



Review Article : Open Access

Mechanistic insights into phytonanotechnology and phytomedicine integration for enhanced vegetable nutraceuticals

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Article Info

Article history

Received 14 October 2025

Revised 29 November 2025

Accepted 30 November 2025

Published Online 30 December 2025

Keywords

Phytonanotechnology

Phytomedicine

Nutraceuticals

Vegetable crops

Green synthesis

Functional foods

Bioactive compounds

Abstract

The convergence of phytonanotechnology, phytomedicine and nutraceutical science represents a transformative advancement in sustainable agriculture and human health. Phytonanotechnology rooted in the green synthesis of nanoparticles using plant-derived biomolecules provides an eco-friendly, biocompatible approach to enhancing crop performance and nutritional value. When integrated with phytomedicine, which explores the therapeutic potential of plant bioactives, this interdisciplinary field offers innovative strategies to develop vegetables that function not only as food but also as natural medicines. Vegetable crops are rich repositories of bioactive compounds such as phenolics, flavonoids, carotenoids, alkaloids and saponins, all of which possess potent antioxidant, anti-inflammatory, antidiabetic and anticancer properties. However, the bioefficacy of these phytochemicals is often limited by poor solubility, low stability and reduced bioavailability. Green-synthesized nanoparticles derived from plants address these challenges by improving the stability, delivery and bioavailability of bioactive compounds while simultaneously acting as elicitors that stimulate their biosynthesis within the plant system. Metal and metal oxide nanoparticles such as ZnO, Fe₃O₄ and SiO₂ enhance nutrient uptake, activate secondary metabolic pathways and fortify vegetables with essential micronutrients, thereby improving both yield and nutraceutical quality. Moreover, phytoengineered nanoparticles provide sustainable solutions for stress management, controlled nutrient release and biofortification in vegetable crops. By integrating nanotechnology-driven approaches with phytomedicinal principles, it becomes possible to cultivate next-generation functional vegetables that combine high productivity with therapeutic benefits. This integration aligns with the vision of sustainable, health-oriented agriculture, promoting food systems that nourish, heal and protect both people and the environment. Phytonanotechnology thus emerges as a key enabler in bridging agriculture, nutrition and healthcare - paving the way toward a future where vegetables serve as powerful nutraceuticals in global wellness and disease prevention.

1. Introduction

Vegetables are indispensable components of the human diet and are fundamental to achieving global nutritional security and public health. They provide an array of essential nutrients, including carbohydrates, proteins, vitamins, minerals and dietary fiber, which are vital for maintaining normal physiological functions. In addition to these nutrients, vegetables are rich sources of bioactive phytochemicals such as phenolics, flavonoids, carotenoids, alkaloids, glucosinolates

and saponins that exhibit remarkable pharmacological properties. These compounds contribute to antioxidant, anti-inflammatory, antidiabetic, antimicrobial and anticancer activities, thereby making vegetables vital not only as food but also as preventive medicine. The World Health Organization recommends a daily consumption of at least 400 g of fruits and vegetables to minimize the risk of chronic diseases, yet this goal remains unmet in many parts of the world. Enhancing the nutritional and functional properties of vegetables has therefore become a key strategy for improving both human health and sustainable agricultural productivity. Vegetables are increasingly recognized as natural repositories of compounds with therapeutic potential. Lycopene in tomato, sulforaphane in broccoli, quercetin in onion and allicin in garlic exemplify how dietary vegetables can provide pharmacologically active molecules that protect against oxidative stress and disease (Bhattacharya *et al.*, 2022). Regular consumption of such vegetables has been associated with reduced

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incidences of cardiovascular diseases, metabolic disorders and certain cancers. Moreover, vegetables play a crucial socio-economic role in many developing countries by providing income and employment, particularly for smallholder farmers and women. Thus, improving their nutraceutical value not only contributes to better health outcomes but also supports economic sustainability. The growing awareness of the relationship between diet and disease has led to a surge in demand for vegetables that offer functional benefits beyond basic nutrition, giving rise to the concept of “functional” and “nutraceutical” vegetables.

Phytomedicine is the use of plant-derived compounds for therapeutic purposes forms an important link between traditional knowledge and modern healthcare. Plants have been used for thousands of years in systems such as Ayurveda and Traditional Chinese Medicine and many modern drugs have been derived from phytochemicals originally identified in medicinal plants. Unlike synthetic drugs that target single pathways, phytomedicines act synergistically, influencing multiple physiological processes. Vegetables, though primarily cultivated for food, contain numerous bioactive compounds that make them potential phytomedicinal sources. Bitter melon possesses insulin-like properties that aid in glucose regulation, spinach provides lutein and nitrates beneficial for cardiovascular health and cruciferous vegetables like cabbage and broccoli contain glucosinolates with cancer-preventive properties. These examples blur the boundary between food and medicine, strengthening the concept of “food as medicine.” Despite their promise, many phytochemicals have limitations such as poor solubility, instability and low bioavailability, which hinder their therapeutic effectiveness. Nanotechnology offers innovative solutions to these challenges. When combined with plant science, it has led to the emergence of phytonanotechnology, an interdisciplinary field that uses plant extracts for the green synthesis of nanoparticles (Murugan *et al.*, 2025). These nanoparticles are typically composed of metals or metal oxides such as silver, gold, zinc oxide, or iron oxide and possess unique physicochemical properties that enhance their reactivity and biological function. Phytonanotechnology is environmentally friendly and cost-effective, avoiding the toxic chemicals often used in conventional synthesis methods. It provides a sustainable platform for applications in agriculture, food technology and medicine. In vegetable production, phytonanotechnology holds promise for enhancing growth, yield and nutraceutical quality. Nanoparticles can act as elicitors, stimulating secondary metabolic pathways that lead to increased accumulation of beneficial phytochemicals. Studies have shown that zinc oxide and silicon dioxide nanoparticles enhance phenolic and flavonoid content in vegetables such as tomato and pepper, improving their antioxidant capacity. In addition, nanofertilizers enable controlled nutrient release, increasing efficiency and reducing environmental contamination. From a human health perspective, nanotechnology enhances the delivery and stability of bioactive compounds. Nanoencapsulation of phytochemicals like curcumin, lycopene and quercetin improves their solubility and absorption, thereby increasing their bioefficacy. Applying such nanotechnological strategies in vegetable cultivation could yield crops that are naturally enriched with stable, bioavailable nutraceutical compounds.

Integrating phytonanotechnology with phytomedicine thus offers a holistic approach to developing functional and nutraceutical vegetables that serve both agricultural and health purposes. The synergy between these two disciplines lies in their complementary phytomedicine identifies therapeutic compounds, while phytonanotechnology enhances their stability, delivery and bioavailability. This integration

supports the emerging concept of “Farm to Functionality,” in which innovations at the cultivation level translate directly into health benefits at the consumer level. It also aligns with sustainable agriculture and environmental conservation goals by promoting green technologies and reducing chemical dependency. However, this promising integration must be guided by rigorous biosafety assessments and regulatory standards to ensure that nanoparticles used in edible crops pose no risk to human health or the environment. Further research is needed to understand nanoparticle-plant interactions, optimize dosage and establish safe and effective application methods. Advanced molecular and omics-based tools can unravel how nanoparticles influence secondary metabolite biosynthesis, enabling precise enhancement of nutraceutical properties (Panda *et al.*, 2024). Integrating phytonanotechnology with phytomedicine represents a transformative approach for the next generation of functional and nutraceutical vegetables. By merging sustainable nanotechnology with the therapeutic potential of plant-derived compounds, it is possible to produce vegetables that not only nourish but also heal. This interdisciplinary convergence bridges the gap between agriculture and medicine, paving the way for sustainable food systems that support both planetary health and human well-being.

