving an optimal balance between efficacy and safety remains a key consideration in phytonanotechnology research. Another important aspect of phytosynthesis is the reproducibility and standardization of nanoparticle production. Variability in plant extract composition due to species differences, growth conditions, developmental stages and extraction methods can lead to inconsistencies in nanoparticle characteristics (Kookana *et al.*, 2020). This variability poses challenges for large-scale production and regulatory approval. Recent studies have emphasized the need for standardized protocols, including detailed characterization of plant extracts, reaction conditions and nanoparticle properties, to ensure consistency and reliability (Kah *et al.*, 2022). Advances in analytical techniques and process optimization are expected to play a pivotal role in addressing these challenges. From an environmental perspective, phytosynthesized nanoparticles are considered more sustainable than their chemically synthesized counterparts. The avoidance of toxic solvents and reducing agents significantly reduces environmental pollution and occupational hazards. Moreover, the biodegradability of plant-derived capping agents enhances the environmental fate of these nanoparticles, potentially reducing long-term accumulation in soil and water systems (Carvalho, 2021). This aspect is particularly important for fruit crops, which are often cultivated in ecologically sensitive regions and directly consumed by humans.

The relevance of phytosynthesized nanoparticles to fruit crop management extends beyond their synthesis to their functional integration into agricultural practices. Their compatibility with foliar sprays, soil amendments, seed treatments and postharvest applications provides flexibility in deployment across different stages of fruit production (Raliya *et al.*, 2021). Additionally, the possibility of tailoring nanoparticle properties through controlled synthesis enables the development of crop-specific and stress-specific formulations, enhancing precision horticulture approaches. Despite significant progress, several challenges remain in translating phytosynthesis from laboratory-scale studies to field-level applications in fruit crops. Issues related to scalability, cost-effectiveness, shelf-life stability and regulatory compliance need to be addressed before widespread adoption can be achieved (Elmer and White, 2022). Furthermore, comprehensive assessments of long-term environmental and food safety impacts are essential to build public trust and regulatory confidence in phyto-nanotechnology.

3. Physicochemical characterization of phytosynthesized nanoparticles

Comprehensive physicochemical characterization is a critical step in understanding the functional behavior, biological interactions and application potential of phytosynthesized nanoparticles in fruit crops. The unique properties of nanoparticles, including their size, morphology, crystallinity, surface chemistry and stability, largely determine their uptake, translocation, bioavailability and biological effects in plant systems. Given that phytosynthesized nanoparticles are produced using complex plant extracts containing diverse phytochemicals, detailed characterization is essential to ensure reproducibility, safety and efficacy. Advanced analytical techniques are therefore routinely employed to elucidate the structural and functional attributes of these nanomaterials before their deployment in fruit crop management (Kah *et al.*, 2022; Tripathi *et al.*, 2023).

3.1 Particle size, shape and morphology

Particle size and morphology are among the most influential factors governing the interaction of nanoparticles with fruit crop tissues. Phytosynthesized nanoparticles typically exhibit sizes ranging from a few nanometers to several tens of nanometers, depending on the plant source, synthesis conditions and metal precursor used (Singh *et al.*, 2021). Smaller nanoparticles possess a higher surface area-to-volume ratio, which enhances their reactivity and facilitates efficient penetration through plant barriers such as cuticles, stomata and root epidermal cells. In fruit crops, nanoparticles with sizes below 50 nm have been reported to show improved foliar absorption and vascular transport compared to larger particles (Lv *et al.*, 2022). Morphological characteristics such as spherical, rod-shaped, triangular, cubic, or hexagonal structures also influence nanoparticle behavior. Phytosynthesized nanoparticles are predominantly spherical due to isotropic growth regulated by phytochemical capping agents, although, anisotropic shapes may form under specific synthesis conditions (Rai *et al.*, 2021). Shape-dependent differences in cellular interaction, dissolution rate and antimicrobial activity have been reported, suggesting that morphology plays a role in determining functional performance in fruit crop systems. Transmission electron microscopy (TEM) and scanning electron microscopy (SEM) are widely used to visualize nanoparticle morphology and assess size distribution with high spatial resolution.

3.2 Crystallinity and structural properties

Crystallinity is a defining characteristic that influences the stability, solubility and reactivity of phytosynthesized nanoparticles. Crystalline nanoparticles generally exhibit greater structural stability and predictable physicochemical behavior compared to amorphous forms. X-ray diffraction (XRD) analysis is the primary technique used to determine crystalline structure, phase composition and average crystallite size of phytosynthesized nanoparticles (Khan *et al.*, 2021). Diffraction patterns typically reveal characteristic peaks corresponding to face-centered cubic or hexagonal crystal structures, depending on the type of metal or metal oxide synthesized. In fruit crop applications, the crystalline nature of nanoparticles affects nutrient release dynamics and antimicrobial efficacy. For instance, crystalline zinc oxide or iron oxide nanoparticles synthesized using plant extracts have shown enhanced micronutrient availability and redox activity, contributing to improved physiological performance under stress conditions (Seleiman *et al.*, 2022). The Scherrer equation is often employed to estimate crystallite size, although, discrepancies

between crystallite size and particle size may arise due to aggregation or surface coatings derived from plant metabolites. Understanding these structural attributes is essential for tailoring nanoparticles to specific horticultural applications.

3.3 Surface chemistry and functional groups

Surface chemistry plays a pivotal role in determining the biological identity and functional behavior of phytosynthesized nanoparticles. Unlike chemically synthesized nanoparticles that require synthetic stabilizers, phytosynthesized nanoparticles are naturally capped with plant-derived biomolecules, including phenolics, flavonoids, proteins, polysaccharides and organic acids (Ahmed *et al.*, 2021). These surface-bound compounds influence nanoparticle stability, solubility and interaction with plant cells and pathogens. Fourier transform infrared spectroscopy (FTIR) is commonly used to identify functional groups associated with nanoparticle surfaces. FTIR spectra typically reveal characteristic absorption bands corresponding to hydroxyl, carboxyl, amine and carbonyl groups, confirming the involvement of plant phytochemicals in nanoparticle synthesis and stabilization (Iravani and Varma, 2020). In fruit crops, these surface functional groups enhance nanoparticle adhesion to leaf surfaces, facilitate cellular uptake and modulate physiological responses. Additionally, the presence of bioactive capping agents can impart intrinsic antimicrobial and antioxidant properties, contributing to the multifunctional nature of phytosynthesized nanoparticles.

