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REVIEW ARTICLE

# Harnessing the power of foliar nanofertilizers to enhance vegetable crop performance

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## Abstract

The utilization of foliar nanofertilizers in vegetable crop enhancement has garnered significant attention in recent agricultural research. This review delves into the significant role of foliar nanofertilizers in augmenting the productivity and resilience of vegetable crops. Beginning with the introduction of this concept, it elucidates the vital need for nanofertilizers in modern agriculture. This paper outlines the numerous advantages of nanofertilizers over conventional fertilizers, emphasizing their potential to revolutionize agricultural practices. It discusses various modes of nanofertilizer application, with a particular focus on their efficacy as foliar sprays. Furthermore, this review examines the intricate mechanisms underlying the foliar application of nanofertilizers, elucidating how these nanomaterials interact with plant physiology to enhance nutrient uptake and utilization. By analyzing empirical studies, it evaluates the effects of foliar nanofertilizers on vegetable growth and yield highlights their efficacy in optimizing crop performance. Additionally, this review highlights the application of foliar nanofertilizers in mitigating abiotic and biotic stresses in vegetable crops and their role in improving resilience to adverse environmental conditions and pest infestations. It also addresses the challenges and limitations associated with the broader adoption of nanofertilizers, including regulatory concerns and potential environmental impacts. Finally, this article provides insights into the prospects and research directions in the field of foliar nanofertilizers, underscoring the importance of continued innovation to harness their potential for sustainable agriculture.

## Keywords

foliar nutrition; nanoparticles; quality; vegetables; yield

## Introduction

The global population is rapidly expanding, leading to a growing need for agricultural products. However, traditional fertilizers have significant drawbacks such as pollution and soil degradation. Traditional fertilization methods often encounter challenges, such as nutrient loss through leaching or volatilization, inefficient nutrient uptake by plants and environmental pollution (1). The pervasive use of chemical fertilizers damages the soil structure, disrupts mineral cycles, kills soil microbes, harms plants and disrupts food chains in ecosystems, ultimately affecting future generations. Nanotechnology fertilizers offer a promising solution for addressing these challenges more effectively and sustainably. Nanofertilizers, a subset of agricultural nanotechnology, have demonstrated considerable potential in enhancing crop growth and yield (2). These fertilizers are designed to dispense nutrients to plants more efficiently and precisely, thereby reducing the need for fertilizer use and minimizing nutrient runoff into the environment.

Nanofertilizers are substances typically composed of nanoparticles at the nanometer scale, designed to contain both macro- and micronutrients for controlled delivery to crops (3, 4). Nanofertilization methods can be categorized based on how nutrients are taken up by the crop, including seed priming, soil application and foliar application. Nanofertilisers composed of nanoparticles which interact with the soil through various reactions and alter their physicochemical properties. Nanofertilisers formulated with silica nanoparticles which can improve soil structure by enhancing the aggregation of soil particles. This can reduce soil compaction, improve porosity and increase air and water movement within the soil. Similarly, metal oxide nanoparticles (such as titanium dioxide or zinc oxide) can influence the soil pH and act as buffers by either lowering or raising soil pH depending on their composition; slight pH shift can make certain nutrients more bioavailable to plants which makes an impact on plant nutrient uptake (5). Foliar applications, in particular, transport nutrients directly to the intended plant organ, aiding in alleviating stress-related issues (6). Furthermore, foliar nanofertilizers are deemed suitable for field applications because of their ability of gradual delivery of nutrients to plants at a controlled pace, thereby minimizing the potential toxicity symptoms associated with fertiliser application to the soil(7). Foliar application of ZnO nanoparticles at 40 mg $L^{-1}$ twice on carrot cv. Fire Wedge $F_1$ resulted in the highest root length 22.8 cm, the largest root volume 330.0 $cm^3$ and the largest root diameter 6.44 cm (8). The application of nano fertilizer (Super Micro Plus), liquid seaweed fertilizer and a hypertonic plant growth regulator resulted in significantly higher yields than other treatments in a study conducted on potatoes (9). This combination led to notable increase in fresh tuber yield (32.76 Mg $ha^{-1}$), dry tuber yield (7.280 Mg $ha^{-1}$), vegetative yield (2.194 Mg $ha^{-1}$) and biological yield (10.110 Mg $ha^{-1}$).

Additionally, foliar application is a more straightforward and cost-effective method than incorporating nanofertilizers into the soil (10). Vegetables play a significant role in Indian agriculture and nutritional sustainability because of their short growth cycle, high productivity, nutritional value, economic feasibility and the capacity to create both on-farm and off-farm employment opportunities. India benefits from diverse agro climates characterized by distinct seasons, enabling the cultivation of a wide variety of vegetables. Although nanofertilizers have not been widely adopted so far, some studies have demonstrated the positive impact of foliar nanofertilizers on the increased yield of vegetable crops, such as potato. The combination of two foliar sprays of nano-urea, along with a 50% less fertilsers used in the farmers' fertilizer practices, resulted in a yield increase of 6-16% in potatoes, compared to the yield from farmer fertilizer practices, across the different regions where the experiments were conducted (11).

Foliar application of nanofertilizers is a promising method for enhancing the growth, yield and quality of vegetable crops. This technique involves applying nanoparticles loaded with nutrients directly onto the leaves, facilitating effective nutrient absorption and utilization by plants. This study aimed to explore the role of foliar nanofertilizers in vegetable crop improvement.

