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REVIEW ARTICLE

Nanofertilizers in vegetable crops: Harnessing nanotechnology for improved crop nutrition and environmental sustainability

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Abstract

Nanofertilizers represent a groundbreaking advancement in agricultural technology, offering a sustainable solution to enhance crop nutrition and address the challenges of global food security. Traditional fertilizers, while essential for crop production, often result in significant nutrient losses, environmental pollution and soil degradation due to low nutrient use efficiency (NUE). In contrast, nanofertilizers, engineered at the nanoscale, provide precise and controlled nutrient delivery, minimizing losses and maximizing plant uptake. These innovative fertilizers improve NUE, enhance crop yields and reduce environmental impacts such as nutrient leaching and water pollution. By leveraging nanotechnology, nanofertilizers facilitate better nutrient absorption, improved root development and enhanced stress tolerance in plants, leading to higher-quality produce and extended shelf life, particularly in fresh-cut vegetables. This review explores the transformative potential of nanofertilizers in sustainable agriculture, highlighting their mechanisms of action, benefits and applications across various crops. Despite their promise, challenges such as regulatory concerns, production costs and potential ecological risks must be addressed to ensure their safe and widespread adoption. As the global population continues to grow, nanofertilizers stand at the forefront of agricultural innovation, offering a pathway to sustainable crop production and food security. Future research should focus on optimizing nanofertilizer formulations, assessing long-term environmental impacts and developing cost-effective production strategies to facilitate their large-scale adoption.

Keywords: controlled nutrient release; crop productivity; nanofertilizer; smart fertilizers; sustainable agriculture; yield enhancement

Introduction

Agriculture is a cornerstone of global food security, requiring innovative solutions to sustain productivity amidst rising populations and environmental challenges. Traditional chemical fertilizers are integral to crop production but often lead to environmental issues such as nutrient leaching, heavy metal accumulation and soil degradation. Because traditional fertilizers have a relatively low nutrient utilization efficiency (about 18-20 % for phosphorus, 35-40 % for potassium and 30-35 % for nitrogen), the leaching of these nutrients from the soil has led to a significant loss in soil fertility (1). Overuse or improper application can disrupt soil health and reduce nutrient use efficiency (NUE). To address these issues, researchers are exploring innovative solutions like nanofertilizers, which ensure precise nutrient delivery and reduce losses. In the last few decades, nanotechnology has been considered as a projecting technology with plentiful applications in agriculture (2). Nanotechnology plays a vital role in crop production with environmental safety, ecological sustainability and economic stability (3). Nanotechnology leverages particles smaller than 100 nm to enhance nutrient absorption and minimize environmental impact. Nanofertilizers are engineered for higher uptake through leaf pores and stomatal openings, ensuring better nutrient transport between plant cells via plasmodesmata channels (50-60 nm). Nanofertilizers are gaining importance due to their ability to improve nutrient delivery and reduce environmental loss. Vegetable crops, due to their short growth cycle and high nutrient demand, stand to benefit significantly from these technologies. While previous reviews have provided general overviews of nanofertilizers in agriculture, the present review narrows the scope to vegetable crops and incorporates the most recent advancements up to 2025, with emphasis on field-level responses, NUE and quality enhancement (4, 5). These fertilizers enhance crop performance by improving photosynthesis, root development and fruit quality. Studies confirm that slow-release properties and improved absorption through nano-scale channels significantly improve nutrient delivery efficiency (6). Hence, researchers have developed macronutrient nanofertilizers for both laboratory and field-grown plants (4). The application of nanofertilizer is promising and efficient for the translocation of nutrients to the desired parts of the plant (7). This review explores nanofertilizers potential to transform crop nutrition through improved efficiency and sustainability. A growing interest in precision agriculture and the need for environmentally safe nutrient delivery systems make this review a timely contribution to the field of vegetable crops, which is becoming increasingly important in global food security.

Conventional fertilizer *vs.* nanofertilizer

Conventional fertilizers are typically applied to crops by spraying or broadcasting, with the final concentration reaching the plant being a crucial determinant in choosing the application method. However, in practical scenarios, the actual concentration reaching the targeted site is often far below the desired minimum because of various factors such as leaching, drifting, drainage, evaporation, degradation by soil moisture and degradation by light and microbes. Studies estimate that significant portions of applied fertilizers, including 40-70 % of nitrogen, 80-90 % of phosphorus and 50-90 % of potassium, disappear into the environment each year, leading to substantial economic and sustainability losses (8). The efficiency of conventional nitrogenous fertilizers is only 30-60 %, while phosphatic fertilizers suffer losses ranging from 8% to 90 % owing to the bonding of chemicals in soil, rendering them unavailable for plants (9). These issues have led to repeated fertilizer and pesticide applications, disrupting the natural nutrient balance of the soil and causing environmental pollution, which adversely affects the flora and fauna. Therefore, optimizing the use of chemical fertilizers to meet crop needs while avoiding environmental impacts is critical. Nanotechnology offers a promising solution by introducing nanoscale or nanostructured materials as carriers or using controlled-release approaches to develop “smart” fertilizers that enhance nutrient effectiveness (up to 50 %) and minimize environmental contamination (10). Nano-fertilizers, operating at the nanometer scale, deliver nutrients to crops by encapsulating them in nanoparticles coated with thinner protective polymeric films or in the shape of nanoscale particles or emulsions (11). Surface nanomaterial coatings on fertilizer particles provide stronger adhesion, facilitating controlled release (12). Nano-fertilizers have shown promising results in improving agricultural output and quality, boosting nutrient utilization efficiency and lowering production costs, thereby contributing to agricultural sustainability. Analysis of nanofertilizer datasets reported median efficacy gains of 18-29 % in comparison to conventional fertilizers (13).