2. Concept and scope of phytonanotechnology

Nanotechnology has emerged as a transformative scientific field with profound implications across agriculture, medicine and environmental sciences. It involves the manipulation and application of materials at the nanometer scale, typically between 1 and 100 nanometers, where materials exhibit unique physicochemical, optical and biological properties that differ significantly from their bulk counterparts. Within this broad scientific spectrum, phytonanotechnology has evolved as a specialized and eco-friendly branch that integrates principles of plant science and nanotechnology. It refers to the synthesis, characterization and application of nanoparticles using plant-derived biomolecules as reducing, stabilizing and capping agents. The term “phyto” is derived from the Greek word for plant, reflecting the central role of botanical extracts in the synthesis process. Unlike traditional physical and chemical methods that often rely on toxic reagents and high-energy input, phytonanotechnology utilizes naturally occurring phytochemicals such as phenolics, flavonoids, terpenoids, alkaloids, proteins and sugars for nanoparticle formation. This approach not only aligns with the principles of green chemistry but also contributes to sustainability by reducing environmental and biological hazards. The concept of phytonanotechnology gained prominence in the early 2000s, following rapid developments in green nanotechnology and increasing environmental concerns associated with conventional synthesis methods. Initially, nanotechnology in agriculture focused on improving input efficiency through nanofertilizers, nanopesticides and nanosensors. However, researchers soon realized that plants themselves could serve as natural nanofactories capable of reducing metal ions into stable nanoparticles under mild conditions. Early studies demonstrated the ability of plant extracts such as *Azadirachta indica* (neem), *Camellia sinensis* (tea), *Aloe vera* and *Ocimum sanctum* to produce silver and gold nanoparticles with controlled size and shape (Al-Ishaq *et al.*, 2020). This discovery revolutionized the field by introducing a sustainable, cost-effective and biocompatible route for nanoparticle production. Over the past two decades, phytonanotechnology has diversified to include the synthesis of a wide range of metallic, metal oxide, bimetallic

and polymeric nanoparticles. Its applications now extend from plant growth promotion and disease resistance to drug delivery, diagnostics and functional food development.

Phytonanotechnology embodies a convergence of plant biochemistry, nanoscience and biotechnology. Plants contain a vast diversity of biomolecules that can function as both reducing and stabilizing agents during nanoparticle synthesis. Phenolic compounds and flavonoids, for example, possess hydroxyl and carbonyl groups capable of donating electrons to reduce metal ions such as Ag^+ , Au^{3+} , or Zn^{2+} into their corresponding nanoparticles. Simultaneously, these biomolecules adsorb onto the nanoparticle surface, providing stability and preventing aggregation. The resulting nanoparticles often exhibit biofunctional properties inherited from their plant precursors, such as antioxidant, antimicrobial and catalytic activities. Thus, phytonanotechnology is not merely a synthetic process but a biomimetic approach that leverages the inherent metabolic and biochemical capabilities of plants to produce multifunctional nanomaterials. The scope of phytonanotechnology has expanded rapidly, especially within the context of agriculture and food systems. In vegetable crop production, for instance, nanoparticles synthesized *via* plant extracts have shown potential to enhance germination, nutrient uptake, photosynthetic efficiency and stress tolerance. They also act as elicitors that stimulate secondary metabolism, leading to the accumulation of valuable phytochemicals that contribute to the nutraceutical and functional properties of vegetables. Furthermore, nanoparticles synthesized using edible plant extracts are inherently biocompatible and suitable for use in food and medical applications, minimizing toxicity concerns associated with chemically synthesized nanoparticles. Beyond agriculture, phytoengineered nanoparticles have found applications in drug delivery systems, cancer therapy, antimicrobial coatings, environmental remediation and biosensing technologies. Their versatility arises from tunable properties such as size, morphology and surface chemistry, which can be modulated through variations in plant species, extract concentration, pH, temperature and reaction time during synthesis.

2.1 Evolution phytonanotechnology

Phytonanotechnology can be defined as the plant-mediated synthesis, stabilization and application of nanoparticles through biological molecules derived from plant tissues, extracts, or secretions. It represents a green nanotechnology approach that replaces hazardous chemicals with renewable plant resources in nanoparticle fabrication. This technique capitalizes on the natural reducing power of phytochemicals to transform metal ions into nanoscale particles under mild conditions, typically at room temperature and neutral pH. The evolution of phytonanotechnology is rooted in the broader history of nanoscience, which began with Richard Feynman's visionary lecture "There's Plenty of Room at the Bottom" in 1959, highlighting the potential of atomic-scale manipulation. The discovery of fullerenes and carbon nanotubes in the late 20th century, followed by the Nobel Prize-winning work of Binnig and Rohrer on scanning tunneling microscopy, laid the foundation for modern nanotechnology (Rahman *et al.*, 2023). However, the ecological and economic drawbacks of conventional synthesis methods, which often involved toxic chemicals and high energy requirements, prompted the search for green alternatives. By the early 2000s, researchers began exploring biological systems including bacteria, fungi, algae and plants for nanoparticle production. Among these, plants were

identified as the most promising biofactories due to their rich secondary metabolite profiles, scalability and ease of extraction.

The earliest demonstration of plant-mediated nanoparticle synthesis was reported using *Medicago sativa* (alfalfa), where gold nanoparticles were formed within plant tissues. Subsequently, several other plants were used for extracellular synthesis, paving the way for large-scale, eco-friendly production. The field gained rapid traction because of its simplicity, cost-effectiveness and alignment with sustainable development goals. Today, phytonanotechnology has evolved into a multidisciplinary platform encompassing agriculture, medicine, environmental science and materials engineering. It stands as a model of circular bioeconomy, where plant-derived waste materials such as peels, leaves and seeds can be repurposed for nanoparticle synthesis, adding value to agricultural byproducts.

2.2 Green synthesis of nanoparticles using plant extracts

Green synthesis using plant extracts is the cornerstone of phytonanotechnology. It involves a one-step bioreduction process in which phytochemicals present in the extract act as reducing, stabilizing and capping agents. Typically, a metal salt solution (such as silver nitrate, chloroauric acid, or zinc sulfate) is mixed with an aqueous or ethanolic plant extract. Within minutes to hours, the solution changes color, indicating nanoparticle formation due to the surface plasmon resonance phenomenon. Parameters such as pH, temperature, extract concentration and metal ion concentration influence the size, shape and yield of nanoparticles. Phytochemicals such as polyphenols, terpenoids, alkaloids and proteins play distinct roles during synthesis. Polyphenols and flavonoids act as electron donors, reducing metal ions to their zero-valent state, while proteins and polysaccharides stabilize the nanoparticles through surface adsorption. For example, in *Azadirachta indica*, terpenoids and flavonoids are responsible for silver ion reduction, whereas in *Camellia sinensis*, catechins and polyphenols perform a similar function. The green synthesis process is highly versatile and can produce a wide variety of nanostructures including spherical, triangular, rod-shaped and cubic nanoparticles, depending on the plant extract and reaction conditions. One of the unique features of this approach is that it incorporates biological functionality into the synthesized nanoparticles. The phytochemical capping not only provides colloidal stability but also imparts biological activity such as antimicrobial or antioxidant effects (Altimimi *et al.*, 2024). Thus, the resulting nanoparticles are often more biocompatible and therapeutically potent than those synthesized by conventional methods. Moreover, the process is scalable, rapid and suitable for industrial applications since it does not require specialized equipment or hazardous reagents.