3.4 Surface charge and colloidal stability

Surface charge, commonly expressed as zeta potential, is a key indicator of nanoparticle stability in suspension. Phytosynthesized nanoparticles generally exhibit negative or moderately positive zeta potential values due to the adsorption of plant-derived biomolecules on their surface (Kah *et al.*, 2020). Nanoparticles with high absolute zeta potential values are more stable due to electrostatic repulsion, which prevents aggregation and sedimentation. Colloidal stability is particularly important for agricultural applications, as nanoparticles are often applied as aqueous suspensions through foliar sprays or soil drenches. Unstable formulations may aggregate, reducing bioavailability and application efficiency. Dynamic light scattering (DLS) is widely used to assess hydrodynamic size distribution and zeta potential, providing insights into nanoparticle dispersion behavior under different environmental conditions (Zhang *et al.*, 2021). In fruit crop systems, stable nanoparticle suspensions ensure uniform coverage, improved uptake and consistent biological responses.

3.5 Optical properties and UV-visible spectroscopy

UV-visible spectroscopy is a rapid and effective technique for monitoring nanoparticle formation and optical properties. Phytosynthesized metallic nanoparticles exhibit characteristic surface plasmon resonance (SPR) bands resulting from collective oscillation of electrons on the nanoparticle surface when exposed to light (Raliya *et al.*, 2021). The position, intensity and shape of SPR peaks provide valuable information about particle size, shape, concentration and aggregation state. In fruit crop research, UV-visible spectroscopy is frequently used to confirm nanoparticle synthesis and monitor reaction kinetics during phytosynthesis. Shifts in SPR peaks may indicate changes in particle size or surface modification due to different plant extracts or synthesis conditions. Optical properties also influence light absorption and scattering, which may indirectly affect

photosynthetic processes when nanoparticles interact with leaf tissues. Although, the physiological implications of nanoparticle optical properties are still under investigation, emerging evidence suggests their potential role in modulating light-use efficiency in plants (Hasan *et al.*, 2023).

3.6 Elemental composition and purity

Determining elemental composition and purity is essential to ensure the safety and effectiveness of phytosynthesized nanoparticles intended for fruit crop applications. Techniques such as energy-dispersive X-ray spectroscopy (EDX or EDS) coupled with electron microscopy are commonly employed to confirm the presence of target elements and assess purity (Khan *et al.*, 2021). Inductively coupled plasma-mass spectrometry (ICP-MS) may also be used for quantitative elemental analysis, particularly when evaluating micronutrient-based nanoparticles. Elemental analysis is critical for distinguishing nanoparticles from residual plant-derived impurities or unreacted metal precursors. In fruit crops, accurate knowledge of elemental composition helps in determining appropriate dosages and minimizing the risk of phytotoxicity or metal accumulation in edible tissues. Ensuring high purity and controlled composition is therefore essential for both agronomic performance and food safety considerations.

3.7 Importance of characterization for fruit crop applications

The comprehensive physicochemical characterization of phytosynthesized nanoparticles provides a scientific foundation for their rational application in fruit crops. Variations in size, shape, surface chemistry and stability can lead to markedly different biological outcomes, emphasizing the need for standardized characterization protocols (Kookana *et al.*, 2020). In fruit crops, where edible tissues are directly consumed, understanding nanoparticle behavior is particularly important to balance efficacy with safety. Moreover, characterization data enable meaningful comparisons across studies and facilitate the development of regulatory frameworks for nano-enabled agricultural inputs. As phytonanotechnology advances toward field-scale implementation, detailed characterization will play a crucial role in ensuring consistency, reproducibility and public acceptance (Elmer and White, 2022).

4. Uptake, translocation and interaction of phytosynthesized nanoparticles in fruit crops

Understanding the uptake, translocation and interaction of phytosynthesized nanoparticles within fruit crop systems is essential for optimizing their efficacy and ensuring biosafety. Once applied to plants, nanoparticles interact with complex anatomical, physiological and biochemical barriers that influence their absorption, movement, accumulation and biological activity. These processes are governed by nanoparticle physicochemical properties such as size, shape, surface charge and surface chemistry, as well as plant-specific traits including species, developmental stage, tissue structure and environmental conditions (Kah *et al.*, 2022; Tripathi *et al.*, 2023). In fruit crops, which often exhibit perennial growth habits and complex canopy architectures, understanding nanoparticle fate within plant systems is particularly critical for targeted and sustainable applications.

4.1 Pathways of nanoparticle entry into fruit crops

Phytosynthesized nanoparticles can enter fruit crops through multiple pathways depending on the mode of application, including

foliar application, soil/root uptake and seed or propagule treatments. Foliar application is one of the most commonly employed methods in fruit crops due to its rapid response and direct delivery to metabolically active tissues. Nanoparticles applied to leaf surfaces may enter through stomatal openings, cuticular cracks, trichomes and hydrophilic pores in the cuticle (Lvet *et al.*, 2022). Due to their nanoscale dimensions, Phytosynthesized nanoparticles exhibit enhanced penetration compared to bulk formulations, particularly when stabilized by plant-derived capping agents that improve adhesion and wettability. Root uptake represents another major entry route, especially for nanoparticles applied through soil amendments or fertigation systems. Nanoparticles in the rhizosphere interact with root exudates, soil colloids and microbial communities before being absorbed by root epidermal cells (Raliya *et al.*, 2021). Entry may occur through apoplastic pathways *via.*, cell wall pores or symplastic pathways following endocytosis. In fruit crops with extensive root systems, such as citrus, mango and apple, root-mediated uptake offers a promising route for sustained nutrient delivery and stress mitigation. Seed and propagule treatments, although, less common in perennial fruit crops, have also been explored in nursery-stage plants to enhance early vigor and stress tolerance (Seleimanet *et al.*, 2022).