Nanofertilizers exhibit controlled dispersion of agrochemicals, targeted distribution, reduced toxicity and improved nutrient absorption (14). This controlled release prevents premature conversion of nutrients into unavailable forms, which is attributed to the nanoparticles’ significant surface area-to-volume ratio, lubricity, small size for precise targeting, good mobility and low toxicity (Fig. 1) (15). The improved penetration of nanofertilizers reduces the amount of fertilizer required and minimizes nutrient leaching and runoff, thereby mitigating environmental pollution (16). Consequently, using nanofertilizers for efficient penetration in plant tissues contributes to better crop yields, improved nutritional quality and overall agricultural sustainability (17). The high penetration rate of nanofertilizers makes them essential for better nutrient availability to the plant and, in turn, for healthy seedling growth. For example, nano-ZnO exhibits more peanut seed germination and root development than zinc sulfate in bulk (18). Therefore, incorporating nanotechnology into fertilizer development holds significant promise for improving agricultural productivity while minimizing environmental impact. Numerous researchers have reported significant effects of various nanoparticles and nano-fertilizers on growth and yield parameters in vegetable crops, which are summarized in Table 1.

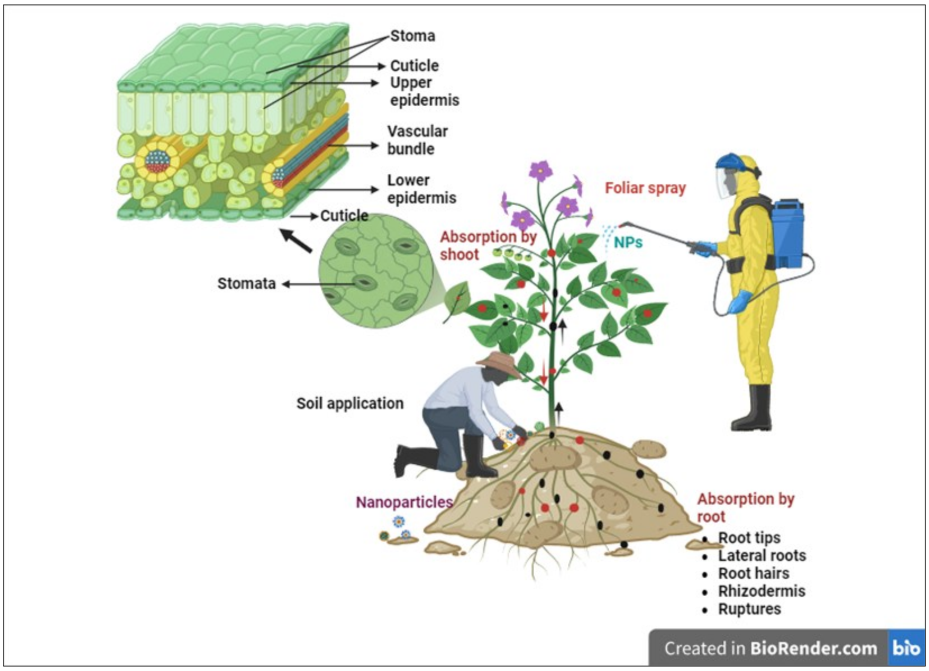

Fig. 1. NPs uptake through shoot and root system in plants.

Table 1. Effect of nanofertilizer in various vegetable crops

Crop	Nanofertilizers	Effects	References
Tomato, eggplant	Zinc (Zn) 1 mg/L nanofertilizer	Reduces fungal disease and improves germination	(72)
Tomato	5 g L^{-1} pramukh foliar spray + RDF @ 125:60:100 kg NPK/ha	Enhanced the yield parameters	(73)
Pepper	Basal application of slow-release nanofertilizer Liulitian 2 at a dose of 2.63 g along with top dressing applied twice at doses of 1.32 g and 0.66 g	Stimulated plant growth, decreased nutrient leaching, improved soil enzyme activity, improved nutrient utilization and enhanced the soil environment	(74)
Sweet pepper	Foliar application of nano-fertilizer Nano Active Forte in concentrations of 1 % and 4 kg/ha	Total yield, marketable yield, dry matter content, soluble solids, total sugar, vitamin C, carotenoid content and phosphorus and potassium content increased	(75)
Potato	Foliar application of NPK nanofertilizer in a concentration of 50 %	Enhanced the harvest index, economic yield, benefit-cost ratio, nutrient usage efficiency and starch content while lowering the nitrate level	(76)
Potato	Foliar application of zinc nanoparticles at concentrations of 300 ppm and 500 ppm	Elevated levels of starch, total phenolics, anthocyanin content and catalase and peroxidase activity	(77)
Brinjal	Nano potassium soil application (1.5 g/L)	Enhanced values of the parameters related to vegetative growth, such as iron and zinc levels, dry biomass, plant height, leaf area and leaf count. Improvements in yield and the factors affecting yield were also noted	(78)
Okra	Foliar application of lithovit nanofertilizer (0.75 g/L)	Height, number of leaves, branches, leaf area, pod length and diameter, weight, pods per plant and total yield increased	(79)
Okra	100 % Nano Urea @ 1.23 l ha^{-1}+ 100 % Nano DAP @ 1.23 l ha^{-1} + K RD @ 83.3 kg ha^{-1}	Enhanced the physico-chemical properties of the soil, growth and yield parameters	(80)
Cucumber	Liquid nano NPK applied foliarly (6 and 9 mL/ plant)	Increased the weight of the plants, total yield and vegetative metrics such as plant height, number of leaves per plant, leaf area and plant weight; also increased the qualitative parameters such as TSS, chlorophyll content and fruit hardness	(81)
Pumpkin	The foliar treatment of 2.5 g/1000 mL of nano potassium nanofertilizer	Increased the fresh and dry weight of roots, as well as the stem diameter, plant height, number of branches and leaves per plant	(82)
Cabbage	Nano iron & Nano NPK	Enlarge the height and circumference of the head	(83)
Vegetable cowpea	0.2 % Nano DAP seed treatment and two foliar sprays and 3 % Zn EDTA	Improved growth and yield parameters	(84)
Vegetable cowpea	75 % RDN + two foliar spray of 2 mL/L nano DAP and nano Zn at flowering and pod initiation	Enhanced growth and yield parameters	(85)
Onion	Chitosan application with 15 % nano nitrogen	Increased growth and yield attributes	(86)

Advantages of nanofertilizers

Improved NUE

Nanofertilizers reduce nutrient loss through leaching and volatilization, ensuring more nutrients reach the plant (19).