2.3 Advantages over conventional nanotechnology

Phytonanotechnology offers several advantages over traditional physical and chemical methods of nanoparticle synthesis. First and foremost, it adheres to the principles of green chemistry, eliminating the use of toxic reducing agents such as sodium borohydride, hydrazine, or organic solvents. The process uses water or mild organic solvents as reaction media, reducing environmental pollution and occupational hazards. Second, it operates under ambient temperature and pressure, thereby conserving energy and lowering production costs. From a biological standpoint, plant-mediated nanoparticles are more biocompatible and less toxic than chemically synthesized ones. The phytochemical coating enhances their stability in biological

systems and improves their interaction with biomolecules, making them suitable for biomedical and agricultural applications. Additionally, the diversity of plant species provides a natural library of reducing agents, allowing precise control over nanoparticle morphology and functionalization. For instance, extracts from aromatic or medicinal plants not only determine nanoparticle characteristics but also contribute to their biological functionality, offering dual benefits of synthesis and bioactivity. In agricultural contexts, phytonanotechnology supports sustainable crop management by reducing dependency on synthetic agrochemicals. Nanofertilizers derived from plant-based nanoparticles improve nutrient efficiency and minimize leaching losses (Mughal *et al.*, 2021). Similarly, plant-synthesized silver or zinc oxide nanoparticles can act as natural antimicrobials against phytopathogens, reducing pesticide use. The technology also aligns with the circular economy by utilizing agricultural residues such as fruit peels, leaves and husks as raw materials for nanoparticle synthesis. This not only minimizes waste but also adds value to otherwise discarded biomass.

Furthermore, phytonanotechnology bridges the gap between nanoscience and phytomedicine by enabling the development of functional nanomaterials for nutraceutical and therapeutic applications. For example, nanoparticles synthesized using medicinal plant extracts have shown synergistic antioxidant and antimicrobial properties, enhancing their potential use in food preservation and drug delivery. Thus, the advantages of phytonanotechnology extend beyond environmental sustainability to include enhanced functionality, cost-effectiveness and applicability across diverse scientific domains.

2.4 Characterization and stability of phytoengineered nanoparticles

Characterization of phytoengineered nanoparticles is critical to understanding their physicochemical properties, stability and biological behavior. Various analytical and spectroscopic techniques are employed to determine particle size, morphology, crystallinity, surface charge and functional groups associated with phytochemical capping. UV-Visible spectroscopy is typically the first tool used to confirm nanoparticle formation by detecting surface plasmon resonance (SPR) peaks. For example, silver nanoparticles exhibit characteristic SPR absorption around 420–450 nm, while gold nanoparticles show peaks near 520–550 nm. Shifts in peak position or intensity indicate changes in particle size or aggregation state. Fourier Transform Infrared Spectroscopy (FTIR) is used to identify functional groups involved in the reduction and stabilization process. Peaks corresponding to hydroxyl (–OH), carbonyl (C=O) and amine (–NH) groups indicate the participation of phenolics, proteins and other biomolecules in nanoparticle formation. X-ray diffraction (XRD) analysis reveals the crystalline nature and phase composition of nanoparticles by matching diffraction peaks to standard databases such as the Joint Committee on Powder Diffraction Standards (JCPDS). The crystallite size can be estimated using the Scherrer equation. Scanning Electron Microscopy (SEM) and Transmission Electron Microscopy (TEM) provide detailed insights into nanoparticle morphology, size distribution and surface texture. TEM images, in particular, can reveal lattice fringes that confirm crystallinity at the atomic scale. Dynamic Light Scattering (DLS) and zeta potential analysis are employed to evaluate particle size distribution and colloidal stability. A high absolute zeta potential

value (typically $> \pm 30$ mV) indicates strong electrostatic repulsion among particles, preventing aggregation and ensuring stability. Additionally, Energy Dispersive X-ray Spectroscopy (EDX) and X-ray Photoelectron Spectroscopy (XPS) are used for elemental and surface composition analysis, confirming the presence of metal ions and their oxidation states. Thermogravimetric Analysis (TGA) assesses the thermal stability of nanoparticles and the amount of organic capping derived from plant biomolecules.

The stability of phytoengineered nanoparticles is influenced by factors such as pH, ionic strength, temperature and storage conditions. The presence of plant-derived biomolecules provides both electrostatic and steric stabilization, preventing particle aggregation. Moreover, the natural antioxidant compounds present in the extracts protect the nanoparticles from oxidation and photodegradation (Lakhani *et al.*, 2025). The stability of these nanomaterials ensures their long-term usability in agricultural formulations, food fortification and biomedical applications.

3. Phytomedicine and nutraceutical potential of vegetable crops

Vegetables have long been recognized as essential components of the human diet, not only as sources of nutrients but also as natural medicines that contribute to disease prevention and health promotion. The growing scientific and public interest in plant-based foods has brought renewed attention to their phytochemical composition and therapeutic potential. In recent years, vegetables have been increasingly studied within the framework of phytomedicine and nutraceuticals, highlighting their role in functional nutrition and preventive healthcare. Phytomedicine refers to the therapeutic use of plant-derived compounds, while nutraceuticals are bioactive constituents derived from foods that provide medical or health benefits beyond basic nutrition. Both concepts overlap in the context of vegetables, which are reservoirs of vitamins, minerals and phytochemicals with pharmacological properties. The increasing incidence of chronic diseases such as cardiovascular disorders, diabetes, cancer and obesity has led to a shift in dietary research toward identifying and utilizing plant-based foods with proven therapeutic efficacy (Khan *et al.*, 2022). Vegetable crops, in particular, represent an abundant, accessible and sustainable source of these bioactive compounds.

3.1 Overview of phytomedicine and nutraceuticals

Phytomedicine has deep roots in traditional healing systems such as Ayurveda, Unani and Traditional Chinese Medicine, where plants have been used for centuries to treat a variety of ailments. The modern scientific interpretation of phytomedicine builds upon this traditional wisdom by identifying, isolating and characterizing specific bioactive molecules responsible for therapeutic effects. Phytochemicals such as alkaloids, flavonoids, terpenoids, phenolics and saponins have been recognized for their pharmacological activities including antioxidant, anti-inflammatory, antimicrobial and anticancer properties. Unlike synthetic pharmaceuticals, phytomedicines often act synergistically, targeting multiple biochemical pathways to restore physiological balance. This holistic mechanism is particularly valuable in managing chronic diseases that have multifactorial etiologies, such as metabolic syndrome, arthritis and neurodegenerative disorders. Nutraceuticals, a concept that combines “nutrition” and “pharmaceutical,” refer to natural food-derived substances that provide medical or health benefits. The term, first introduced by

Stephen DeFelice in 1989, bridges the gap between nutrition and pharmacology. Nutraceuticals include a wide range of compounds such as vitamins, minerals, polyphenols, carotenoids and essential fatty acids. Vegetables are an important class of nutraceutical foods because of their high concentration of bioactive compounds and low caloric content. Regular consumption of vegetables has been correlated with reduced incidence of chronic diseases, improved immune function and enhanced longevity (Acharya, 2019). Nutraceuticals derived from vegetables not only act as antioxidants and detoxifying agents but also modulate key physiological processes such as lipid metabolism, glucose homeostasis and inflammatory responses.

The integration of phytomedicine and nutraceuticals into mainstream dietary and therapeutic practices reflects a growing recognition of the medicinal value of everyday foods. Unlike synthetic drugs, which often target specific molecular pathways, phytochemicals exert multifaceted effects, interacting with enzymes, receptors and transcription factors to promote health. Moreover, they are generally safe, affordable and compatible with long-term consumption. As such, phytomedicine and nutraceuticals derived from vegetables represent an essential pillar of preventive medicine and functional nutrition.