## *Need For Nanofertilizers*

Chemical fertilizers are employed to enhance crop productivity; however, they have detrimental effects on soil fertility and disrupt mineral quality. The long-term use of these fertilizers can harm soil structure, mineral cycling, microbial communities and plant health. Nanotechnology is a rapidly growing field that is being utilized in agriculture and plant science for the development of nanofertilizers. Nanoparticles used as fertilizers aim to mitigate the negative effects of conventional chemical fertilizers, such as polluting water sources through leaching, negative impact into the surroundings (12).

## *Advantages of Nanofertilizers*

Nanofertilizers have numerous advantages for sustainable and environmentally friendly crop production (13). Some of its advantages are as follows:

1. Nanofertilizers enable efficient incorporation and consumption of nutrients without experiencing elevated losses.
2. Nanofertilizers help mitigate the risk of environmental contamination by minimizing nutrient loss through leaching.
3. Nanofertilizers generally exhibit greater diffusion and solubility than traditional synthetic fertilizers do.
4. Nanofertilizers provide a controlled and gradual release of nutrients to crop plants, in sharp contrast with the rapid and spontaneous nutrient delivery associated with chemical fertilizers.
5. Plants can readily absorb nanoparticles through nano-sized pores, molecular transporters and root exudates. The uptake of nanoparticles by plants enhances nutrient absorption through a variety of ion channels.
6. A smaller quantity of nanofertilizers is required for application than synthetic fertilizers because of their minimal nutrient loss characteristics.
7. Polymer-coated fertilizers inhibit premature exposure to water and soil, thereby minimizing nutrient loss.
8. Nanofertilizers enhance soil fertility and establish optimal conditions to support the proliferation of microorganisms (14).

## *Modes of Nanofertilizers Application*

### *Soil Application*

Nanofertilizers are typically applied to soil either as suspensions or as dry powders. These nanofertilizers contain nanoparticles of essential nutrients (such as nitrogen, phosphorus, potassium, etc.) or compounds like EDTA (Ethylene Diamine Tetraacetic Acid), citric acid, humic acids and fulvic acids, which bind to nutrients such as iron, zinc, copper, calcium and magnesium, making them more available to plants, which can enhance nutrient availability in plants (15).

**Adsorption onto soil particles:** Upon application to the soil, nanoparticles may interact with soil particles through various processes, such as electrostatic attraction, van der Waals forces, or chemical bonding. This interaction can influence the distribution and mobility of nanoparticles in the soil (16).

**Transport in soil pores:** Nanoparticles can move through the soil matrix via processes such as diffusion, advection and dispersion. The size, shape, surface charge and surface chemistry of nanoparticles influence their mobility in soil pores (16).

**Uptake by plant roots:** As nanoparticles such as nano zinc (ZnO), nano copper (CuO) and nano iron ($Fe_2O_3$and $Fe_3O_4$) move through the soil, they encounter plant roots. Nanoparticles may adhere to root surface or penetrate the root tissue through various pathways, including root hair and epidermal cells.

**Translocation within the plants**: Once absorbed by the roots, nanoparticles may be transported within the plant through the vascular system. They can be distributed to different plant tissues, including leaves, stems and reproductive organs, where they affect plant growth and development. The detailed mechanism of nanofertilizers absorption through soil application is shown in Fig. 1.

**Plant response:** Nanoparticles absorbed by plants can interact with cellular components and affect various physiological processes. These responses include changes in nutrient uptake and assimilation, modulation of gene expression, activation of stress responses and alterations in metabolic pathways.

Nanofertilizers can be applied to soil using traditional methods such as broadcasting, side-dressing, or fertigation. Once applied, these nanoparticles interact with plant roots either by adhering to their surfaces or by entering root cells through a process known as endocytosis (17).

### *Seed Treatment*

Seed priming is a technique conducted before sowing that triggers physiological alterations in seeds, leading to accelerated germination and enhanced plant growth and development by modulating metabolic and signaling pathways (18).

During seed priming with nanofertilizers, nanoparticles penetrate the seed coat through tiny openings, cracks, or natural pores. The transportation of nanoparticles is facilitated by the seeds' internal physiological processes, including water uptake and nutrient absorption. Once absorbed by the seed, nanoparticles are distributed within different seed tissues, including the endosperm, embryo and seed coat. The detailed mechanism of nanofertilizers absorption during seed priming is presented in Fig. 2.

Nanoparticles interact with cellular components such as proteins, lipids and nucleic acids. This method facilitates seed germination, seedling emergence and subsequent plant growth by several mechanisms.

**Improved water uptake:** Nanoparticles can create nanoscale water channels on seed surfaces, facilitating water uptake during imbibition and enhancing germination during water-limited conditions.

**Enhanced nutrient uptake:** Nanoparticles can modify the surface properties of seeds, facilitating the absorption of nutrients from the surrounding soil or growth medium. This can lead to improved nutrient uptake efficiency, seedling vigor and overall plant growth.