Environmental benefits

Reduced runoff minimizes the risks of water pollution and eutrophication (20). Nanofertilizers play a crucial role in mitigating eutrophication by reducing the loss of nitrogen and phosphorus nutrients into aquatic ecosystems, thereby decreasing the occurrence of algal blooms and the formation of hypoxic zones. Furthermore, the improved efficiency of nutrient uptake associated with nanofertilizers results in diminished emissions of nitrous oxide (N_2O), a significant greenhouse gas linked to traditional nitrogen fertilizers. Furthermore, certain nano-formulations, including those with bioactive coatings or metal oxides, enhance microbial activity within the rhizosphere and facilitate soil remediation by immobilizing or degrading toxic elements such as cadmium or lead. These characteristics collectively contribute to more sustainable agricultural practices by improving soil health and reducing environmental pollution (21).

Increased crop yields

Studies show significant yield improvement in cereals and horticultural crops, as reported by the Indian Farmers Fertilizer Cooperative (IFFCO) (22). Nanofertilizers offer higher NUE, which results in better vegetative growth and higher productivity in various crops. Around the world, countries such as India, China, Brazil and the USA are testing and adopting nanofertilizers (Fig. 2). As of 2023, IFFCO has reached over 11 million farmers across 20 states in India with nano urea. Field trials have shown yield increases of 8-15 %, while also reducing nitrogen use by up to 50 % (IFFCO) (22). Most used types of nanofertilizers include nano urea, nano zinc and nano DAP.

Precision agriculture

Targeted nutrient delivery systems optimize resource use (9).

Classification of nanofertilizers

Nanofertilizers can be classified into several categories based on their structure, nutrient delivery systems and release patterns (Fig. 3):

1. Based on composition

a. Organic nanofertilizers: Derived from natural organic materials such as plant extracts, compost, or biopolymers (e.g., chitosan and alginate). Example: Chitosan-based nano-NPK.

b. Inorganic nanofertilizers: Synthesized from mineral or synthetic materials. Examples: Nano-ZnO and nano-hydroxyapatite (nHAp).

c. Hybrid nanofertilizers: Combination of organic and inorganic components to improve stability and efficacy. Example: Nano-hydroxyapatite encapsulated in chitosan for enhanced phosphorus delivery.

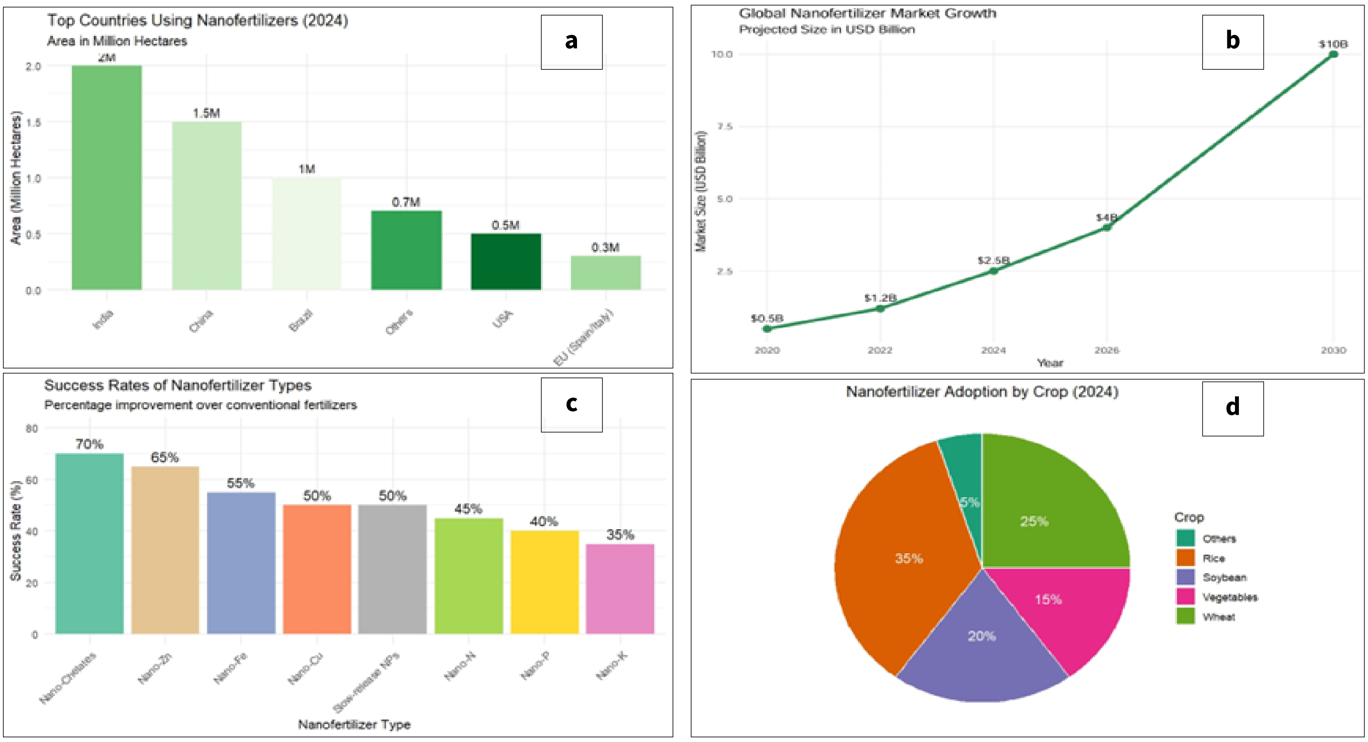

Fig. 2. (a) Top countries using nanofertilizers (2024), (b) Global nanofertilizer market growth, (c) Success rates of nanofertilizer types and (d) Nanofertilizer adoption by crop (2024).