3.2 Bioactive compounds in vegetables

Vegetables are rich in a diverse range of bioactive phytochemicals that serve both defensive and metabolic roles in plants and confer significant health benefits when consumed. The major groups of bioactive compounds include phenolics, flavonoids, alkaloids, terpenoids, carotenoids and saponins, each with unique chemical properties and biological activities. Phenolic compounds are one of the largest groups of plant secondary metabolites and are characterized by the presence of hydroxyl groups attached to aromatic rings. They include phenolic acids, tannins and stilbenes. These compounds act as potent antioxidants, scavenging reactive oxygen species (ROS) and protecting cells from oxidative damage. Phenolic acids such as chlorogenic acid, ferulic acid and caffeic acid are abundant in vegetables like tomato, eggplant and spinach. They play a vital role in reducing oxidative stress, inflammation and lipid peroxidation, thereby contributing to cardiovascular and metabolic health. Flavonoids are another major class of polyphenolic compounds found widely in vegetables such as onions, kale and peppers. They include subgroups such as flavones, flavonols, flavanones, anthocyanins and isoflavones. Quercetin, kaempferol and luteolin are common flavonoids known for their anti-inflammatory, antihypertensive and anticancer properties. Flavonoids exert their effects by modulating cell signaling pathways, inhibiting enzymes involved in inflammation (such as COX and LOX) and scavenging free radicals. Their presence in vegetables contributes significantly to color, flavor and health-promoting attributes. Alkaloids, nitrogen-containing organic compounds, are known for their potent pharmacological properties. While they are often associated with medicinal or toxic plants, several vegetable species also contain beneficial alkaloids. For instance, *Solanum* species like tomato and eggplant produce glycoalkaloids such as tomatine and solanine, which exhibit antimicrobial and anticancer properties at low concentrations. Alkaloids can modulate neurotransmission, influence metabolic enzymes and provide protection against pathogens. Terpenoids constitute one of the most structurally diverse classes of plant metabolites, derived from isoprene units. They are responsible for the aroma, pigmentation and flavor

of many vegetables. Monoterpenes, diterpenes and sesquiterpenes are found in herbs and vegetables such as carrot, celery and spinach. Carotenoids, a subclass of terpenoids, are of particular importance for human health. They include compounds such as β -carotene, lutein and lycopene, which act as antioxidants and precursors of vitamin A. Lycopene in tomato and β -carotene in carrot and pumpkin are known for their protective effects against oxidative stress and cancer (Kutty *et al.*, 2023). Collectively, these phytochemicals contribute to the nutritional, sensory and therapeutic value of vegetables. Their composition and concentration are influenced by factors such as species, variety, growing conditions and postharvest handling. Recent advances in plant biotechnology, elicitor treatment and nanotechnology are being explored to enhance the biosynthesis and bioavailability of these compounds in vegetable crops, thus improving their nutraceutical potential.

3.3 Health-promoting activities of vegetables

Vegetable-derived phytochemicals exhibit a wide range of biological activities that contribute to human health. Among these, antioxidant, anti-inflammatory, antidiabetic, anticancer and cardiovascular protective effects are the most extensively studied. Antioxidant activity is one of the most critical functions of vegetable bioactives. Free radicals and reactive oxygen species contribute to cellular damage, aging and the pathogenesis of chronic diseases. Polyphenols, flavonoids and carotenoids neutralize these radicals by donating electrons or hydrogen atoms, thus preventing oxidative damage. For example, lycopene in tomatoes and β -carotene in carrots efficiently quench singlet oxygen, while flavonoids in onions and spinach enhance endogenous antioxidant enzymes like superoxide dismutase and catalase. Anti-inflammatory effects of vegetables are largely attributed to phenolics and flavonoids, which inhibit inflammatory mediators such as nitric oxide, prostaglandins and cytokines. Quercetin and kaempferol suppress the activation of NF- κ B and MAPK signaling pathways, thereby reducing inflammation-associated tissue damage. Regular consumption of anti-inflammatory vegetables like broccoli, kale and garlic has been linked to lower incidence of arthritis and chronic inflammatory disorders. Antidiabetic properties of vegetables are gaining increasing attention due to the global rise in diabetes prevalence. Bitter melon (*Momordica charantia*), a well-known vegetable in Asian medicine, contains charantin and polypeptide-p, which exhibit insulin-like activity. Similarly, fenugreek (*Trigonella foenum-graecum*) seeds contain trigonelline and 4-hydroxyisoleucine, which enhance insulin sensitivity and glucose uptake. Other vegetables, such as okra and spinach, have been shown to inhibit α -amylase and α -glucosidase enzymes, reducing postprandial hyperglycemia (Mehta *et al.*, 2025).

Anticancer activity of vegetable phytochemicals has been extensively documented. Glucosinolates and their hydrolysis products (isothiocyanates) from cruciferous vegetables induce phase II detoxifying enzymes and promote apoptosis in cancer cells. Sulforaphane from broccoli is one of the most studied anticancer compounds, known for its ability to inhibit histone deacetylase and modulate epigenetic regulation. Lycopene, quercetin and resveratrol also exhibit antiproliferative and pro-apoptotic effects against various cancer cell lines. The synergistic combination of different bioactives within vegetables enhances their chemopreventive efficacy. Cardiovascular protection is another well-established benefit of vegetable consumption. Phytochemicals such as flavonoids, nitrates and saponins improve endothelial function, reduce oxidative stress and

modulate lipid metabolism. Vegetables like spinach and beetroot are rich in dietary nitrates that enhance nitric oxide production, leading to vasodilation and improved blood flow. Garlic, through its sulfur-containing compounds like allicin, reduces cholesterol synthesis and platelet aggregation. Regular consumption of leafy and cruciferous vegetables has been associated with lower risks of hypertension, atherosclerosis and coronary artery disease. Together, these health-promoting properties underscore the role of vegetables as functional foods that not only provide essential nutrients but also confer long-term health benefits.

3.4 Traditional and ethnomedicinal uses of vegetables

The therapeutic use of vegetables is deeply embedded in traditional medicine systems worldwide. Across Asia, Africa and South America, vegetable crops have been used not only as food but also as remedies for a wide variety of ailments. In Ayurveda, for instance, garlic is regarded as a “Rasayana” or rejuvenator that promotes longevity and vitality. It has been used to treat infections, digestive disorders and cardiovascular diseases. Bitter melon and fenugreek have long been prescribed in Indian and Chinese medicine for managing diabetes and improving digestion. In African traditional medicine, okra pods are used for their mucilaginous properties to soothe gastrointestinal inflammation, while amaranth leaves are valued for treating anemia and hypertension. The ethnomedicinal applications of vegetables are not limited to their bioactive compounds but also extend to their holistic role in maintaining physiological balance. For example, leafy greens like spinach and moringa are used as natural tonics to improve immunity and general health, while cruciferous vegetables such as mustard greens and cabbage are incorporated into traditional detox diets for their cleansing and anti-inflammatory effects. These traditional uses are increasingly being validated through modern pharmacological studies, providing scientific evidence for their efficacy.

Moreover, the concept of “food as medicine” forms the cornerstone of preventive health strategies in many cultures. The regular inclusion of vegetables in traditional diets contributes to the prevention of chronic ailments long before the onset of clinical symptoms (Wen *et al.*, 2025). The ethnomedicinal knowledge accumulated over generations offers valuable insights into developing modern nutraceuticals and functional foods derived from vegetables. Integrating traditional wisdom with contemporary scientific research can lead to the discovery of novel therapeutic compounds and promote the sustainable utilization of vegetable biodiversity for global health.

4. Integration of phytonanotechnology and phytomedicine

The integration of phytonanotechnology and phytomedicine represents a revolutionary convergence of two powerful scientific paradigms: one focused on nanoscale manipulation for enhanced functionality and the other rooted in the therapeutic potential of plant-derived bioactive compounds. While phytomedicine capitalizes on the healing properties of plant-based metabolites, phytonanotechnology enhances the efficiency, stability and delivery of these compounds through nanoengineering. This integration creates a synergistic framework where nanomaterials derived from plants interact with phytochemicals to amplify their biological efficacy, improve bioavailability and enable targeted therapeutic actions. The concept not only bridges agriculture and medicine but also establishes a sustainable model of functional food and drug development using natural systems (Ulas *et al.*, 2025).

In the context of vegetable crops, the integration of these two fields has particular relevance. Vegetables are rich in diverse phytochemicals such as flavonoids, phenolics, terpenoids, carotenoids, alkaloids and saponins that exhibit strong pharmacological effects. However, the therapeutic use of many of these compounds is restricted by issues of instability, poor solubility and low bioavailability. Nanotechnology offers tools to overcome these limitations by encapsulating, stabilizing, or modifying the delivery of bioactive molecules. Moreover, when nanoparticles are synthesized using plant extracts—a hallmark of phytonanotechnology—they inherently carry surface-bound phytochemicals, forming natural nanoconjugates that exhibit enhanced biological properties (Osman *et al.*, 2024). Thus, integrating these approaches opens new avenues for developing nutraceutical vegetables and functional foods that not only nourish but also provide targeted therapeutic benefits.