**Stress tolerance**: Nanoparticles can induce stress tolerance in seeds by modulating antioxidant enzyme activity and osmolyte accumulation. This helps seeds withstand adverse environmental conditions, such as drought, salinity and temperature extremes. Gold and silver nanoparticles were used to prime onion seeds. Internalization studies, carried out using instrumental neutron activation analysis and gas chromatography-mass spectrometry, confirmed that the treated nanoparticles were absorbed into onion seeds. A series of greenhouse and field trials have demonstrated improved seed germination, emergence, growth and yield compared to both unprimed and hydroprimed seeds. Seed priming with AuNPs resulted in a significant increase in emergence percentage (63.2%) compared with the unprimed control (37.4%) when data from both years were analyzed together. An average yield increase of 23.9% was observed in AuNPs treated onions, compared to unprimed onions (19). Nano silicon dioxide at 8 g L$^{-1}$ resulted in a higher percentage of seed germination in tomatoes (20).

**Activation of metabolic processes:** Nanoparticles can stimulate the expression of genes related to plant growth and development, leading to accelerated metabolic processes and enhanced seedling vigor.

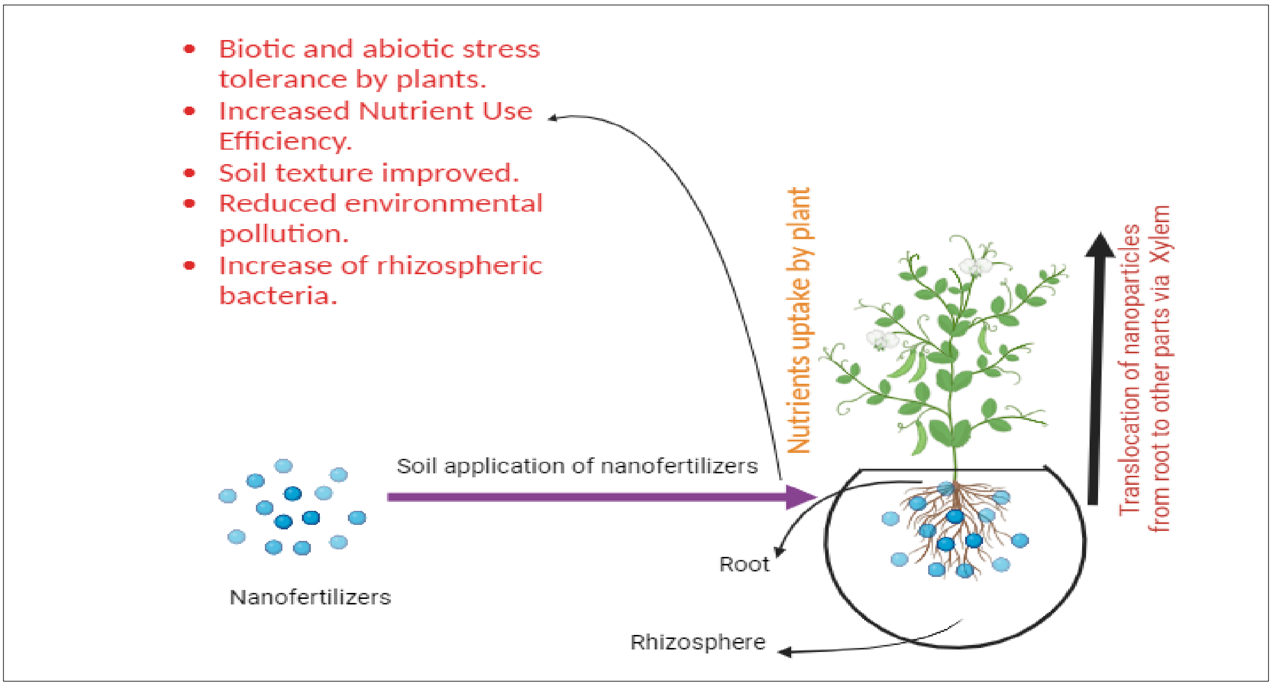

**Fig. 1.** Nanoparticles are absorbed by the roots and transported through the plant via the xylem.

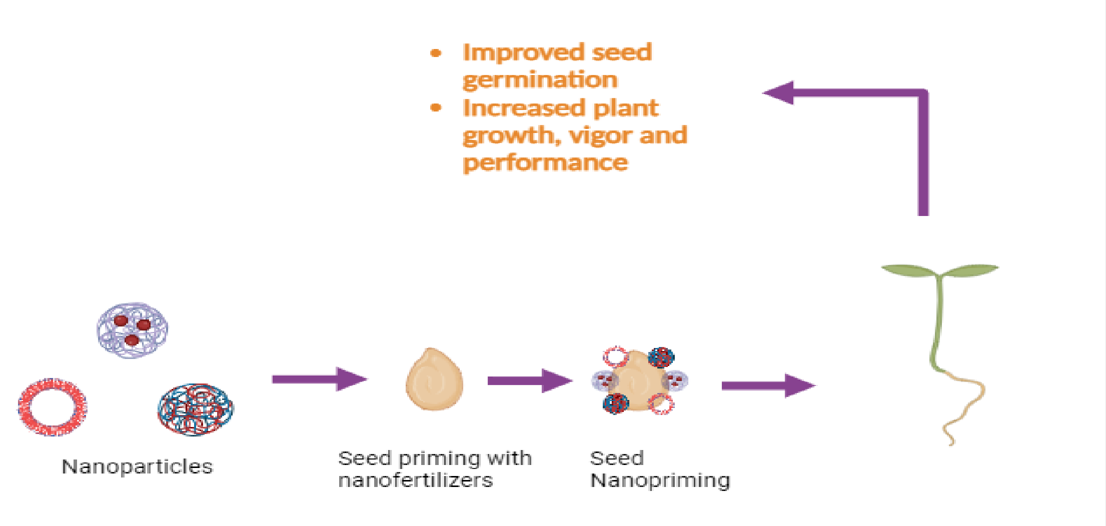

**Fig. 2.** Nano-priming forms nanopores in seeds, enhancing water uptake, ROS production and antioxidant responses, boosting germination and vigor.