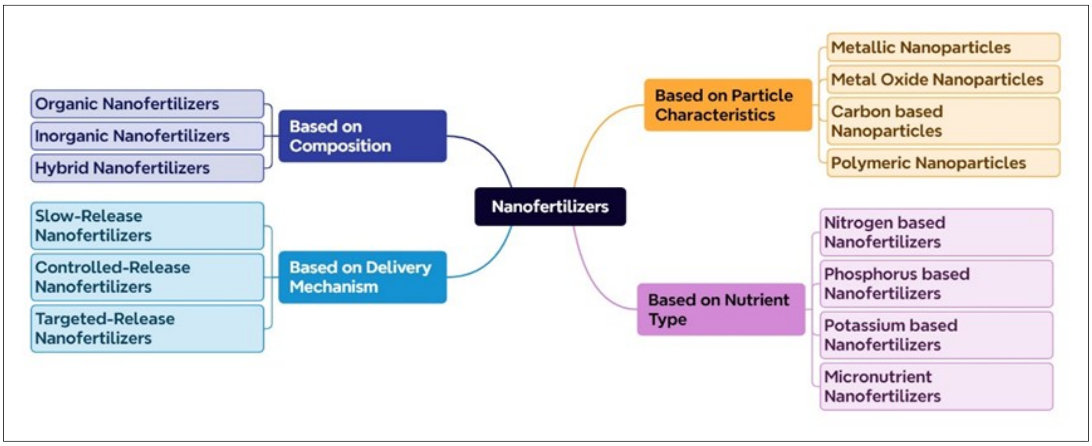

Fig. 3. Classification of nanofertilizers.

2. Based on delivery mechanism

a. Slow-release nanofertilizers: Gradually release nutrients over an extended period. Example: Urea-loaded nanoclay composites.

b. Controlled-release nanofertilizers: Release nutrients at a predetermined rate, often via a polymer coating or encapsulation. Example: Polymer-coated urea.

c. Targeted-release nanofertilizers: Release nutrients in response to specific environmental triggers (e.g., pH, moisture and root exudates). Examples: pH-sensitive nano-P fertilizers for acidic soils.

3. Based on particle characteristics

a. Metallic nanoparticles: Composed of metals with antimicrobial or catalytic properties. Examples: Nanosilver (Ag) and nanocopper (Cu).

b. Metal oxide nanoparticles: Widely used as micronutrient carriers. Examples: Zinc oxide (ZnO), iron oxide (Fe_2O_3) and titanium dioxide (TiO_2).

c. Carbon-based nanoparticles: It offers a high surface area and high adsorption capacity. Examples: Carbon nanotubes (CNTs) and fullerenes.

d. Polymeric Nanoparticles: Made from biodegradable polymers for encapsulation and sustained nutrient release. Examples: chitosan nanoparticles and PLGA-based systems.

4. Based on nutrient type

a. Nitrogen-based nanofertilizers - Example: Nanourea and nano-ammonium sulfate.

b. Phosphorus-based nanofertilizers - Example: Nano-hydroxyapatite.

c. Potassium-based nanofertilizers - Example: Potassium-loaded zeolite nanoparticles.

d. Micronutrient nanofertilizers (zinc, iron, manganese, etc.)

Application methods and uptake efficiency

The efficacy of nanofertilizers is contingent not only upon their formulation but also on the methods and timing of their application. Foliar application is frequently employed for rapid nutrient delivery and is most effective during the early vegetative stages, when leaf area and stomatal activity are optimal. Conversely, soil application is favored for slow- or controlled-release nanofertilizers, which gradually supply nutrients over time and facilitate root development. The frequency of application typically involves one to two foliar sprays, commonly scheduled at 20-25 days and 45-50 days after planting, contingent upon the specific crop and formulation. These strategies enhance nutrient uptake efficiency and mitigate losses through volatilization, runoff and leaching.

Nanofertilizers: Innovative solutions for sustainable agriculture and enhanced nutrient management

Nanofertilizers support sustainable agriculture by enhancing NUE and reducing environmental losses through controlled nutrient release. They minimize leaching, greenhouse gas emissions and nutrient runoff, protecting soil and water health. Additionally, lower application rates and improved plant uptake contribute to long-term soil fertility and resource conservation. Carbon nanotubes (CNTs) are a type of nanofertilizer known for their ability to interact with plant roots and stimulate growth by enhancing hormone production (23). These nanomaterials, made from rolled-up sheets of carbon atoms, improve soil fertility by increasing carbon and nutrient levels. Their unique properties allow them to efficiently absorb and release nutrients, improve soil structure, retain moisture and support overall plant development. While excessive fertilizer applications can have negative effects, low concentrations of CNTs have been shown to promote seed germination, root growth and water uptake without causing toxicity to plants.

Nanofertilizers are formulated with nanoparticles that regulate the release of nutrients into the soil, enabling farmers to achieve comparable crop yields with reduced fertilizer usage. Various strategies have been developed to design nanofertilizers that minimize nutrient loss and conserve water. One approach involves embedding the nanofertilizer in a porous matrix, allowing nutrients to be released gradually over time (24). Another technique includes altering the nanofertilizer's surface to enhance hydrophilicity, thereby improving its water retention capacity and reducing evaporation. Examples of nanofertilizers designed to control nutrient and water loss include urea coated with nanoparticles of elements such as iron oxide, sulfur, calcium, magnesium, zinc, copper, molybdenum, boron, ammonium sulfate and potassium (25). Additionally, nanobeads and nanoemulsions have emerged as effective solutions for mitigating nutrient and water loss in soil.