4.1 Conceptual framework: Synergy between green nanoparticles and phytochemicals

The conceptual foundation of integrating phytonanotechnology with phytomedicine lies in the synergistic interaction between green-synthesized nanoparticles and phytochemicals. Green nanoparticles, synthesized through plant-mediated methods, are inherently coated or capped with bioactive phytoconstituents. These biomolecules act not only as reducing and stabilizing agents during synthesis but also impart biological functionality to the nanoparticles. Consequently, the resulting hybrid nanostructures possess dual attributes: the physicochemical advantages of nanomaterials (such as large surface area and reactivity) and the therapeutic potential of phytochemicals (such as antioxidant and anti-inflammatory properties).

This synergy results in materials that are biocompatible, eco-friendly and capable of interacting favorably with biological systems. For instance, silver nanoparticles synthesized using *Azadirachta indica* or *Ocimum sanctum* extracts are more stable and exhibit higher antimicrobial activity than chemically synthesized counterparts due to the presence of flavonoids and terpenoids on their surface (Gayathri *et al.*, 2024). Similarly, zinc oxide nanoparticles produced from *Moringa oleifera* or *Allium sativum* extracts display enhanced antioxidant and growth-promoting effects because of phytochemical capping. In essence, phytoengineered nanoparticles are not merely passive carriers; they are bioactive hybrids that integrate structural and biological functions. Thus, the synergy between nanoparticles and phytochemicals creates a continuous feedback system: plants help synthesize nanoparticles, nanoparticles enhance plant metabolite production and both jointly contribute to therapeutic applications.

4.2 Mechanisms of nanoparticle-phytochemical interaction

The integration of nanoparticles and phytochemicals operates through multiple molecular and physicochemical mechanisms that enhance the performance of bioactives. These mechanisms include improved stability, controlled release, targeted delivery and enhanced solubility and absorption. Understanding these interactions is crucial for developing effective nano-phytomedicine formulations and functional vegetables.

4.2.1 Enhanced bioavailability and stability of bioactives

One of the major limitations in the utilization of phytochemicals is their poor bioavailability, primarily due to low solubility, rapid metabolism and degradation under physiological conditions. For

example, compounds like curcumin, resveratrol and quercetin exhibit remarkable *in vitro* activity but limited *in vivo* efficacy because they are quickly metabolized or degraded. Nanoparticle integration provides a solution by protecting these molecules from environmental and enzymatic degradation. When phytochemicals are encapsulated within or adsorbed onto nanoparticles, they are shielded from oxidation, hydrolysis and photodegradation. For instance, curcumin encapsulated in chitosan nanoparticles shows prolonged stability and improved pharmacokinetic profiles compared to free curcumin. Similarly, nanoencapsulated lycopene derived from tomatoes exhibits higher retention of antioxidant activity under light and heat stress. The nanoformulation provides a physical barrier that prevents the interaction of bioactives with oxygen or light, thereby extending their shelf life and therapeutic potential. Phytosynthesized nanoparticles themselves are often stabilized by plant biomolecules such as phenolics and polysaccharides, which provide additional protection against aggregation and degradation (Abegunde *et al.*, 2024). This dual-layer stabilization chemical (from plant metabolites) and physical (from nanoparticle encapsulation) is a hallmark of phytonanotechnology's advantage over synthetic nanomaterials.

4.2.2 Controlled release and targeted delivery

Controlled release and targeted delivery are among the most significant contributions of nanotechnology to phytomedicine. Conventional plant extracts or phytochemical supplements often suffer from burst release and low tissue specificity, leading to suboptimal efficacy. Nanoparticles can be engineered to release bioactive compounds in a sustained or stimulus-responsive manner, depending on environmental factors such as pH, temperature, or enzyme presence. For example, polymeric nanoparticles loaded with phenolic compounds can release their contents gradually, maintaining a consistent therapeutic concentration over extended periods. In human health applications, nanoparticles enhance the targeted delivery of phytochemicals to specific tissues or organs. Lipid or polymer based nanocarriers can cross biological barriers such as the intestinal wall or blood-brain barrier, improving the systemic distribution of bioactives. In agriculture, nanoparticle-based carriers can deliver elicitors or nutrients directly to specific plant tissues, maximizing metabolic responses while minimizing wastage. Targeted delivery also minimizes potential side effects and enhances the therapeutic index of phytochemicals (Nejatian, 2022). For instance, nano-curcumin formulations show improved accumulation in cancer cells due to the enhanced permeability and retention effect, while sparing healthy tissues. Similarly, zinc oxide and silica nanoparticles can be used to transport phytochemicals directly into plant chloroplasts or vacuoles, enhancing stress resistance and secondary metabolite accumulation.

4.2.3 Improved solubility and absorption of phytoconstituents

Many potent phytochemicals are hydrophobic and exhibit poor water solubility, which severely limits their absorption in the gastrointestinal tract or within plant tissues. Nanotechnology offers several solutions to this problem by increasing the surface area and dispersion of these compounds in aqueous environments. Nanoemulsions, liposomes and solid lipid nanoparticles are particularly effective in enhancing the solubility and bioaccessibility of lipophilic phytochemicals such as carotenoids, curcuminoids and essential oils. For example, encapsulation of lycopene or β -carotene in nanoemulsion systems significantly enhances their solubility and intestinal absorption. Similarly, quercetin nanoparticles exhibit higher

cellular uptake and bioavailability than free quercetin (Dhir *et al.*, 2024). In plants, nanoparticle carriers can enhance the foliar uptake of hydrophobic bioactives, improving their translocation and bioefficacy. The small size of nanoparticles allows them to cross biological membranes, including plant cuticles and cell walls, facilitating efficient delivery of nutrients or elicitors. The improvement in solubility and absorption not only enhances therapeutic performance but also reduces the dosage required to achieve desired effects, minimizing potential toxicity and cost. This makes nano-phytomedicine an economically and pharmacologically viable approach for functional vegetable development and therapeutic applications.

4.3 Influence on secondary metabolite biosynthesis pathways in plants

Beyond their role as carriers and stabilizers, nanoparticles themselves can act as biochemical elicitors, influencing secondary metabolite biosynthesis in plants. Secondary metabolites such as phenolics, flavonoids, terpenoids, alkaloids and glucosinolates are key contributors to the medicinal and nutraceutical value of vegetables. The interaction between nanoparticles and plant cells triggers a cascade of physiological and molecular responses that activate metabolic pathways leading to the enhanced accumulation of these compounds (Yang *et al.*, 2025).

Nanoparticles can influence secondary metabolism through several mechanisms:

- 1. Induction of oxidative stress signaling:** Low concentrations of nanoparticles can generate mild reactive oxygen species (ROS), which act as secondary messengers to activate defense-related pathways. This controlled oxidative stress stimulates the expression of genes such as phenylalanine ammonia-lyase (PAL), chalcone synthase (CHS) and peroxidase (POD), leading to increased synthesis of phenolics and flavonoids.
- 2. Activation of hormonal and signaling pathways:** Nanoparticles can modulate plant hormones like salicylic acid, jasmonic acid and ethylene, which are closely associated with secondary metabolism. For example, silver nanoparticles have been shown to induce salicylic acid-mediated pathways that enhance flavonoid production in tomato and pepper.
- 3. Nutrient modulation:** Metal nanoparticles such as zinc, iron and silicon can act as micronutrient sources, influencing enzyme activities involved in metabolite synthesis. Zinc oxide nanoparticles, for instance, enhance carotenoid and phenolic biosynthesis by serving as cofactors for key metabolic enzymes.
- 4. Epigenetic and transcriptomic regulation:** Recent omics-based studies have revealed that nanoparticles can alter the expression of transcription factors such as MYB, WRKY and bHLH, which regulate secondary metabolic pathways. These molecular changes result in increased accumulation of bioactive compounds that contribute to the nutraceutical quality of vegetables.