**Hormonal regulation:** Nanoparticles can modulate the synthesis and signaling of plant hormones, such as auxins, cytokinins and gibberellins, which play crucial roles in seed germination and early seedling growth.

**Protection against pathogens:** Nanoparticles with antimicrobial properties can protect seeds from seed-borne pathogens, reduce the risk of seedling diseases and improve overall plant health. Metallic nanoparticles (MNPs) are promising broad-spectrum antimicrobial agents that can target a broad range of plant pathogens, including bacteria, fungi and viruses. Different types of MNPs such as silver, copper, zinc, iron and gold have been explored for their antimicrobial properties. The unique physicochemical characteristics of MNPs, including their small size, large surface area and high reactivity, allow them to interact with plant pathogens at the molecular level. This interaction can lead to cell membranes damage, disruption of cellular respiration and production of reactive oxygen species (21).

### *Foliar Application*

Applying fertilizers directly to the leaf surface of plants allows for rapid nutrient absorption and bypasses the root system. Nanoparticles are absorbed by the leaf through cuticular pores, stomata and leaf tissue. Inside the leaves, nanoparticles move in two ways: via apoplastic and symplastic pathways.

In the apoplastic pathway, nanoparticles move through the extracellular spaces of plant tissues by diffusion. This movement is particularly relevant for nanoparticles that do not readily enter plants. In the symplastic pathway, nanoparticles move through the interconnected cytoplasm of plant cells. Both pathways contribute to the overall distribution and translocation of nanoparticles in plants. Once inside the leaves, nanoparticles can be transported within the plant through the vascular tissue.

Foliar application is viable even under adverse soil and weather conditions and facilitates direct nutrient absorption by plants, thereby minimizing fertilizer waste. Consequently, the use of nanofertilizers for foliar application enhances nutrient use efficiency (NUE) and accelerates crop growth. Nanofertilizers exhibit heightened reactivity. Owing to their small size and unique surface properties, they are more chemically reactive than bulk fertilizers. This enhanced reactivity means that they can more effectively interact with plant cells and soil, promoting faster and more efficient uptake of nutrients by plants and can permeate through the cuticle, ensuring controlled discharge and precise delivery to target areas (22). The mechanism of nanofertilizers absorption through foliar application is shown in Fig. 3.

## Role of Nanofertilizers

The conventional method of applying fertilisers to the soil has various limitations in terms of nutrient accessibility for plants. Hence, foliar application is the most effective approach for rectifying nutrient deficiencies and enhancing crop yield and quality (23). Nano-coated materials larger than 10 nm in size enhance penetration through stomata despite being larger than 10 nm and having a high surface area relative to their volume. This increases their reactivity and ability to interact with stomatal cells, helping them to move more effectively through the stomata (24). Nanofertilizers possess a significant surface area, high absorption capacity and controlled release kinetics tailored to specific sites, rendering them an intelligent delivery system (25). Nanocarriers frequently deliver nutrients precisely when and where they are required. Thus, it is pertinent to highlight key research studies that have shown the penetration and movement of nano-fertilizers through leaves, their effects on crop productivity, yield enhancement, plant resilience to environmental stresses and the reduction of heavy metal toxicity.

Foliar nanofertilizers are likely to offer a new means to address the high production challenges in agricultural systems.

## Effects of Foliar Nanofertilizers on Growth and Yield of Vegetable Crops

### *Solanaceous Vegetables*

The *Solanaceae* family, primarily found in tropical regions, comprises approximately 75 genera and 2000 species. Among its notable vegetable genera are *Solanum* (including potatoes and eggplants), *Lycopersicon* (tomatoes) and *Capsicum* (peppers) (26).

Optimal results for enhancing various growth parameters and overall yields of tomato cv. Arka Rakshak were achieved through a combination of 50% nitrogen, along with 100% phosphorus and potassium, supplemented with 50% zinc applied inorganically to the soil. Additionally, a series of foliar sprays were applied: the first with nano nitrogen, the second with nano zinc and the third with nano copper (27).