4.2 Translocation and distribution within plant tissues

Following entry, phytosynthesized nanoparticles may be translocated within fruit crops through vascular tissues, primarily the xylem and phloem. Xylem-mediated transport facilitates the upward movement of nanoparticles from roots to aerial tissues driven by transpiration, while phloem transport enables redistribution from source to sink organs, including developing fruits (Zhang *et al.*, 2021). The extent and efficiency of translocation depend on nanoparticle size, solubility and surface properties, as well as plant physiological status. Studies have shown that smaller nanoparticles with hydrophilic surface coatings are more readily translocated within plant tissues, whereas larger or aggregated particles tend to accumulate at the site of entry (Lv *et al.*, 2022). In fruit crops, nanoparticle accumulation has been reported in roots, leaves, stems and fruits, although, concentrations generally decrease with increasing distance from the application site. Controlled translocation is desirable for nutritional enhancement and disease management, but excessive accumulation in edible fruit tissues raises food safety concerns. Therefore, understanding distribution patterns is essential for balancing efficacy and safety in fruit crop applications.

4.3 Cellular uptake and intracellular localization

At the cellular level, phytosynthesized nanoparticles interact with plant cells through complex mechanisms involving adsorption, internalization and intracellular trafficking. Nanoparticles may adhere to cell walls through electrostatic interactions or hydrogen bonding with cell wall components such as cellulose, pectins and hemicelluloses (Hasan *et al.*, 2023). Internalization into plant cells often occurs *via.*, endocytosis, a process influenced by nanoparticle size, surface charge and functionalization. Once inside the cell, nanoparticles may localize in various organelles, including vacuoles, chloroplasts, mitochondria and the cytoplasm. Vacuolar sequestration is considered a detoxification mechanism that limits potential cytotoxic effects, while localization in chloroplasts and mitochondria may directly influence photosynthesis and respiration (Tripathi *et al.*, 2023). In fruit crops, such intracellular interactions can modulate

metabolic pathways associated with growth, stress response and fruit development. However, excessive nanoparticle accumulation at the cellular level may disrupt membrane integrity and enzyme function, highlighting the importance of dose optimization.

4.4 Interaction with plant metabolic and signalling pathways

Phytosynthesized nanoparticles do not act merely as passive carriers but actively interact with plant metabolic and signalling networks. Upon uptake, nanoparticles can influence gene expression, enzyme activity and hormonal balance, thereby modulating physiological processes in fruit crops (Latef *et al.*, 2021). One of the key mechanisms involves the regulation of reactive oxygen species (ROS) homeostasis. At optimal concentrations, nanoparticles can enhance antioxidant enzyme activities such as superoxide dismutase, catalase and peroxidase, leading to improved stress tolerance. Conversely, excessive nanoparticle exposure may induce oxidative stress, resulting in cellular damage. Nanoparticles have also been shown to interact with plant hormone signalling pathways, including auxins, cytokinins, gibberellins and abscisic acid, which play crucial roles in fruit set, development and ripening (Seleiman *et al.*, 2022). In addition, phytosynthesized nanoparticles may act as elicitors, triggering defense-related signalling cascades involving salicylic acid, jasmonic acid and ethylene pathways. Such interactions contribute to enhanced resistance against pathogens and abiotic stresses in fruit crops.

4.5 Influence of nanoparticle properties and plant factors

The fate and behavior of phytosynthesized nanoparticles within fruit crops are strongly influenced by both nanoparticle characteristics and plant-specific factors. Particle size, shape, surface charge and surface functionalization determine mobility, bioavailability and interaction with plant tissues (Kah *et al.*, 2020). For instance, negatively charged nanoparticles may exhibit reduced membrane penetration but greater stability in suspension, whereas positively charged particles may show enhanced cellular uptake but higher phytotoxic potential. Plant species, developmental stage and physiological condition also play critical roles in nanoparticle uptake and response. Young, actively growing tissues generally exhibit higher uptake rates than mature tissues, while stress conditions may alter membrane permeability and transport processes (Savary *et al.*, 2022). In perennial fruit crops, seasonal variations in growth and metabolism further influence nanoparticle behavior, underscoring the need for crop and stage-specific application strategies.

5. Role of phytosynthesized nanoparticles in fruit crop nutrition

Adequate and balanced nutrition is a fundamental requirement for optimal growth, productivity and fruit quality in horticultural systems. Fruit crops, owing to their high biomass production and prolonged growth cycles, demand precise and sustained nutrient supply throughout different phenological stages. However, conventional fertilization practices often suffer from low nutrient use efficiency due to leaching, fixation, volatilization and uneven distribution within plant tissues. In this context, phytosynthesized nanoparticles have emerged as innovative nano-enabled nutrient carriers capable of enhancing nutrient availability, uptake and utilization in fruit crops. Their nanoscale dimensions, high surface area and biologically active surface coatings allow them to interact more effectively with plant physiological processes, offering new opportunities for sustainable fruit crop nutrition management (Dimkpa and Bindraban, 2020; Raliya *et al.*, 2021).

5.1 Enhancement of macroand micronutrient availability

Phytosynthesized nanoparticles play a significant role in improving the availability of both macro and micronutrients in fruit crops. Nanoformulations of essential nutrients such as nitrogen, phosphorus, potassium, zinc, iron, copper, manganese and calcium have been shown to exhibit superior solubility and mobility compared to conventional bulk fertilizers (Kah *et al.*, 2020). When synthesized using plant extracts, these nanoparticles are naturally capped with phytochemicals that enhance their dispersion and prevent aggregation, ensuring sustained nutrient release in the rhizosphere and phyllosphere. Micronutrient deficiencies are particularly prevalent in fruit crops due to high nutrient demand during flowering and fruit development stages. Phytosynthesized zinc and iron nanoparticles have demonstrated improved uptake efficiency and translocation, leading to enhanced chlorophyll synthesis, enzyme activation and metabolic regulation (Seleiman *et al.*, 2022). The controlled release behavior of nanonutrients reduces nutrient losses through leaching and fixation, thereby improving nutrient availability over extended periods. This is especially beneficial in perennial fruit orchards, where maintaining optimal soil fertility is a long-term challenge.