In vegetable crops like tomato, broccoli and chili, nanoparticle treatments have been associated with elevated levels of antioxidants, phenolics and vitamins. For example, zinc oxide nanoparticles increased phenolic content and antioxidant enzyme activity in tomato fruits, while silver nanoparticles enhanced capsaicinoid accumulation

in chilli plants. Such findings suggest that controlled nanoparticle application can be strategically used to biofortify vegetables with therapeutic compounds, aligning with the goal of developing nutraceutical crops. Importantly, the elicitor effect of nanoparticles depends on their concentration, size and exposure duration (Thatyana *et al.*, 2023). At optimal doses, nanoparticles act as beneficial stimulants; however, excessive levels may cause phytotoxic effects by inducing oxidative stress beyond the plant's tolerance threshold. Therefore, precise optimization and safety assessment are essential for practical applications.

5. Applications in functional and nutraceutical vegetable production

The practical integration of phytonanotechnology into vegetable production represents one of the most promising advancements in sustainable agriculture and functional food development. Nanotechnology-based agricultural inputs, when designed and synthesized through green routes, can enhance both productivity and phytochemical accumulation in vegetables, thus improving their nutraceutical and functional quality. The unique physicochemical properties of nanoparticles including high surface area-to-volume ratio, reactivity and controlled-release capacity enable them to interact precisely with plant tissues and biochemical pathways (Pattoo *et al.*, 2023). This interaction leads to improved nutrient availability, stimulation of secondary metabolite biosynthesis, enhanced stress tolerance and fortification of crops with essential micronutrients. Functional vegetables are those that provide specific health benefits beyond basic nutrition, largely due to their enriched phytochemical content. Nutraceutical vegetables, on the other hand, contain bioactive compounds that offer preventive or therapeutic properties. Phytonanotechnology bridges the gap between these two categories by enhancing both yield and bioactive compound accumulation. The development of nanofertilizers, nano-bioformulations, nano-elicitors and nanoparticle-based fortification strategies has opened new pathways for improving the biochemical and nutritional attributes of vegetable crops while maintaining environmental sustainability.

5.1 Nanofertilizers and nano-bioformulations for enhancing phytochemical accumulation

Nanofertilizers are nanoscale nutrient carriers engineered to release nutrients in a controlled, sustained manner, thereby increasing nutrient-use efficiency and minimizing losses due to leaching or volatilization. Unlike conventional fertilizers, which often suffer from poor bioavailability, nanofertilizers can penetrate plant tissues more effectively and deliver nutrients directly to metabolic sites. The slow and targeted release of nutrients ensures continuous availability throughout the plant's growth stages, leading to improved physiological performance and enhanced phytochemical synthesis. Metal-based nanoparticles such as zinc oxide (ZnO), iron oxide (Fe₂O₃) and silicon dioxide (SiO₂) have been widely investigated as nanofertilizers in vegetables. Zinc oxide nanoparticles, for example, play a vital role in enzymatic activation and protein synthesis, influencing pathways responsible for phenolic and flavonoid production. Studies have shown that foliar application of ZnO nanoparticles in tomato (*Solanum lycopersicum*) and spinach (*Spinacia oleracea*) increases total phenolic and flavonoid content, enhancing antioxidant potential. Similarly, iron oxide nanoparticles improve chlorophyll biosynthesis and photosynthetic efficiency, indirectly contributing to increased carbohydrate and carotenoid accumulation in leafy vegetables (Rani *et al.*, 2023).

Nano-bioformulations that combine nanoparticles with microbial inoculants (such as *Azotobacter*, *Pseudomonas* and *Trichoderma* species) offer synergistic effects by promoting both nutrient availability and plant defense responses. These bioinspired formulations stimulate phytohormone production, enhance root architecture and upregulate genes related to secondary metabolism. For instance, nano-encapsulated biofertilizers containing zinc and iron nanoparticles have been shown to improve vitamin C and β -carotene content in tomato fruits. The integration of such nanofertilizers with organic cultivation systems provides a dual benefit improved yield and superior nutritional quality aligning with the concept of nutraceutical agriculture.

5.2 Nanoelicitors for improving antioxidant and nutraceutical properties

Elicitation is a well-established strategy for inducing the biosynthesis of secondary metabolites in plants. Nanoelicitors, derived from metal or metal oxide nanoparticles synthesized through phyto-mediated routes, act as abiotic elicitors that trigger the plant's defense mechanisms and enhance the production of bioactive compounds. The elicitor effect occurs through the generation of mild oxidative stress and the activation of signaling pathways involving phytohormones such as salicylic acid, jasmonic acid and ethylene. When applied in appropriate concentrations, nanoelicitors such as silver (Ag), zinc oxide (ZnO) and silicon dioxide (SiO₂) nanoparticles stimulate enzymes like phenylalanine ammonia-lyase (PAL), chalcone synthase (CHS) and polyphenol oxidase (PPO), which are key regulators of phenolic and flavonoid biosynthesis (Khan *et al.*, 2022). This results in higher accumulation of antioxidants and nutraceutical compounds in vegetables. For instance, silver nanoparticles applied to chilli (*Capsicum annuum*) plants have been found to enhance capsaicinoid and phenolic content, while zinc oxide nanoparticles in tomato increase lycopene, ascorbic acid and total phenolics.

Nanoelicitors also improve the overall antioxidant defense system by enhancing the activity of enzymes such as superoxide dismutase (SOD), catalase (CAT) and peroxidase (POD), which collectively mitigate oxidative stress (Kushwaha *et al.*, 2021). This biochemical modulation not only enhances the plant's tolerance to environmental stressors but also increases the accumulation of health-promoting phytochemicals in edible tissues. Furthermore, the elicitation effect is highly tunable depending on the nanoparticle size, concentration and exposure time offering opportunities for precision modulation of phytochemical profiles in nutraceutical vegetables.

5.3 Nanoprimering of vegetable seeds for quality and resilience enhancement

Seed priming is a pre-sowing treatment that enhances germination, vigor and stress tolerance. Nanoprimering involves soaking seeds in nanoparticle suspensions, allowing nanoparticles to penetrate the seed coat and interact with the embryo. This leads to enhanced metabolic activity, enzyme activation and stress resilience in the early stages of plant development. Nanoprimering also has long-term effects on plant growth, secondary metabolism and nutrient assimilation, which ultimately influence the nutraceutical quality of the harvested vegetables. Nanoparticles such as zinc oxide, titanium dioxide (TiO₂) and silica (SiO₂) have been extensively used for nanoprimering in vegetables. Zinc oxide nanoparticles improve germination rate, root elongation and seedling vigor in tomato and spinach, while also enhancing antioxidant enzyme activities. TiO₂ nanoparticles

promote chlorophyll synthesis and light absorption, resulting in better photosynthetic performance and biomass accumulation. Nano-primed seeds show quicker emergence, uniform growth and enhanced tolerance to drought, salinity and temperature stress (Okeke *et al.*, 2023).

Moreover, nanoprimering can act as an early elicitor of secondary metabolism. In tomato, nanoprimering with silicon nanoparticles has been shown to increase total phenolic content and flavonoid accumulation at maturity. The nanoparticles trigger redox signaling during germination, priming the plant's defense system and metabolic machinery. This phenomenon, often described as "nanoprimering-induced memory," ensures a stronger and faster physiological response under subsequent stress conditions. As a result, nanoprimering not only improves crop establishment and yield but also enhances the nutraceutical quality of vegetables, contributing to sustainable and health-oriented agriculture.