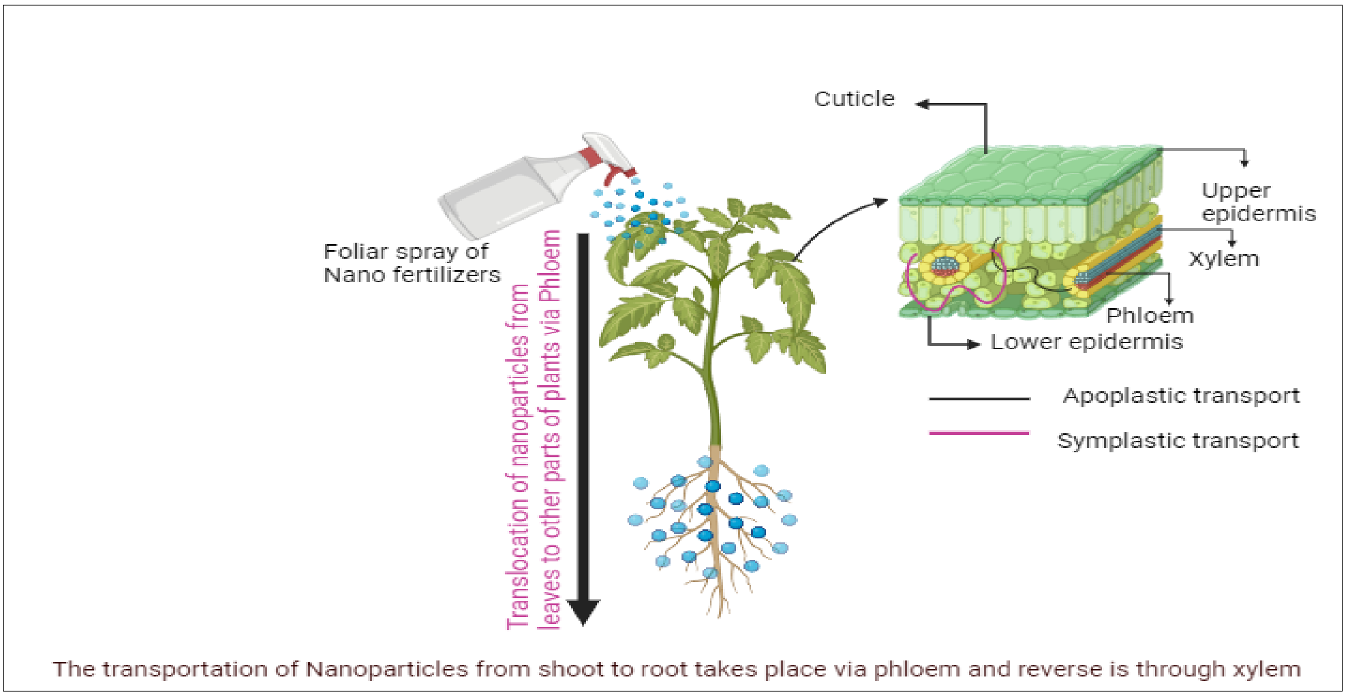

**Fig. 3.** Nanoparticles enter leaves via stomata, moving through apoplastic and symplastic pathways and reach roots via phloem, especially in storage root crops.

The use of nano-silicon fertilizer (NSF), nano-chelated potato-specific fertilizer (NPS) and nano-chelated complete micro (NCM) resulted in increased fresh tuber yields and improved various parameters associated with potato growth and yield when compared to the control group (28). Tri-spray treatment (NSF+NCM+NPS) in potato cultivation resulted in maximized fresh tuber yield enhanced water use efficiency (WUE) and agronomic efficiency (AE). Employing nano-ZnO at a concentration of 50 mg L$^{-1}$ resulted in notable enhancements in transplant growth, photosynthetic efficiency, levels of macronutrients, as well as enzymatic and non-enzymatic antioxidant activities. These findings contribute to the development of robust eggplant transplants (29).

The foliar application of nanofertilizer (nano nitrogen, nano copper, nano zinc) at specified rates (Nitrogen at 4mL L$^{-1}$, Copper at 2mL L$^{-1}$, Zinc at 2mL L$^{-1}$) in conjunction with the recommended soil fertilizer dosage in chilli was found to enhance all growth characteristics (29).

### Cruciferous Vegetables

Cruciferous vegetables, categorized within the *Brassicaceae* or mustard family, are estimated for their nutritional richness and associated health advantages. Examples include vegetables, such as cabbage, cauliflower, broccoli, kale, turnip, Brussels sprouts and others.

Research has demonstrated that the application of nano-DAP at various levels at 50% P, 100% N & K + Foliar Spray of nano -DAP at 2 mL L$^{-1}$ at 25-30 days after transplanting and 100% RD of N & K + Seedling root-dip treatment of n-DAP at 5 mL L$^{-1}$, proved to be remarkably effective in enhancing the growth attributes of cabbage heads (30).

Spraying broccoli with nano fertilizers (K 27%, Zn 12% and Fe 9%) at a concentration of 2 g L$^{-1}$, three times during the growth period, resulted in a notable increase in vegetative growth compared to untreated plants (31).

### Cucurbitaceous Crops

Cucurbits are a significant category of vegetable crops within the *Cucurbitaceae* family, comprising 118 genera and 825 species and showing substantial genetic variability. These include cucumbers, melons, watermelons, pumpkins and squash.

An experiment involving the application of three different concentrations of nanofertilizers, $N_20$, $P_20_5$ and $K_20$, on three distinct cucumber hybrids, Roni, Modhish and Baher, recorded that applying a concentration of 3 mg L$^{-1}$ of nanofertilizer on Roni hybrids notably enhanced plant length and leaf area. Similarly, on Modhish hybrids, the same concentration significantly boosted yield per plant, fruit yield and total fruit yield. Additionally, on Baher hybrids, the 3 mg L$^{-1}$ concentration led to a significant increase in the leaf area and the number of leaves per plant (32).

The application of nanofertilizers at various volumes (3, 4.5, 6 and 9 mL) led to significant enhancements in cucumber growth and yield (33). These improvements included increased plant height, number of leaves per plant, chlorophyll content, yield and NPK % in both leaves and fruits compared with the control treatment. Specifically, the application of 6 mL of NPK resulted in yield increases of 4.84% and 53.42% in the first and second seasons, respectively.