5.2 Improvement of nutrient uptake and use efficiency

One of the major advantages of phytosynthesized nanoparticles is their ability to enhance nutrient uptake and use efficiency in fruit crops. Due to their small size and large surface area, nanoparticles can penetrate plant tissues more efficiently and reach target sites at lower application rates compared to conventional fertilizers (Lv *et al.*, 2022). Foliar-applied nanonutrients can enter through stomata and cuticular pores, while root-applied nanoparticles can traverse apoplastic and symplastic pathways, facilitating efficient absorption. Improved nutrient use efficiency reduces the total amount of fertilizer required, thereby lowering production costs and minimizing environmental impacts. Studies have reported that nanofertilizer applications can achieve comparable or superior nutritional outcomes at significantly reduced doses, highlighting their potential for precision nutrition in fruit crops (Raliya *et al.*, 2021). Furthermore, phytosynthesized nanoparticles can modulate the expression of nutrient transporter genes and enhance enzymatic activity involved in nutrient assimilation, leading to more efficient utilization of absorbed nutrients (Hasan *et al.*, 2023).

5.3 Influence on plant growth and physiological processes

Enhanced nutritional status resulting from phytosynthesized nanoparticle application directly influences growth and physiological performance in fruit crops. Improved nutrient availability and uptake contribute to enhanced root development, leaf area expansion, photosynthetic efficiency and biomass accumulation (Latef *et al.*, 2021). Nanonutrients such as iron and magnesium play critical roles in chlorophyll biosynthesis and photosynthetic electron transport, while zinc and manganese are essential cofactors for numerous metabolic enzymes. Phytosynthesized nanoparticles have also been reported to influence stomatal conductance, transpiration rates and water-use efficiency, thereby optimizing physiological processes under both normal and stress conditions (Seleiman *et al.*, 2022). In fruit crops, these physiological improvements translate into better flowering, fruit set and fruit retention, ultimately contributing to higher yields and improved crop performance.

5.4 Enhancement of fruit yield and yield attributes

Improved nutritional management through phytosynthesized nanoparticles has a direct impact on fruit yield and yield-related attributes. Enhanced nutrient availability during critical developmental stages supports reproductive growth, leading to increased flower initiation, improved pollination success and reduced fruit drop (Zhang *et al.*, 2021). In several fruit crops, nano-nutrient applications have been associated with increased fruit number, size and weight, reflecting improved sourcesink relationships. The sustained release and targeted delivery of nutrients also ensure continuous nutrient supply during fruit enlargement and maturation phases. This is particularly important in fruit crops with extended fruit development periods, where nutrient deficiencies can severely compromise yield potential. By improving nutrient use efficiency and reducing nutrient stress, phytosynthesized nanoparticles contribute to stable and enhanced fruit yields under diverse growing conditions.

5.5 Improvement of fruit quality and nutritional attributes

Beyond yield enhancement, phytosynthesized nanoparticles significantly influence fruit quality and nutritional composition. Adequate micronutrient supply is essential for the synthesis of sugars, organic acids, vitamins and secondary metabolites that determine fruit flavor, color, texture and nutritional value (Slavin and Lloyd, 2021). Nano-nutrient applications have been reported to increase total soluble solids, sugaracid balance, vitamin C content and mineral concentration in fruits (Wang *et al.*, 2022). Phytosynthesized nanoparticles may also stimulate the biosynthesis of antioxidant compounds such as phenolics, flavonoids and carotenoids, thereby enhancing the nutraceutical value of fruits. The presence of phytochemical coatings on nanoparticles may further contribute to these effects by acting as elicitors of secondary metabolism. Improved fruit quality not only enhances consumer acceptance but also increases market value and export potential, particularly in quality-sensitive international markets.

5.6 Integration with sustainable and precision nutrition strategies

The use of phytosynthesized nanoparticles aligns closely with the principles of sustainable and precision nutrition in fruit crop production. By reducing fertilizer inputs, minimizing nutrient losses and enhancing efficiency, nano-enabled nutrition contributes to environmentally responsible horticulture (Carvalho, 2021). Moreover, the possibility of tailoring nanoparticle formulations to specific nutrient requirements, crop species and growth stages enables site-specific and stage-specific nutrient management. Integration of phytosynthesized nanoparticles with precision horticulture tools such as fertigation systems, sensor-based nutrient monitoring and decision support systems can further optimize nutrient delivery in fruit orchards (Godfray *et al.*, 2021). Such approaches are particularly relevant under climate change scenarios, where nutrient dynamics are increasingly influenced by variable environmental conditions.

6. Role of phytosynthesized nanoparticles in abiotic stress tolerance of fruit crops

Abiotic stresses represent one of the most significant constraints to sustainable fruit crop production worldwide. Fruit crops are frequently exposed to adverse environmental conditions such as

drought, salinity, extreme temperatures and oxidative stress, which collectively impair growth, yield and fruit quality. Climate change has further intensified the frequency and severity of these stresses, posing serious challenges to orchard productivity and stability. Conventional management practices, including irrigation, soil amendments and chemical protectants, often provide limited and short-term relief. In this context, phytosynthesized nanoparticles have emerged as promising nano-enabled tools capable of enhancing stress tolerance in fruit crops by modulating physiological, biochemical and molecular responses (Latef *et al.*, 2021; Hasan *et al.*, 2023).

6.1 Role in drought stress tolerance

Drought stress is one of the most critical abiotic constraints affecting fruit crops, particularly in arid and semi-arid regions. Water deficit conditions disrupt cellular homeostasis, reduce photosynthetic activity and impair nutrient transport, ultimately leading to yield losses. Phytosynthesized nanoparticles have been shown to mitigate drought-induced damage by enhancing water-use efficiency, maintaining cellular integrity and improving physiological resilience (Seleiman *et al.*, 2022). Application of phytosynthesized nanoparticles can improve root architecture by promoting deeper and more extensive root systems, thereby enhancing water uptake from soil profiles. Additionally, nanoparticles influence stomatal regulation, allowing plants to balance transpiration and carbon assimilation under limited water availability (Lv *et al.*, 2022). Enhanced accumulation of osmolytes such as proline, glycine betaine and soluble sugars has also been reported in nanoparticle-treated plants, contributing to osmotic adjustment and cellular hydration during drought stress (Latef *et al.*, 2021).