Role of nanofertilizers in different vegetable crops

The transformative potential of nano-nitrogen fertilizers (NFs) in enhancing nitrogen use efficiency (NUE) for sustainable agriculture (26). Key points include the development of slow-release and controlled-release NFs, which significantly reduce nutrient losses through leaching and gaseous emissions. These fertilizers improve plant growth, yield and environmental sustainability by minimizing nitrogen pollution. Potassium nanofertilizer applied at rates of 300 kg/ha and 400 kg/ha resulted in maximum tomato yield, increased number of fruits per plant, fruit weight and fruit size and plant height and tail size (27). In another investigation, the effect of engineered nanomaterials with added nitrogen, phosphorus and potassium on the growth and yield of French beans was examined (28). Fertigation with nano NPK fertilizer increased the potato cv. Arizona yields, high WUE and uniform nutrient distribution in the soil (29). Nutrient deficiency and excess can negatively affect potato growth and seedling quality. Micronutrient deficiencies, especially of zinc, iron, manganese and boron, are an important issue in semi-arid regions with climates such as the Mediterranean (30).

Nanofertilizers can effectively address this deficiency by delivering trace nutrients such as Zn, Fe, Mn and B in a gradual and controlled manner. Additionally, in a study on drumsticks (*Moringa oleifera*), treatment with nano-chelated iron, GA_3 and organic fertilizer Acadian at various concentrations showed promising results in enhancing plant growth and productivity. Lower concentrations of GA_3 in nanofertilizers positively influence the production of α-tocopherols, stigmasterols and campesterol (31). In a study, the effect of NPK nanofertilizer 20:20:20 at 4, 8 and 12 kg/ha, as well as commercial NPK mono-fertilizer at 34:56:56 kg/ha, administered as a soil amendment on dwarf long beans, resulting in increased chlorophyll content and a number of leaves across all treatments. The best results were observed with nanofertilizers at 8 kg/ha (32). Similarly, in another study, the impact of nanofertilizer NPK 20:20:20 at 4, 8 and 12 kg/ha, as well as mono-fertilizer NPK 34:56:56 kilograms per hectare, on dwarf long been revealed significant increases in growth parameters in treated plants across all treatments (33). Red beans treated with nitrogen biofertilizers exhibited increased yield and yield components, with K-chelate nanofertilizers showing the potential to substitute chemical fertilizers (34). Additionally, foliar organic nanoscale NPK fertilization in okra at 0.4 % concentration resulted in enhanced nutrient status in the post-harvest soil (35). Nano spray resulted in a higher okra yield (9.6 %) than NPK addition using chemical fertilizers (36).

Nanotechnology in the growth, yield and quality of vegetable crops

The influence of nanoparticles on the productivity and quality of vegetable crops is considerable, with their effects being contingent upon various factors such as the nanoparticle type, concentration, crop variety and agricultural methods employed. They offer various benefits, including enhanced nutrient uptake, improved water-use efficiency, better nutrient absorption, heightened stress tolerance, increased resistance to pests and diseases, improved soil health, controlled release of nutrients, extended shelf life, precision agriculture capabilities and enhanced photosynthesis. Moreover, nanoparticles can contribute to stress tolerance, pest and disease resistance and overall soil health improvement. Additionally, NPs can serve as carriers for biopesticides or antimicrobial agents, thereby preventing yield losses and preserving crop quality. Nevertheless, nanoparticle application in agriculture remains an area of ongoing research and development. Adherence to local regulations and guidelines is crucial to ensure both safety and sustainability in their use.

Notably, foliar application of chitosan nanoparticles at a concentration of 60 mg/L to snap beans significantly enhanced various growth parameters, including plant height, leaf and branch numbers and fresh and dry biomass (37). The observed effects can be attributed to the activation of various biological processes in plants, influenced by the chemical composition of chitosan and its application rate (38). Furthermore, there was a notable enhancement in the growth attributes of brinjal when treated with 1/4th the recommended dose of fertilizer (RDF) along with ZnO NP at 4500 mg/ha (39). This increase in yield and biomass, despite the reduced fertilizer dose, was likely due to the presence of ZnO NP. Nanoparticles have shown promise in improving the growth and yield characteristics of numerous crops (Table 2). Nano zinc oxide applied as a foliar spray at a concentration of 10 mg/L for six weeks significantly improved plant growth, biomass accumulation and nutrient content in *Cyamopsis tetragonoloba* (40). The use of nanoparticles positively affects the antioxidant system and improves germination in tomato and squash seeds (41). Applying nano-zinc fertilizer at a dosage of 40 mg/L significantly increased shoot and yield indicators and significantly changed the amount of Fe, K, P, N and Zn in the leaves (42).

Zinc oxide (ZnO) nanoparticles, used as nanofertilizers, have been shown to improve germination rates, sugar, protein and antioxidant activity levels in cabbage and tomato crops (43). Copper oxide and zinc sulphate in nanoparticle form exhibited greater effectiveness in tomato and eggplant yields than their bulk counterparts of copper oxide and zinc oxide (44). A 21 % increase in tomato fruit yield with 10 mg/L of selenium nanoparticle application (45). Additionally, the combined application of Cu-NPs and Se-NPs at concentrations of 10 mg/L and 20 mg/L, respectively, resulted in a 25 % increase in the tomato fruit's average weight relative to the control. When cowpeas (*Vigna unguiculata* L. Walp.) were treated with foliar Fe nanoparticles at 0.5 g/L, chlorophyll content increased by 10 % compared to conventional Fe forms (46). Applying silver nanoparticles (AgNPs) as a foliar spray at a concentration of 50 mg/L over 40 days enhanced the growth and biomass of *Vigna sinensis*. This improvement was attributed to increased root nodulation and enhanced soil bacterial diversity (47).

Cyamopsis tetragonoloba (L.) Taub. (cluster beans), applying 10 mg/L ZnO nanoparticles to the foliage increased phosphorus quantity, leaf protein content and chlorophyll levels (40). Foliar application of 60 mg/L chitosan nanoparticles to snap bean plants led to elevated levels of protein, vitamin C, zinc, iron, phosphorus, potassium and nitrogen in the pods (37). Furthermore, plants exposed to chitosan nanoparticles (Ch-NPs) at the same concentration exhibited the maximum chlorophyll content in their leaves. Red radish plants treated with 9.6 tons per hectare of chicken manure, along with green-synthesized zinc oxide nanoparticles (60 mg/L) and iron oxide nanoparticles (50 mg/L), showed enhanced levels of anthocyanins, phenols, tannins, flavonoids, crude protein and carbohydrates, as well as iron and zinc in their roots (48).