The application of 300 mg L$^{-1}$ Zinc nanoparticles and 200 mg L$^{-1}$ iron nanoparticles as foliar spray at three growth stages in cucumber resulted in improvements in various growth parameters (34).

These included vine length, number of fruits per plant, total leaf chlorophyll content, fruit characteristics such as dimension and weight, accumulation of seed constituents (TSS, TSP, starch and oil content) and attributes related to seed yield (number of seeds per fruit, 1000 seed weight, seed yield per hectare). These enhancements were observed compared to those in untreated plants and those treated with higher doses of Fe and Zn nanoparticles.

The application of silica nanofertilizer to the leaves of musk melon greatly enhanced plant height, stem thickness, internode length and the total number of bisexual flowers. The also results in more bold ovaried flowers (35).

The foliar application of ZnO oxide nanoparticles to the leaves increased the productivity, improved market value and health-promoting attributes of melon produce (36).

The use of 9g of Nano NPK (19:19:19) $L^{-1}$in bottle gourd cultivar Sarita resulted in superior vine length, primary branch count, time to emergence of the first female flower, time to fruit setting and time to fruit harvesting compared to other treatments. On the other hand, employing 7.5g of Nano NPK (19:19:19) $L^{-1}$ led to optimal outcomes in terms of total fruit count per vine, fruit weight, yield per hectare, TSS, ascorbic acid content and moisture percentage, ultimately resulting in highest Benefit-to-Cost (B:C) ratio (37) .

### *Leguminous Vegetable*

Vegetable legumes such as garden peas, French beans, cowpeas, cluster beans, lima beans, winged beans and similar varieties, play a crucial role in maintaining a nutritious diet because of their high protein content. These legumes are rich sources of carbohydrates, vitamins, minerals and various bioactive compounds that are beneficial to human health. With increasing awareness of the importance of a balanced diet, there is growing demand for both fresh and processed vegetable legumes among consumers. Ensuring high yields of vegetable legumes is essential, but poses significant challenges, primarily due to the slow pace of yield improvement and the negative effects of both biotic and abiotic stresses on their cultivation (38).

An experiment showed that the use of nano-micronutrient fertilizers significantly affected the physical quality of pods and the yield of fresh pods in snap bean plants (39). The application of nano-micronutrient spray solutions containing manganese (Mn), iron (Fe) and zinc (Zn) at a concentration of 50 mg $L^{-1}$ (in the form of oxide compounds) resulted in a notable improvement in both pod quality and yield. This improvement was observed after three spray applications administered at intervals of 21, 31 and 41 days after seeding.

Another study found that using half the recommended amount of nitrogen (10 kg $ha^{-1}$), full phosphorus (30 kg $ha^{-1}$) and full potassium (10 kg $ha^{-1}$) as an initial application, followed by foliar administration of nitrogen in the form of nano urea and zinc as nano zinc at a rate of 2 ml $L^{-1}$ individually 30 days after sowing (DAS), resulted in improved growth and yield in bush-type vegetable cowpeas (40).

Application of 75 % RDF of N through prilled urea combined with a 0.4 % nano-urea foliar spray at 45 and 60 DAS resulted in superior performance in terms of total NPK content of leaves, whole plants and pod yield compared to other treatments(41). The use of balanced nanofertilizer NPK (20-20-20) in *Cucurbita pepo* L has also been shown to increase the yield and improve the vegetative and fruiting characteristics of the crop (42).

### *Root and Tuber Crops*

Roots and tubers are plant species that produce starchy underground structures such as roots, tubers, rhizomes, corms and stems. They are primarily used for human consumption, either in raw form or processed into various food products. Additionally, they are used as animal feed and as raw materials for starch, alcohol and beer production.

Despite their high-water content, ranging from 70% to 80%, these crops are predominantly composed of carbohydrates, particularly starches, which make up approximately 16% to 24% of their total weight. These crops are primarily cultivated by marginal farmers and often yield more calories per hectare per day than other crops (43).

Root and tuber crops are the second most important groups of crop plants after cereals. Roots and tubers contribute 5.4% of energy to global food security (44).

The application of a mixture of nanosized microelements (Fe, Mn, Zn and B) at a concentration of 200 mg $L^{-1}$, combined with 1% urea, significantly improved the yield and quality of the sugar beet variety Farida. Additionally, incorporating this fertilizer rate in nanoparticle form helped to reduce the requirement for micronutrients and nitrogen fertilizers for the plants (45).

It was found that using a combination of ZnO and FeO nanoparticles at concentrations of 60 ppm and 50 ppm, respectively, enhanced the physical characteristics and nutritional levels of red radish. Additionally, increasing the levels of iron and zinc in radish roots did not negatively affect human health. The research concluded that environmental friendly nanofertilizers derived from green synthesis methods, such as ZnO and FeO, positively influence the growth, yield and nutritional content of radish (46).

Foliar nourishment of sweet potatoes (cv. Beauregard) plant leaves with ZnO nanoparticles at a concentration of 1000 mg $L^{-1}$ rebalanced the leaf with Fe and Mn contents under high $CaCO_3$ Stress conditions (47).

### *Leafy Vegetables*

Leafy vegetables encompass a wide variety of crops from diverse botanical families. These vegetables are characterized by their edible portions as leaves (48, 49).