6.2 Role in salinity stress mitigation

Salinity stress poses a major challenge to fruit crop production in coastal regions and irrigated areas affected by soil salinization. High salt concentrations disrupt ion homeostasis, induce osmotic stress and generate oxidative damage in plant tissues. Phytosynthesized nanoparticles have demonstrated the ability to alleviate salinity stress by regulating ion balance, enhancing antioxidant defenses and improving metabolic stability (Hasan *et al.*, 2023). Nano-formulations of essential nutrients such as zinc, iron and silicon synthesized through plant-based routes have been shown to reduce sodium uptake while maintaining potassium and calcium homeostasis in plants (Kah *et al.*, 2020). This selective ion regulation helps preserve membrane integrity and enzymatic function under saline conditions. Furthermore, phytosynthesized nanoparticles enhance the activity of antioxidant enzymes, thereby reducing salt-induced oxidative stress and lipid peroxidation. These mechanisms collectively contribute to improved growth and fruit development under saline environments.

6.3 Role in temperature stress tolerance

Extreme temperature conditions, including both heat and cold stress, significantly affect fruit crop productivity and quality. High temperatures can impair photosynthesis, pollen viability and fruit set, while low temperatures may cause chilling injury and metabolic dysfunction. Phytosynthesized nanoparticles have shown potential in enhancing tolerance to temperature extremes by stabilizing cellular structures and regulating stress-responsive pathways (Zhang *et al.*, 2021). Under heat stress, nanoparticles can enhance the synthesis of

heat shock proteins and antioxidants, which protect cellular proteins and membranes from thermal damage (Hasan *et al.*, 2023). Improved chlorophyll stability and photosynthetic efficiency have also been observed in nanoparticle-treated plants exposed to elevated temperatures. In cold stress conditions, phytosynthesized nanoparticles may help maintain membrane fluidity, regulate carbohydrate metabolism and reduce oxidative injury, thereby improving cold tolerance in fruit crops.

6.4 Modulation of antioxidant defense systems

Oxidative stress is a common consequence of most abiotic stresses, characterized by excessive production of reactive oxygen species (ROS) that damage cellular components. The ability of phytosynthesized nanoparticles to modulate antioxidant defense systems is a key mechanism underlying their stress-mitigating effects. At optimal concentrations, nanoparticles enhance the activities of enzymatic antioxidants such as superoxide dismutase, catalase, peroxidase and ascorbate peroxidase, as well as non-enzymatic antioxidants including phenolics, flavonoids and ascorbic acid (Latef *et al.*, 2021). By maintaining ROS homeostasis, phytosynthesized nanoparticles protect cellular membranes, proteins and nucleic acids from oxidative damage. This antioxidant regulation is particularly important in fruit crops, where oxidative stress can adversely affect fruit development, ripening and postharvest quality. The phytochemical coatings present on plant-derived nanoparticles may further enhance antioxidant capacity, providing synergistic protection against stress-induced oxidative damage (Ahmed *et al.*, 2021).

6.5 Regulation of hormonal and molecular responses

Phytosynthesized nanoparticles influence plant hormonal balance and gene expression, thereby contributing to abiotic stress tolerance at the molecular level. Stress conditions often alter the levels of plant hormones such as abscisic acid, auxins, cytokinins and ethylene, which regulate growth and stress responses. Nanoparticle treatments have been shown to modulate hormone signalling pathways, helping plants maintain growth-stress balance under adverse conditions (Seleiman *et al.*, 2022). At the molecular level, phytosynthesized nanoparticles can regulate the expression of stress-responsive genes involved in antioxidant defense, osmolyte biosynthesis, ion transport and signal transduction (Tripathi *et al.*, 2023). Such regulation enhances the plant's adaptive capacity and resilience to environmental stressors. Although, molecular-level studies in fruit crops are still limited, emerging evidence suggests that nanoparticle-mediated gene regulation plays a crucial role in stress adaptation.

6.6 Interaction with soil-plant-microbe systems under stress

The effectiveness of phytosynthesized nanoparticles in stress mitigation is also influenced by their interaction with soil and rhizosphere microbial communities. Beneficial soil microorganisms play an important role in nutrient cycling, stress tolerance and plant health. Phytosynthesized nanoparticles, owing to their biogenic origin, are generally more compatible with soil microbiota than chemically synthesized nanomaterials (Carvalho, 2021). Under abiotic stress conditions, nanoparticles may indirectly enhance plant resilience by improving microbial activity, nutrient availability and root-microbe interactions. However, excessive nanoparticle concentrations may disrupt microbial communities, highlighting the importance of dose optimization and environmental assessment (Kookana *et al.*, 2020). Understanding these interactions is essential

for developing holistic stress management strategies in fruit crop systems.

7. Role of phytosynthesized nanoparticles in disease control and plant protection of fruit crops

Plant diseases caused by fungal, bacterial and viral pathogens pose serious threats to fruit crop productivity, quality and economic sustainability. Fruit crops are particularly vulnerable to diseases due to their long growth cycles, dense canopies and favorable microclimates that promote pathogen proliferation. Conventional disease management strategies rely heavily on synthetic fungicides and bactericides, which, although, effective in the short term, have led to increasing problems such as pathogen resistance, environmental contamination, non-target toxicity and pesticide residues in fruits. In response to these challenges, phytosynthesized nanoparticles have emerged as promising alternatives or supplements to conventional plant protection measures. Their unique physicochemical properties and biogenic origin enable effective pathogen suppression while supporting sustainable and environmentally friendly fruit crop production (Elmer and White, 2022; Khan *et al.*, 2021).

7.1 Antimicrobial properties of phytosynthesized nanoparticles

Phytosynthesized nanoparticles exhibit strong antimicrobial activity against a wide range of plant pathogens due to their nanoscale size, high surface reactivity and phytochemical coatings. Metallic nanoparticles such as silver, copper and gold, as well as metal oxide nanoparticles like zinc oxide and copper oxide, have demonstrated broad-spectrum antifungal and antibacterial effects when synthesized using plant extracts (Khan *et al.*, 2021). The presence of plant-derived capping agents enhances nanoparticle stability and bioactivity, contributing to their antimicrobial efficacy. The antimicrobial mechanisms of phytosynthesized nanoparticles include disruption of pathogen cell membranes, generation of reactive oxygen species, interference with enzyme function and inhibition of nucleic acid synthesis (Rai *et al.*, 2021). These multi-target modes of action reduce the likelihood of resistance development compared to single-site chemical fungicides. In fruit crops, nanoparticle-based treatments have shown effectiveness against several economically important pathogens, including those responsible for fruit rots, leaf spots, blights and cankers.