Liquid fertilizers, such as Ferbanat and Nanonat, enhanced plant growth and yield in cucumber cultivation. Application of Nanonat at a dosage of 4.0 L/ha produced the highest average fruit weight of 149.01 g and fruit length of 16.87 cm, while Ferbanat at a rate of 3.0 L/ha produced the largest fruit diameter of 37.15 mm. Nanonat at 3.0 L/ha also led to the highest total soluble solids (TSS) content of 4.11 %, whereas Ferbanat at 4.0 L/ha resulted in the highest dry matter content of 2.31 % and chlorophyll content of 44.90 % (49). Compared to non-nano iron forms, the use of nano iron had a greater impact on the grain output of faba beans. Combined use of nanofertilizers, nano-chelated zinc and boron and traditional NPK fertilizers significantly enhanced vegetative growth and accelerated vegetative development (50). However, traditional N-P-K fertilizer enhanced both plant growth and tuber yield while also significantly increasing the nitrate content in the tubers. Soil fertility, organic matter and cultivation techniques influence the amount of nitrate present in potato tubers (51).

Table 2. Impact of nanoparticles on various vegetable crops growth, productivity and quality

Crop	Nanoparticles used	Traits improved	References
Tomato	Application of carbon nanoparticles 10, 20 and 40 µg/L	Improved germination of tomato seeds, root and shoot biomass	(87)
Chilli	Seed invigoration using ZnO nanoparticles at a concentration of 1000 mg/kg	The application of zinc oxide nanoparticles increased the percentage of germination and improved the aged chilli seeds quality	(88)
Carrot	The foliar application of graphene oxide and ZnO nanoparticles at a concentration of 0.10 mg/mL enhanced the effectiveness of the treatment	The application resulted in increased plant growth, carotenoids, chlorophyll and proline contents, while also reducing nematode galling and multiplication	(89)
Cucumber	Exposed to diluted copper ferrite nanoparticles (5 ppm) in Hoagland Nutrient's solution (100 mL)	The treatment augmented the fresh weight, chlorophyll content, protein content and the levels of superoxide dismutase (SOD) and peroxidase (POD) in both shoots and roots. Additionally, it enhanced the uptake of iron and copper by both the roots and shoots	(90)
Pumpkin	Application of metal nanocolloids, such as NKAg and NKCu, foliarly (50 mL/L)	Increased total soluble solid (TSS), lipid peroxidation, protein content in leaves and superoxide dismutase (SOD) activity on the 29th day of the pumpkin seedlings' growth	(91)
Bitter gourd	Application of carbon nanoparticles 1.5-5.0 nm; 0.943-47.2 nM	Treatments with fullerol enhanced lycopene, biomass, yield and chemicals with anticancer and antidiabetic properties	(92)
Onion	Zinc nanoparticles soil application (0.5, 1.5 and 3 mg/L)	Increased plant height, number of leaves, number of heads and reduced the incidence of fungus *Phythium aphanidermatum*	(93)
Spinach	CuO mixed with soils 200 mg/kg for 60 days	Enhanced photosynthetic efficiency leads to increased biomass production	(94)

Impact of nano fertilizers on fresh-cut vegetable quality

Nano fertilizers improve the bioavailability of essential nutrients, leading to higher concentrations of vitamins, minerals and antioxidants in fresh-cut vegetables. For example, zinc oxide nanoparticles have been shown to increase the zinc content in leafy greens, enhancing their nutritional profile. In spinach (*Spinacia oleracea*), nano calcium carbonate treatments significantly enhanced the pectin content, which contributes to improved firmness and cell wall integrity during cold storage (52). ZnO NP in combination with ultrasound treatment significantly improved the fresh-cut lettuce stored for 8 days. Key enhancements include the color (L* value (34.53); a* value (-5.89); b* value (15.00), chlorophyll (2.75 mg/100 g), firmness (25.66), browning index (40.63), total phenolic content (0.95 mg/100 g), PAL activity (54.91 $U\cdot h^{-1}\cdot g^{-1}$), catalase activity (41.78 $U\cdot min^{-1}mg^{-1}$); ABTS free-radical scavenging ability (137.62 µmol/L), polyphenol oxidase activity (0.85 $U\cdot min^{-1}\cdot g^{-1}$) and MDA (1.97 µmol/g) (53). Nano fertilizers containing antioxidants or enzymes like catalase can inhibit enzymatic browning, a common issue in fresh-cut produce. Nano fertilizers reduce postharvest losses by delaying senescence and microbial spoilage. For instance, silver nanoparticles have antimicrobial properties that can inhibit the growth of pathogens on fresh-cut vegetables, extending their shelf life. The antimicrobial properties of certain nano fertilizers, such as those containing copper or silver nanoparticles, help control microbial load on fresh-cut vegetables, ensuring food safety.

Mechanisms of action

Nanoparticles release nutrients gradually, ensuring sustained availability to plants. The small size and high surface area of nanoparticles facilitate efficient absorption by plant roots and leaves. Nano fertilizers reduce oxidative stress by scavenging free radicals, thereby preserving the quality of fresh-cut vegetables. Certain nanoparticles inhibit the growth of spoilage microorganisms, enhancing the safety and shelf life of produce. Despite their potential, the use of nano fertilizers in agriculture faces several challenges: The safety of nanoparticles for human health and the environment is still under investigation. The production of nano fertilizers is currently expensive, limiting their widespread adoption. Excessive use of nano fertilizers may lead to nanoparticle accumulation in plants and soil, posing ecological risks. There is a need for standardized protocols for the application and dosage of nano fertilizers.