Utilizing nitrogen in the nano form enhances fertilizer efficiency, even at doses lower than the recommended levels, while simultaneously mitigating excess loss and environmental contamination. Nano-formulated nitrogen fertilizer, applied through a combination of 75% fertigation and 25% foliar application, has been shown to increase nitrogen uptake and improve nitrogen utilization efficiency. Additionally, foliar application of nano nitrogen leads to increased levels of β-carotene and crude protein by fostering enhanced growth and fertilizer utilization efficiency (50).

A pot experiment conducted in sandy soil evaluated the impact of nano-nitrogen loaded in modified zeolite compared with conventional fertilizers on lettuce. Different combinations of 100%, 75%, 50% and 25% of the recommended dose of conventional nitrogen fertilizer, along with 100ml, 75ml, 50ml and 25ml of 1000ppm Nano N solution, were applied to lettuce plants. In this study, vegetative growth and yield parameters were measured and the results indicated that the use of nano nitrogen led to significantly higher values for vegetative growth parameters, including plant fresh weight (PFW), shoot fresh weight (SFW), plant length (PL), leaf area (LA) and plant dry weight compared to conventional fertilizers (51). Effective utilization of green-synthesized copper oxide (CuO) and zinc oxide (ZnO) nanoparticles as nanofertilizers boosted the agronomic characteristics of *Amaranthus hybridus* when applied via hydroponic and foliar methods (52).

## Foliar Nanofertilizer for Biotic and Abiotic Stresses in Vegetable Crops

Biotic stress in plants refers to the adverse effects caused by living organisms such as pathogens (bacteria, fungi and viruses), pests (insects, mites and nematodes), parasites, or competing plants (weeds). These stressors can negatively affect the growth, development and productivity of plants. Biotic stressors may directly damage plant tissues, inhibit nutrient uptake, alter plant physiology and induce plant defense responses. Common examples of biotic stress in plants include fungal infections, insect herbivory, nematode infestations and weeds competition. Effective management of biotic stress for vegetable crop production can be achieved through nanotechnology.

The introduction of nanoparticles in pest management has revolutionized agriculture by significantly reducing the use of pesticides. Various types of nanoparticles, including polymeric, metallic and metal oxide nanoparticles, have demonstrated remarkable effectiveness in addressing biotic stress in crops (53) (Table 1). Among these, silver and copper nanoparticles have garnered extensive research attention because of their potent antimicrobial properties (54, 55). Nonetheless, chitosan nanoparticles have emerged as pivotal players in plant biotic stress management studies because of their antimicrobial efficacy, biocompatibility and biodegradability, making them the preferred choice for controlling such stresses in plants (56, 57).

Abiotic stress in plants refers to the adverse effects of non -living factors, such as extreme weather, salinity and pollution. Unlike biotic stressors, which are living organisms, abiotic stressors originate from the physical and chemical components of the environment. Abiotic stress can disrupt various physiological processes in plants, including water balance, photosynthesis, nutrient uptake and cellular metabolism. These stresses can lead to reduced growth, decreased productivity, wilting, leaf chlorosis, tissue damage, ultimately reducing crop yields and, in severe cases, causing plant death.

Nanoparticles have emerged as a promising strategy for mitigating the adverse effects of abiotic stresses on plants. Metal nanoparticles have various beneficial applications in plant systems. Moreover, nanoparticles have shown promise in stimulating the production of phytohormones, thereby regulating plant growth and metabolism in response to abiotic stressors. In particular, chitosan nanoparticles, with the ability to release nitric oxide, have been effective in alleviating the detrimental effects of saline stress (53). The applications of nanofertilizers for alleviating biotic and abiotic stresses are presented in Table.1 below.

## Challenges

Nanomaterials have wide applications in agriculture, primarily as nanofertilizers and carriers of fungicides and pesticides. Nanofertilizers are used to enhance crop growth, improve soil fertility and increase agricultural yield while maintaining sustainability (68). They are integral to precision farming practices and are increasingly recognized for their ability to mitigate the negative impacts of inefficient chemical fertilizer use, such as water pollution and eutrophication (69).

For successful field applications, determining the optimal activity and concentration of nanofertilizers is critical for achieving maximum yields with minimal losses (70). Furthermore, evaluating residual nanofertilizers during in planta studies is essential to reduce the potential risks to other organisms in the ecosystem" (71). Safety measures must be developed and implemented concurrently, focusing on the type, size and shape of nanoparticles suitable for crop production

Factors, such as solubility, stability, surface reactivity and charge significantly influence the effectiveness of nanofertilizers in agricultural practices. Despite the increasing adoption of nanofertilizers, there remains a lack of specific protocols for their field application, resulting in non-specific reactivity in plants across different species (72). Additionally, the mechanisms of nanofertilizer absorption and their interactions within plants are not fully understood. Therefore, it is imperative for research groups, funding organizations, policymakers and leaders from both the private and public sectors to familiarize themselves with guidelines tailored to the use of NFs, with a focus on prioritizing the interests of farmers (73).