7.2 Control of fungal diseases in fruit crops

Fungal diseases represent the most widespread and damaging category of plant diseases in fruit crops, affecting both pre-harvest and postharvest stages. Phytosynthesized nanoparticles have shown considerable potential in managing fungal pathogens by inhibiting spore germination, mycelial growth and biofilm formation (Elmer and White, 2022). Nanosilver, nanocopper and zinc oxide nanoparticles synthesized using plant extracts have been reported to suppress fungal pathogens at relatively low concentrations, minimizing phytotoxic effects. In fruit crop systems, nanoparticle applications can be integrated into existing disease management programs as foliar sprays, trunk injections, or postharvest treatments. The sustained antimicrobial activity of phytosynthesized nanoparticles allows prolonged protection against fungal infections, reducing the frequency of chemical fungicide applications. Moreover, their effectiveness under diverse environmental conditions enhances disease control reliability in orchard systems characterized by variable climates.

7.3 Management of bacterial and viral diseases

Bacterial diseases in fruit crops, such as blights, cankers and wilts, are often difficult to control due to limited availability of effective bactericides and the emergence of resistant strains. Phytosynthesized nanoparticles offer an alternative approach by directly inhibiting bacterial growth and disrupting pathogenicity mechanisms (Khan *et al.*, 2021). Silver and copper-based nanoparticles have been particularly effective against bacterial pathogens due to their ability to penetrate bacterial cell walls and interfere with metabolic processes. Although, direct antiviral activity of nanoparticles in plants is less well understood, phytosynthesized nanoparticles can indirectly suppress viral diseases by strengthening host defense mechanisms and reducing vector populations (Elmer and White, 2022). By enhancing plant vigour and inducing systemic resistance, nanoparticles may limit viral replication and spread within fruit crops. This indirect mode of action is particularly valuable given the lack of curative treatments for most plant viral diseases.

7.4 Induction of plant defense responses

Beyond direct antimicrobial effects, phytosynthesized nanoparticles play a significant role in activating plant defense responses. Nanoparticles can act as elicitors, triggering innate immune responses in fruit crops through the activation of defense-related signalling pathways (Tripathi *et al.*, 2023). These pathways involve key signalling molecules such as salicylic acid, jasmonic acid and ethylene, which regulate systemic acquired resistance and induced systemic resistance. Activation of defense enzymes such as phenylalanine ammonia-lyase, peroxidases, chitinases and β -1,3-glucanases enhances the plant's ability to resist pathogen invasion. Additionally, increased accumulation of phenolics, lignin and phytoalexins strengthens physical and biochemical barriers against pathogens (Latef *et al.*, 2021). The dual role of phytosynthesized nanoparticles in direct pathogen inhibition and host defense activation provides a robust and sustainable disease management strategy for fruit crops.

7.5 Role in integrated disease management strategies

Phytosynthesized nanoparticles can be effectively integrated into integrated disease management (IDM) programs for fruit crops. Their compatibility with biological control agents, cultural practices and reduced-risk fungicides makes them suitable components of holistic plant protection systems (Carvalho, 2021). Nanoenabled formulations can reduce reliance on conventional pesticides, thereby lowering environmental risks and production costs. In orchard systems, nanoparticle-based treatments may be combined with practices such as pruning, sanitation, resistant cultivars and biological control to achieve durable disease suppression. The ability to tailor nanoparticle properties for specific pathogens and crop stages further enhances their utility in precision disease management. Such integrated approaches are particularly important for fruit crops, where disease pressure is high and market demands for residue-free produce are stringent.

8. Postharvest applications of phytosynthesized nanoparticles in fruit crops

Postharvest losses constitute a major challenge in fruit supply chains, particularly in developing countries where inadequate storage, transportation and handling infrastructure exacerbate quality deterioration and decay. Fruits are highly perishable commodities

due to their high moisture content, active metabolism and susceptibility to microbial infections. Postharvest losses not only reduce economic returns to growers but also compromise food and nutritional security. Conventional postharvest treatments rely on synthetic fungicides, preservatives and controlled atmosphere technologies, which may raise concerns regarding chemical residues, environmental impact and consumer acceptance. In this context, phytosynthesized nanoparticles have emerged as innovative and sustainable alternatives for improving postharvest quality, extending shelf-life and reducing losses in fruit crops (Rai *et al.*, 2021; Elmer and White, 2022).

8.1 Antimicrobial control of postharvest pathogens

Postharvest diseases caused by fungal and bacterial pathogens are among the leading causes of fruit spoilage during storage and transport. Phytosynthesized nanoparticles exhibit strong antimicrobial activity against postharvest pathogens through multiple mechanisms, including membrane disruption, oxidative stress induction and inhibition of spore germination (Khan *et al.*, 2021). Nanosilver, nanocopper and zinc oxide nanoparticles synthesized using plant extracts have shown effectiveness against common postharvest pathogens responsible for fruit rots and decay. The biogenic nature of phytosynthesized nanoparticles enhances their suitability for postharvest applications, as plant-derived capping agents reduce toxicity and improve compatibility with fruit tissues. When applied at optimal concentrations, these nanoparticles can suppress microbial growth without adversely affecting fruit quality attributes such as color, texture and flavor. Their broad-spectrum antimicrobial activity also reduces the need for multiple chemical treatments, contributing to simplified and safer postharvest management practices.

8.2 Nanocoatings for shelf-life extension

Nanocoatings incorporating phytosynthesized nanoparticles represent one of the most promising postharvest applications in fruit crops. These coatings form thin, uniform layers on fruit surfaces, acting as semi-permeable barriers that regulate gas exchange, reduce moisture loss and delay ripening processes (Rai *et al.*, 2021). By modulating respiration rate and ethylene production, nanocoatings help maintain fruit firmness, freshness and visual appeal during storage. Phytosynthesized nanoparticles embedded in edible coatings can also provide sustained antimicrobial protection, further enhancing shelf-life extension. The integration of natural polymers such as chitosan, starch, or alginate with plant-derived nanoparticles creates synergistic effects that improve coating functionality and safety. Such nanoenabled coatings align well with consumer preferences for natural and residue-free postharvest treatments.