Nanotechnology in post-harvest handling (nano-based edible coatings)

Vegetables are highly valued by consumers and are essential for a healthy diet. However, after harvest, plants undergo a variety of biological processes that vary depending on the type of vegetable, such as respiration and ethylene synthesis. Vegetables are living goods; therefore, even after harvesting, they continue to respire and transpire. The rates at which these activities occur frequently are a good indicator of how long they will remain in storage; higher rates correspond to shorter shelf lives. Along the entire distribution chain, packaging plays a crucial role in preserving the quality and extending the longevity of food products. They help shield food from toxins, microbes and chemicals that can harm it, especially when it is being transported or stored. Food packaging materials must be safe, lightweight, affordable, reusable and resistant to environmental and physical stressors, among other requirements. Coatings are a popular post-harvest method for agricultural products, providing answers to the problems posed by crop storage (Fig. 4). Many polymeric materials offer safe packaging options. However, biopolymer-based packaging is becoming increasingly popular because it is affordable, environmentally friendly and biodegradable (54). The application of nanotechnology (NT) as a means of enhancing food preservation and extending shelf life has grown in popularity. Nanocomposites, which show encouraging properties and the incorporation of nanomaterials into polymeric packaging materials, have the potential to enhance the quality and properties of food packaging (55).

Low-density polyethylene was embedded with Ag-NPs between SiO_2 and TiO_2 to create nanocomposite films to pack carrots. The physicochemical characteristics of the carrots were preserved by these films, which also showed strong antibacterial activity, making them appropriate for post-

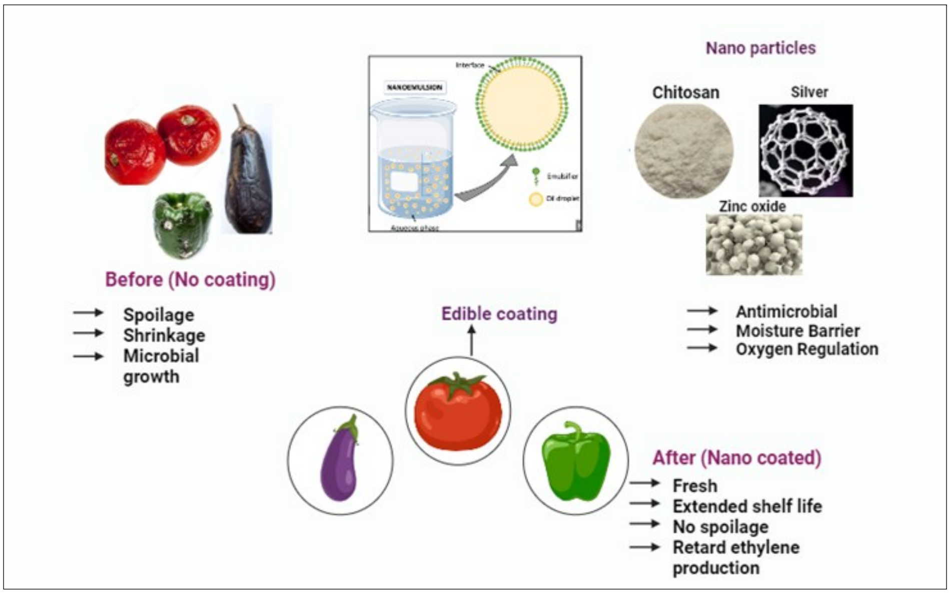

Fig. 4. Nano-based edible coating on vegetables.

harvest quality preservation (56). Chitosan polyvinyl alcohol hydrogel-derived nanocomposites with varying levels of copper nanoparticles (0.1-10 mg/g) for application on jalapeno pepper crops (57). Their research showed improvements in the post-harvest characteristics of pepper fruits, as well as the growth parameters of jalapeno pepper crops. Incorporation of copper nanoparticles results in lignification of the pericarp cell wall, which contributes to greater fruit firmness in tomatoes (58). The increased process of the PAL enzyme, which is important for the structure of lignin, caused this effect. The shelf life of fruit can be increased by increasing its hardness (59). The combination of selenium nanoparticles (10 mg/L) and copper nanoparticles (50 mg/L) increases tomato fruit firmness by around 48 % (45). Numerous researchers have reported the significant effects of various nanocoatings on vegetable crops, which are summarized in Table 3.

Problems with conventional coating

- Non-degradable.
- Water loss.
- Poor stability.
- Presence of spores.

Smart nanofertilizers for efficient water and nutrient utilization

Nanofertilizers can significantly improve NUE by reducing losses due to leaching, volatilization and runoff. This efficiency directly impacts water use by ensuring that fewer resources are wasted. Studies indicate that crops treated with nanofertilizers exhibit better growth and yield with reduced irrigation frequency (60). Nanofertilizers incorporated into hydrogel matrices improve soil water retention by enhancing moisture-holding capacity. These hydrogels act as water reservoirs, gradually releasing nutrients and water to plants, especially under drought stress conditions (61). Nanofertilizers fortified with potassium and silicon enhance drought tolerance in crops by improving root water uptake, osmotic regulation and stomatal function. Nano-silicon is particularly effective in reducing water loss through transpiration by strengthening leaf cuticles in cucumber (62). Nanotechnology enables precision agriculture through the site-specific delivery of nutrients, which optimizes water use. Nano-enabled smart fertilizers ensure efficient resource utilization, reducing the need for over-irrigation and mitigating waterlogging risks (63). The study demonstrates that combining foliar-applied mixed nanofertilizer (MNFf) with soil-applied commercial fertilizer (CFs) significantly improves tomato growth, NUE and productivity. The [MNFf + CFs] treatment notably enhances the nutritional content of tomatoes, including protein, fiber and essential minerals, while also boosting antioxidant properties. This approach offers a sustainable alternative to reduce the overuse of conventional fertilizers in agriculture (64). The effectiveness of nano nitrogen (nN) under varying water regimes, combining bulk nitrogen (bN) with nano nitrogen via drip and foliar application for lettuce cultivation was evaluated. Results indicate that the combination of 75 % nN via drip irrigation and 25 % nN via foliar application significantly improves growth parameters, nitrogen uptake and nutrient efficiency while minimizing fertilizer use. This approach presents a promising strategy for sustainable agriculture by reducing nitrogen fertilizer application and mitigating environmental pollution (65).