5.4 Nanoparticle-based fortification of vegetables for micronutrient enrichment

Micronutrient malnutrition, commonly referred to as "hidden hunger," affects billions of people worldwide, particularly in developing countries. Vegetables, being a major component of the daily diet, serve as ideal vehicles for delivering essential micronutrients such as iron (Fe), zinc (Zn) and selenium (Se). Conventional biofortification strategies often face challenges related to nutrient loss, low bioavailability and soil immobilization. Nanoparticle-based fortification offers a promising alternative by enabling controlled nutrient release, enhanced absorption and improved stability of micronutrients. Iron nanoparticles (Fe NPs) are used to improve iron content and chlorophyll formation in leafy vegetables such as spinach and amaranth. Iron plays a crucial role in hemoglobin synthesis and enzymatic reactions related to energy metabolism. Nano-iron fertilizers enhance iron availability in the rhizosphere, reducing iron deficiency chlorosis and improving nutritional content in edible tissues (Nayab *et al.*, 2023).

Zinc nanoparticles (Zn NPs) contribute to enzyme activation, protein synthesis and hormone regulation. Application of ZnO nanoparticles in tomato and lettuce not only increases zinc accumulation but also stimulates secondary metabolism, resulting in higher levels of antioxidants and phenolics. Similarly, selenium nanoparticles (Se NPs) have gained attention due to their dual role as antioxidants and immune boosters. Selenium fortification through nanoparticles enhances selenoprotein formation and protects plants against oxidative stress, while improving the functional quality of vegetables such as garlic, onion and broccoli (Durazzo *et al.*, 2020). The biofortification potential of nanoparticles extends beyond mineral enrichment to include enhanced bioactive compound retention. For example, nano-selenium treatments increase glucosinolate and vitamin C levels in broccoli, while nano-zinc applications boost lycopene and flavonoid content in tomatoes. These findings illustrate the potential of nanoparticle-based interventions in producing nutrient-dense vegetables with improved nutraceutical profiles.

6. Mechanistic insights and omics perspectives

Understanding the mechanisms underlying the interaction between nanoparticles and plant systems is critical for harnessing the full potential of phytonanotechnology in vegetable crop improvement. When nanoparticles enter plant tissues, they interact with cellular

components, trigger signaling cascades and alter gene expression and metabolic pathways. These molecular events can influence both primary and secondary metabolism, leading to enhanced growth, stress tolerance and accumulation of nutraceutical compounds (Magne, 2022). Recent advances in omics technologies including transcriptomics, metabolomics and proteomics have provided valuable insights into these mechanisms, allowing researchers to elucidate the complex responses of vegetable plants to nanoparticle exposure.

6.1 Uptake, translocation and localization of nanoparticles in vegetable tissues

Nanoparticles can enter plants through various routes, primarily *via* foliar application, root uptake, or seed priming. Their entry depends on factors such as particle size, surface charge, composition and plant species. In vegetables, root uptake is the most common pathway, where nanoparticles are absorbed through the root epidermis, often *via* the apoplastic (cell wall) and symplastic (cytoplasmic) routes. The small size of nanoparticles (1-100 nm) allows them to pass through cell wall pores or enter cells *via* endocytosis. Once inside, they are translocated through the xylem to aerial parts and redistributed *via* the phloem, depending on their solubility and interaction with plant biomolecules (Dos Santos *et al.*, 2023).

Studies using imaging techniques such as transmission electron microscopy (TEM), scanning electron microscopy (SEM) and energy-dispersive X-ray spectroscopy (EDS) have confirmed nanoparticle localization in root cortex, vascular bundles and leaf chloroplasts (Manocha *et al.*, 2022). For example, zinc oxide nanoparticles applied to tomato roots have been found to accumulate in leaf mesophyll tissues, while silver nanoparticles localize near stomatal openings and trichomes in pepper leaves. The distribution pattern influences both nutrient dynamics and elicitation of secondary metabolism. Once internalized, nanoparticles may dissolve partially, releasing ions that serve as cofactors for enzymes involved in metabolic and antioxidant pathways. Thus, understanding nanoparticle uptake and localization is fundamental to optimizing their use for nutraceutical enhancement in vegetable crops.

6.2 Molecular signaling and stress-responsive gene modulation

Nanoparticles can trigger a network of molecular signaling pathways that regulate plant growth, defense and metabolism. At optimal concentrations, they act as mild stressors that induce controlled reactive oxygen species (ROS) generation. These ROS act as secondary messengers, activating antioxidant defense systems and signaling cascades involving plant hormones such as salicylic acid, jasmonic acid and ethylene. This controlled oxidative stress enhances the plant's adaptive response to environmental challenges. Gene expression studies in vegetables have shown that nanoparticle exposure upregulates stress-responsive and metabolic genes. For instance, zinc oxide nanoparticles induce the expression of phenylalanine ammonia-lyase (PAL), chalcone synthase (CHS) and peroxidase (POD) genes in tomato, promoting phenolic and flavonoid biosynthesis. Similarly, silicon nanoparticles modulate the expression of superoxide dismutase (SOD) and catalase (CAT) genes, enhancing oxidative stress tolerance. In chilli plants, silver nanoparticles activate capsaicin biosynthetic genes such as capsaicin synthase and pAMT, leading to increased capsaicinoid accumulation (Tiwari *et al.*, 2023).

These molecular responses suggest that nanoparticles act as elicitors, reprogramming plant metabolic and defense pathways to favor the synthesis of nutraceutical compounds. However, the concentration and exposure duration are critical while low doses stimulate beneficial responses, high concentrations can disrupt redox homeostasis and inhibit growth. Therefore, understanding nanoparticle-induced molecular signaling is key to developing safe and effective nano-enabled strategies for enhancing phytochemical production.

6.3 Metabolomics and transcriptomics approaches in phyto-nano research

Recent advancements in omics technologies have greatly expanded our understanding of how nanoparticles influence plant metabolism at the systems level. Metabolomics provides a snapshot of the biochemical changes induced by nanoparticles, while transcriptomics identifies differentially expressed genes and associated metabolic pathways. In metabolomic studies, nanoparticle treatments have been shown to alter primary metabolites such as sugars, amino acids and organic acids, as well as secondary metabolites including flavonoids, phenolics, terpenoids and glucosinolates. For instance, metabolomic profiling of broccoli treated with zinc oxide nanoparticles revealed increased levels of glucosinolates and their hydrolysis products, indicating activation of sulfur assimilation pathways. Similarly, tomato plants exposed to nano-silicon or nano-iron exhibit elevated levels of lycopene, ascorbic acid and phenolic compounds. These biochemical shifts are closely correlated with transcriptomic data, which show the upregulation of genes involved in phenylpropanoid, carotenoid and terpenoid biosynthesis pathways. Transcriptomic analysis also highlights the activation of defense-related genes, including those coding for transcription factors such as WRKY, MYB and NAC, which regulate secondary metabolite biosynthesis. This molecular-level understanding aids in identifying the genetic targets influenced by nanoparticles and enables precision enhancement of nutraceutical traits in vegetables (Brindhavan, 2025). The integration of metabolomics and transcriptomics provides a holistic view of nanoparticle-plant interactions, paving the way for nano-enabled crop improvement strategies.

6.4 Proteomic and enzymatic responses to nanoparticle exposure

Proteomic and enzymatic studies reveal how nanoparticles influence plant biochemistry at the post-transcriptional and functional levels. Exposure to nanoparticles often results in the upregulation of antioxidant and stress-related enzymes, which are crucial for maintaining redox balance and promoting secondary metabolism. Enzymes such as superoxide dismutase (SOD), catalase (CAT), peroxidase (POD) and ascorbate peroxidase (APX) are commonly enhanced in vegetables treated with nanoparticles. These enzymes mitigate oxidative damage while signaling for metabolic adaptation. Proteomic analyses have identified changes in proteins associated with photosynthesis, carbohydrate metabolism and secondary metabolism. For instance, in nanoparticle-treated spinach and tomato plants, increased abundance of proteins involved in the Calvin cycle and ATP synthesis correlates with improved photosynthetic performance and growth. Simultaneously, proteins linked to phenylpropanoid and flavonoid biosynthesis are upregulated, resulting in higher antioxidant capacity (Nisar and Wan, 2025). Nanoparticles also influence enzymes related to nutrient metabolism, such as nitrate reductase and glutamine synthetase, improving nitrogen

assimilation and promoting amino acid synthesis. These enzymatic modulations collectively contribute to the enhanced nutritional and functional quality of vegetables. Importantly, proteomic studies confirm that nanoparticle exposure triggers adaptive rather than toxic responses when applied within safe concentration ranges.