8.3 Regulation of physiological and biochemical changes during storage

Postharvest physiological processes such as respiration, transpiration, enzymatic browning and senescence significantly influence fruit quality during storage. Phytosynthesized nanoparticles can modulate these processes by interacting with fruit metabolic pathways and antioxidant systems (Hasan *et al.*, 2023). Nanoparticle treatments have been reported to reduce oxidative stress by enhancing antioxidant enzyme activity, thereby delaying senescence and preserving nutritional quality. In addition, phytosynthesized nanoparticles may influence the activity of enzymes involved in cell wall degradation and softening, contributing to improved textural stability. By

maintaining membrane integrity and reducing lipid peroxidation, nanoparticles help preserve fruit firmness and juiciness over extended storage periods. These physiological benefits are particularly important for climacteric fruits, which undergo rapid metabolic changes during ripening.

8.4 Nanopackaging and smart packaging applications

Beyond direct fruit treatments, phytosynthesized nanoparticles are increasingly being explored in nano-packaging and smart packaging systems. Packaging materials incorporated with plant-derived nanoparticles can provide antimicrobial surfaces that inhibit microbial growth on fruit surfaces during storage and transport (Patel *et al.*, 2021). Such active packaging systems enhance food safety and reduce spoilage without the need for direct chemical application to fruits. Smart packaging incorporating phytosynthesized nanoparticles may also include indicators that monitor fruit freshness, gas composition, or microbial activity. These advanced packaging solutions can provide real-time information on fruit quality, enabling better inventory management and reducing waste across the supply chain. The eco-friendly nature of phytosynthesized nanoparticles enhances their suitability for sustainable packaging innovations.

8.5 Reduction of postharvest losses and economic benefits

The integration of phytosynthesized nanoparticles into postharvest management systems has the potential to significantly reduce postharvest losses and improve economic returns for fruit producers and distributors. Extended shelf-life and reduced decay translate into higher marketable yields, improved export potential and reduced food waste (FAO, 2023). For smallholder farmers and supply chain stakeholders, nano-enabled postharvest technologies can enhance profitability and market access. Moreover, the use of plant-based materials and agricultural waste for nanoparticle synthesis supports cost-effective and locally adaptable solutions. This is particularly relevant for fruit-producing regions where postharvest infrastructure is limited and losses are disproportionately high. By improving postharvest efficiency, phytosynthesized nanoparticles contribute to sustainable food systems and nutritional security.

8.6 Safety and regulatory considerations in postharvest use

Despite their promising potential, the postharvest application of phytosynthesized nanoparticles requires careful evaluation of safety and regulatory aspects. Accumulation of nanoparticles on fruit surfaces or within edible tissues may raise concerns regarding consumer health and regulatory compliance (Kookana *et al.*, 2020). Therefore, thorough assessments of nanoparticle residue levels, biodegradability and potential toxicity are essential before commercialization. Regulatory frameworks governing nanoenabled food technologies vary across regions, highlighting the need for standardized guidelines and risk assessment protocols. Transparent communication of safety data and adherence to international standards will be crucial for consumer acceptance and market adoption of nanoparticle-based postharvest treatments (Elmer and White, 2022).

9. Future prospects of phytosynthesized nanoparticles in fruit crop systems

Phytosynthesized nanoparticles hold considerable promise for advancing sustainable fruit crop production in the face of escalating challenges posed by climate change, resource scarcity and increasing

demand for safe and high-quality fruits. Future research is expected to move beyond proof-of-concept laboratory studies toward field-scale validation and commercialization of nanoenabled technologies tailored specifically for fruit crops. One of the key prospects lies in the development of crop and stage-specific nanoparticle formulations that align with the physiological requirements of different fruit species during critical growth, stress and postharvest phases. Such precision-oriented approaches will enhance efficiency while minimizing unintended environmental impacts. Advances in nanoformulation technologies are likely to improve the stability, controlled release and targeted delivery of phytosynthesized nanoparticles. The integration of nanocarriers with biodegradable polymers and smart delivery systems may enable responsive release of nutrients or protective agents based on environmental cues such as moisture, temperature, or pathogen presence. Additionally, combining phytonanotechnology with precision horticulture tools, including sensors, decision-support systems and remote sensing, offers opportunities to optimize orchard management and reduce input wastage. From a sustainability perspective, the use of fruit processing wastes and underutilized plant biomass for nanoparticle synthesis is expected to expand, supporting circular economy models and reducing production costs. However, large-scale adoption will depend on the establishment of clear regulatory frameworks, standardized safety assessment protocols and public acceptance. Collaborative efforts among researchers, industry stakeholders and policymakers will be crucial for translating phytosynthesized nanoparticle research into practical and socially acceptable solutions.

10. Conclusion

Phytosynthesized nanoparticles represent a promising advancement in sustainable fruit crop management by offering eco-friendly, efficient and multifunctional solutions to contemporary horticultural challenges. Through green synthesis routes utilizing plant derived biomolecules, these nanoparticles provide enhanced nutrient delivery, improved tolerance to abiotic stresses and effective control of plant diseases while reducing reliance on conventional agrochemicals. Their ability to modulate physiological, biochemical and defense responses contribute to improved fruit yield, quality and postharvest shelf life. Moreover, the integration of phytonanotechnology with precision horticulture and circular economy approaches supports climate-resilient and resource-efficient fruit production systems. Despite these advantages, challenges related to standardization, biosafety and regulatory acceptance must be addressed to enable large-scale adoption. Continued interdisciplinary research, field validation and evidence-based policy frameworks will be essential for the responsible deployment of phytosynthesized nanoparticles. Overall, phytonanotechnology holds significant potential to reshape sustainable fruit crop production and enhance global food and nutritional security.

Availability of data and material

All data are provided within the manuscript.

Authorship contribution statement

T. Anitha: Supervision, academic oversight, and overall monitoring of the research work; **M. Kabilan:** Conceptualization, supervision, critical review, and overall guidance of the manuscript; **V. Balamurugan:** Software handling, reference management, data organization, and visualization of the review content; **M. Jayakumar:**

Literature survey, data curation, and critical analysis of published studies; **Adnan A. Khan**: Critical review, validation of scientific content, and final approval of the manuscript.