**Table 1.** Foliar Nano fertilizer in combating biotic and abiotic stresses in vegetable crops

| SI NO. | Biotic/Abiotic stresses | Effective Nano fertilizer | Reference |
|---|---|---|---|
| **01.** | Salt stress | Zinc nanoparticles (ZnNPs) at 0.3%, ZnNPs spray at 0.3% in spinach (*Spinacia oleracea* L.) as foliar spray was found to be effective in the accumulation of osmolytes enzymatic and non-enzymatic antioxidant defense systems thus suppressed the NaCl induced stress. | (58) |
| **02.** | Saline water stress | Nano-fertilizer consisting of 79.19% CaCO3 and 4.62% MgCO3% was applied through foliar spraying @ 0.75 g L$^{-1}$ in tomato plant showed improved plant height, leaf number, yield of salt-stressed plants | (59) |
| **03.** | Salt stress | Foliar application of MgO-Nano Particles @ 100 µg mL$^{-1}$ alleviates the inhibitory effects of salt stress on sweet potatoes. | (60) |
| **04.** | Cold stress | The combination of AMF (Arbuscular mycorrhizal Fungi) with a nanoparticle mixture (ZnO-NPs + Se-NPs) as foliar spray in chili plans reduces the harmful effects of cold stress on chili plants. | (61) |
| **05** | Drought stress | The drought-induced decline in the content of phenol and mineral nutrients was mitigated by ZnO NPs foliar application in cucumber seedlings. | (62) |
| **06** | Water stress | Application of zinc oxide nanoparticles at a concentration of 100 parts per million (ppm) via foliar spray on eggplant resulted in enhanced water productivity, thus mitigating the adverse effects of water stress on brinjal production in dry-land agricultural settings. | (63) |
| **07.** | Aphid | Foliar application of the mixture of *Penicillium sp.*10$^{6}$ spora mL$^{-1}$ + nanosilica 5%, in cabbage seedlings increased the mortality of *M. persicae*. | (64) |
| **08.** | Spider mite | Application of SiO-NP and ZnO-NP at 5 ppm in tomato is a eco-friendly management strategy of *T. urticae.* | (65) |
| **09.** | Chocolate spot disease | Ag/SiO2 nanocomposite improved faba bean resistance to *B.cinerea* that causes chocolate spot disease by increasing proline, phenols and defense enzymes (peroxidase and polyphenol oxidase enzymes). | (66) |
| **10.** | *Fusarium oxysporum* | Foliar application $Fe_2O_3$ nanoparticles (at 20 µg mL$^{-1}$) shown antifungal activity against *F. oxysporum* in tomato. | (67) |

## Future Perspectives

Recent publications indicate a growing interest in the foliar application of nanofertilizers, either independently or in conjunction with soil fertilization. This method offers direct benefits to crops, is more accessible and is unaffected by soil reactions. In addition, foliar sprays require smaller quantities, making them more cost-effective and environmentally friendly. Overall, foliar nanofertilizers show promise for sustainable agriculture but require further research before widespread adoption. Challenges such as nanoparticle toxicity, environmental residues and the influence of these factors on agricultural production, along with determining the optimal concentration for effective action, need to be addressed before large-scale implementation. Despite these obstacles, there are expectations of continued advancements in this area in the future:

- Determining the optimal concentration and timing of nanofertilizer application is essential, as it varies across different crops. Thorough trials are necessary to prevent environmental contamination and potential harm to the plants.
- Further investigation into how fertilizer functions within foliage is crucial for pinpointing the specific sites of nanoparticle action.
- Comparative research on various application methods, including soil application, seed priming, root dipping in nutrient solutions and foliar spraying, is required to identify the most effective approaches in different scenarios.
- Focus to be directed towards exploring different nanomaterials and fertilization techniques, as the outcomes may vary depending on the application method employed.
- Despite advancements, significant hurdles remain before widespread adoption, necessitating focus on issues such as toxicity, human health impacts and economic viability.

## Conclusion

Through a comprehensive analysis of current research findings, it is evident that nanofertilizers offer promising solutions to address various challenges faced in conventional agriculture, including nutrient loss, environmental pollution, limited nutrient uptake efficiency and biotic and abiotic stresses faced by vegetable crops. Through foliar nanofertilizer application, vegetable crop production can be substantially improved, leading to increased yield, enhanced nutrient utilization and healthy plants, ultimately leading to sustainable crop production. Nanofertilizers bring about a positive transformation in the agricultural sector by diminishing the quantity of conventional fertilizers currently utilized, while simultaneously enhancing crop yields. Nanofertilizers offer economic advantages to producers by reducing fertilizer loss through leaching and volatilization. Their eco-friendly nature further enhanced their appeal. Although there is uncertainty regarding the environmental impact of nanomaterials, further research is essential to fully understand their long-term impacts and optimize the formulation and application methods of nanofertilizers for widespread adoption in vegetable cultivation. Nonetheless, the potential benefits of nanofertilizers offer significant opportunities to revolutionize vegetable crop management and advance sustainability in the coming years.

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## Authors' contributions

SRP conceptualized the manuscript and prepared the initial draft. TC contributed resources for manuscript preparation and supervised. ST reviewed and supervised the work. SG offered resources and provided a review. PR reviewed and edited the manuscript. KP contributed resources, reviewed and edited the manuscript. IRC performed corrections. All authors read and approved the final manuscript.

## Compliance with ethical standards

**Conflict of interest:** Authors do not have any conflict of interests to declare. No conflict of interest exists among the authors involved in the creation of this article. All authors have provided their consent to submit this article.

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### Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) used ChatGPT -4 to improve the language. After using this tool, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

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