7. Safety, toxicity and environmental considerations

The application of nanotechnology in vegetable crop production offers promising benefits for enhancing yield, nutrition and functional quality; however, the safety and environmental implications of nanoparticles use remain critical concerns. As nanoparticles interact with plant systems, soil microbiota and food chains, understanding their potential phytotoxicity, bioaccumulation and ecological risks is essential. The integration of nanomaterials into agriculture must therefore be guided by thorough risk assessment, dose optimization and regulatory oversight to ensure sustainability and consumer safety.

7.1 Phytotoxicity assessment and dose optimization

While nanoparticles can enhance plant growth and metabolism at optimal concentrations, excessive or unregulated application may cause phytotoxic effects. The small size and high reactivity of nanoparticles enable them to penetrate plant cells and organelles, where they may disrupt physiological processes if applied in high doses. Phytotoxic symptoms can include inhibited germination, stunted growth, chlorosis, reduced chlorophyll content and oxidative stress. For example, high concentrations of silver nanoparticles have been shown to impair root elongation in tomato and lettuce by inducing reactive oxygen species (ROS) overproduction. Therefore, dose optimization is crucial for achieving beneficial effects without toxicity. The toxicity threshold varies according to particle type, size, surface chemistry and plant species. Green-synthesized nanoparticles, owing to their plant-derived organic coatings, are generally less toxic and more biocompatible than chemically synthesized ones (Puttasiddaiah and Bojarska, 2022). Controlled release formulations and nano-biofertilizers can further minimize exposure risks. Standardized protocols for toxicity assessment including germination tests, growth assays and biochemical markers like lipid peroxidation and antioxidant enzyme activity are essential to determine safe and effective dosage ranges for each crop.

7.2 Bioaccumulation and residual effects in edible parts

One of the major concerns associated with nanoparticle application in vegetables is bioaccumulation—the uptake and retention of nanoparticles or their ionic forms in edible tissues. Nanoparticles absorbed by roots or leaves may translocate to fruits and leaves, potentially entering the human food chain. For instance, zinc oxide nanoparticles applied to spinach and tomato have been detected in leaf tissues and fruit pericarp, while silver nanoparticles can accumulate in epidermal cells and vascular tissues. Although, many studies report that plant-derived nanoparticles exhibit minimal toxicity, long-term accumulation could alter nutrient balance and raise food safety concerns. The extent of bioaccumulation depends on nanoparticle solubility, concentration and exposure duration. Biotransformation processes within plants such as oxidation, reduction, or complexation can alter nanoparticle structure, influencing their mobility and toxicity. Therefore, it is important to evaluate both total and bioavailable nanoparticle residues in edible plant parts. Advanced analytical methods such as inductively coupled plasma mass spectrometry (ICP-MS) and X-ray absorption spectroscopy

(XAS) are used for quantifying and characterizing nanoparticle residues in vegetables to ensure compliance with food safety standards (Tamboli *et al.*, 2025).

7.3 Risk evaluation for human consumption and ecosystem balance

Nanoparticle residues in edible vegetables could potentially affect human health, depending on their concentration, chemical composition and persistence. Ingestion of nanoparticles may lead to gastrointestinal irritation, oxidative stress, or bioaccumulation in organs if consumed in excess (Famitha *et al.*, 2024). However, phytoengineered nanoparticles synthesized from plant extracts are generally safer due to their biodegradable and non-toxic organic coatings. Risk evaluation must therefore consider exposure pathways dietary intake, soil contamination and water run off to ensure ecosystem balance. Excessive nanoparticle accumulation in soils can affect beneficial soil micro-organisms and nutrient cycling. Silver and copper nanoparticles, for example, may inhibit microbial respiration and nitrogen fixation at high concentrations (Singh *et al.*, 2018). To maintain ecological equilibrium, continuous monitoring of soil health, microbial diversity and aquatic ecosystems is necessary wherever nanomaterials are applied.

7.4 Regulatory frameworks and guidelines for nanomaterial application in edible crops

The rapid advancement of nanotechnology in agriculture has outpaced regulatory developments, creating a need for comprehensive guidelines and safety frameworks. Currently, international organizations such as the Food and Agriculture Organization (FAO), World Health Organization (WHO) and Organization for Economic Co-operation and Development (OECD) are working to establish risk assessment protocols for nanomaterials used in food systems. Regulations should address nanoparticle characterization, permissible limits, labeling and risk communication. Countries including the United States, the European Union and India have initiated steps to develop nanospecific safety standards under agricultural and food safety laws. However, harmonization at the global level remains a challenge (Rana *et al.*, 2021). A precautionary approach focusing on “safe-by-design” nanoparticles synthesized through green and biodegradable routes should guide the use of nanotechnology in edible crops.

8. Future prospects

The future of phytonanotechnology in functional and nutraceutical vegetable production holds immense promise for advancing sustainable agriculture and human health. Emerging research trends are moving toward the rational design of biofunctional nanoparticles that can precisely regulate plant metabolic pathways to enhance the synthesis of health-promoting phytochemicals. Integration of omics technologies such as genomics, transcriptomics, proteomics and metabolomics will provide deeper insights into nanoparticle-plant interactions, enabling the identification of molecular targets for nutraceutical improvement. Artificial intelligence and predictive modeling are expected to play a significant role in optimizing nanoparticle formulations and dosage levels tailored for specific vegetable species. Future studies must focus on biosafety evaluation, environmental impact assessment and regulatory standardization to ensure that nanomaterials used in edible crops remain safe for both humans and ecosystems. Green synthesis approaches using biodegradable plant-based materials will continue to dominate,

aligning with global sustainability goals. Moreover, the integration of phytonanotechnology with precision agriculture and controlled-environment farming will enable real-time nutrient management and targeted delivery systems, improving crop yield and quality. Overall, the future direction emphasizes a holistic framework where nanotechnology, phytomedicine and functional food science converge to develop next-generation vegetables nutrient-dense, resilient and capable of promoting preventive health and well-being.

9. Conclusion

Phytonanotechnology stands at the forefront of sustainable agricultural innovation, offering dual potential in improving crop productivity and enhancing human health. By harnessing the unique properties of plant-derived nanoparticles, it optimizes nutrient utilization, strengthens stress resilience and stimulates the biosynthesis of valuable phytochemicals. These advancements not only increase yield and quality but also enrich vegetables with bioactive compounds that contribute to disease prevention and overall wellness. The integration of phytomedicine principles into vegetable crop improvement transforms conventional cultivation into a holistic system that unites nutrition, medicine and sustainability. Through green synthesis and molecular precision, phytonano-technology enables the development of functional and nutraceutical vegetables that bridge the gap between food and healthcare. Looking ahead, next-generation nutraceutical agriculture envisions a global shift toward producing vegetables that are not only high-yielding but also therapeutically potent, environmentally friendly and nutritionally superior. This convergence promises to redefine the role of agriculture from feeding populations to fostering long-term human health and ecological balance.

Conflict of interest

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

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Citation

V. Balamurugan, T. Anitha, L.T. Thirumarudhan, M. Kabilan, K. Elavarasan, M. Subasri and Adnan A. Khan (2025). Mechanistic insights into phytonanotechnology and phytomedicine integration for enhanced vegetable nutraceuticals. *Ann. Phytomed.*, **14**(2):230-241. <http://dx.doi.org/10.54085/ap.2025.14.2.23>.