Consent for publication

All authors gave their full consent for publication and submission to this journal.

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References

- Ahmed, S.; Ahmad, M.; Swami, B. L. and Ikram, S. (2021). A review on plants extract mediated synthesis of silver nanoparticles for antimicrobial applications: A green expertise. *J. Adv. Res.*, **28**:1-14.
- Carvalho, F. P. (2021). Agriculture, pesticides, food security and food safety. *Environmental Science and Policy*, **124**:138-145.
- Dimkpa, C. O. and Bindraban, P. S. (2020). Nanofertilizers: New products for the industry? *J. Agric. Food Chem.*, **68**(24):6462-6473.
- Elmer, W. H. and White, J. C. (2022). The future of nanotechnology in plant pathology. *Annu. Rev. Phytopathol.*, **60**:365-388.
- FAO (2023). The state of food and agriculture 2023: Revealing the true cost of food to transform agrifood systems. Food and Agriculture Organization of the United Nations, Rome.
- Godfray, H. C. J.; Mason-D'Croz, D.; Robinson, S. and Thornton, P. K. (2021). Pathways to sustainable food systems. *Nature Food*, **2**(6):394-403.
- Handford, C. E.; Elliott, C. T. and Campbell, K. (2021). A review of the global pesticide legislation and the scale of challenge in reaching the global harmonization of food safety standards. *Integrated Environmental Assessment and Management*, **17**(5):906-915.
- Hasan, M. K.; Liu, X. and Li, Y. (2023). Nanoparticles-mediated regulation of oxidative stress tolerance in plants. *Environ. Exp. Bot.*, **205**:105110.
- Iravani, S. and Varma, R. S. (2020). Green synthesis, biomedical and biotechnological applications of nanoparticles: An overview. *Green Chem.*, **22**(2):264-297.
- Kah, M.; Hofmann, T. and Matzke, M. (2022). Nanopesticides and nanofertilizers: Emerging contaminants or opportunities for risk mitigation. *Environmental Science: Nano*, **9**(2):377-391.
- Kah, M.; Kookana, R. S.; Gogos, A. and Bucheli, T. D. (2020). A critical evaluation of nanopesticides and nanofertilizers against their conventional analogues. *Nature Nanotechnol.*, **15**(6):517-523.
- Khan, I.; Saeed, K. and Khan, I. (2021). Nanoparticles: Properties, applications and toxicities. *Arab. J. Chem.*, **14**(4):103047.
- Khan, M. N.; Mobin, M.; Abbas, Z. K.; AlMutairi, K. A. and Siddiqui, Z. H. (2022). Role of nanomaterials in plants under challenging environments. *Plant Physiol. Biochem.*, **171**:210-223.
- Kookana, R. S.; Boxall, A. B. A.; Reeves, P. T.; Ashauer, R.; Beulke, S.; Chaudhry, Q.; Cornelis, G. and Zuin, S. (2020). Nanopesticides: Guiding principles for regulatory evaluation of environmental risks. *J. Agric. Food Chem.*, **68**(32):8877-8890.
- Latef, A. A. H. A.; Srivastava, A. K.; Saber, H.; Alwaleed, E. A. and Tran, L. S. P. (2021). Nanotechnology for abiotic stress management in plants. *Plant Physiology and Biochemistry*, **160**:292-304.
- Ly, J.; Christie, P. and Zhang, S. (2022). Uptake, translocation, and transformation of metal-based nanoparticles in plants: Recent advances and methodological challenges. *Environmental Science: Nano*, **9**(1):7-24.
- Patel, S.; Goyal, A. and Prakash, O. (2021). Applications of nanotechnology in food packaging: A review. *Food Packaging and Shelf-Life*, **28**:100608.
- Rai, M.; Ingle, A. P. and Gupta, I. (2021). Nanotechnology for the management of plant diseases: Recent advances and future perspectives. *Crop Protection*, **145**:105638.
- Raliya, R.; Saharan, V.; Dimkpa, C. and Biswas, P. (2021). Nanofertilizer for precision and sustainable agriculture: Current state and future perspectives. *J. Agric. Food Chem.*, **69**(19):5302-5314.
- Savary, S.; Willocquet, L.; Pethybridge, S. J.; Esker, P.; McRoberts, N. and Nelson, A. (2022). The global burden of pathogens and pests on major food crops. *Nat. Ecol. Evol.*, **6**(1):3-12.
- Seleiman, M. F.; Al-Suhaibani, N.; Ali, N.; Akmal, M.; Alotaibi, M.; Refay, Y. and Battaglia, M. L. (2022). Nano-fertilization as an emerging fertilization technique: Why can modern agriculture benefit from its use? *Plants*, **11**(2):1-23.
- Singh, J.; Dutta, T.; Kim, K. H.; Rawat, M.; Samddar, P. and Kumar, P. (2021). Green synthesis of metals and their oxide nanoparticles: Applications for environmental remediation. *J. Nanobiotechnol.*, **19**(1):1-24.
- Slavin, J. L. and Lloyd, B. (2021). Health benefits of fruits and vegetables. *Adv. Nutri.*, **12**(4):1186-1192.
- Tripathi, D. K.; Singh, S.; Singh, S.; Pandey, R.; Singh, V. P.; Sharma, N. C.; Prasad, S. M.; Dubey, N. K. and Chauhan, D. K. (2023). Nanoparticles and plants: An emerging alliance for stress tolerance. *J. Hazard. Mater.*, **441**:129856.
- Varma, R. S. (2023). Biomass-derived materials for sustainable nanotechnology. *ACS Sustain. Chem. Eng.*, **11**(4):1432-1445.
- Wang, X.; Zhang, M. and Chen, J. (2022). Fruit consumption and human health: Epidemiological evidence and future perspectives. *Critical Reviews in Food Sci. Nutri.*, **62**(28):7701-7716.
- Zhang, P.; Ma, Y.; Zhang, Z.; He, X.; Guo, Z.; Tai, R.; Zhao, Y. and Chai, Z. (2021). Biotransformation of ceria nanoparticles in cucumber plants. *ACS Nano*, **15**(3):4215-4227.

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