Limitations of nano-fertilizers

Fertilizers that can be applied to soil that enable control over the rate, timing and duration of nutrient release and active absorption by plant roots are generally referred to as smart fertilizers (66). “Any single or composed nanomaterial, multicomponent and/or bioformulation containing one or more nutrients that can adapt timing of the release of nutrients to the plant’s nutrient demand through physical, chemical and/or biological processes, thereby improving crop production and growth and reducing environmental impact when compared with conventional fertilizers” is what constitutes a smart fertilizer. Smart fertilizers fall into three categories: (i) bioformulations, (ii) composite fertilizers and (iii) nano-fertilizers (67). Nanoparticle-based fertilizers, known as nano-fertilizers, come in both powdered and liquid forms, encompassing their production, engineering and usage. These innovative fertilizers can enhance the dynamics of nutrient release and improve plants’ ability to absorb nutrients efficiently. The benefits of using nano-fertilizers include higher crop yields, reduced nutrient waste in the

Table 3. Effect of nano edible coating on different vegetable crops

Crop	Nanoedible coating used	Effect	References
Tomato	Fruits coated with 1.5 % gum Arabic nano formulation	Enhanced the TSS content and decreased the physiological weight loss	(95)
Cherry tomato	Chitosan/Mentha × villosa Huds. essential oils or *Mentha piperita* L.	Inhibits the growth of mycelial organisms and spore germination. Storage does not affect the sensory or physicochemical characteristics	(96)
Green bell peppers	Gum Arabic in aqueous solution of 10 %, silver nanoparticles and silver nanoparticles - gum Arabic solution blend, coatings	Appearance of fruits was improved and peppers showed a lower percentage of microbial decay and were still marketable after 21 days of storage	(97)
Cucumber	Chitosan nanoparticles coating	Both the antioxidant activity and the storage duration were increased	(98)
Fresh-cut melon	Alginate coating and silver nanoparticles used in combination	Preserved the melon's quality, extending its shelf life to almost 11 days	(99)
Carrot	Nano zinc oxide	Nano zinc oxide greatly extends the shelf life by minimizing microbial deterioration during storage	(100)
Green asparagus	Sanitize with sodium hypochlorite (100mg/L) for 15 min, coated with silver nanoparticles for 3 min at room temperature	Increases in ascorbic acid and crude fibers content, stiffness of asparagus spears were all favorably connected with the coating, which also considerably decreased weight loss, crude fiber content and color changes	(52)

environment and improvements in both the nutritional content and storage longevity of produce (67). Blended fertilizers consist of multiple ingredients containing one or more nutrients, designed to leverage material interactions and enhance crucial plant nourishment (67). Fertilizers are typically coated or mixed using a variety of materials, chosen based on their specific properties. These include organic and inorganic coating substances, such as granules and materials with hydrophobic or hydrophilic characteristics (in matrix or gel form), as well as inorganic compounds that have low solubility (68). Globally, the agricultural industry has recognized the critical importance of precise fertilizer application. Though field trials show yield gains of 10-25 %, the expensive expense of nanoformulation and regulatory uncertainty have hindered their widespread use. Nanoparticle buildup in soil is a potential danger, as are the long-term impacts on soil microbiota. This focus stems from the dual needs of enhancing crop yields and minimizing the detrimental effects of excessive fertilization on agricultural ecosystems (67).

While the use of NFs can enhance traditional agricultural practices, certain scientific communities express concerns about their potential negative effects. Overuse of NFs in agricultural systems may lead to severe and lasting environmental problems that cannot be easily reversed (69). However, the substantial effects of ENMs as stress reliever agents depend on numerous parameters, such as the quality of the material (size of particles, morphology/structure, charge and coating), concentration level, diversity of plants and duration/time of application. Careful evaluation of dose administration and the construction of an effective and focused delivery strategy are essential before utilization (69).

Research has shown that exposure to NPs can have negative effects on a variety of organisms, such as fish, birds and insects (70). Although NFs have contributed significantly to sustainable crop production, their availability for marketing as one of the sources of plant nutrients must also be guaranteed. The Green revolution increased food grain production worldwide but at the expense of disproportionate use of synthetic fertilizers, which has seriously damaged the agroecosystem. Nevertheless, green synthesized NFs, bio-synthesized NFs, or nano-biofertilizers should be studied (71). Additional soil and field-based studies are needed to show the effectiveness and, crucially, the reproducibility of ENMs' effects under atmospheric agricultural conditions. Ultimately, economic viability, societal acceptance and regulatory compliance must be considered to realize the goal of commercialization of NFs for large-scale application.

Conclusion

Nanofertilizers represent a transformative approach to sustainable agriculture, offering innovative solutions to enhance crop productivity while addressing the challenges of global food security and environmental sustainability. Their unique properties, such as controlled nutrient release, targeted delivery and reduced resource wastage, position them as a vital tool in meeting the growing food demands of a population projected to exceed 9 billion by 2050. By optimizing nanomaterial composition, release mechanisms and production methods, nanofertilizers have the potential to revolutionize crop nutrition, particularly in developing regions where food security remains a critical concern. The development of advanced nanomaterials and nanoparticles as nutrient carriers has opened new avenues for boosting crop growth and yield. However, the efficacy of these NPs depends on factors such as plant type, application method, size, shape and concentration. Establishing optimal dosages and tailoring nanofertilizers to specific plant requirements will be key to maximizing their benefits. Furthermore, the integration of greener nanomaterials and NPs into crop nutrition strategies can mitigate nanotoxicological risks, paving the way for environmentally friendly agricultural practices. As research continues to refine nanofertilizer technologies, their scalability and affordability will determine their widespread adoption. By overcoming current challenges, nanofertilizers can become an accessible and sustainable solution for farmers worldwide, ensuring food security while minimizing environmental impacts. In the face of climate change and resource scarcity, nanofertilizers stand at the forefront of agricultural innovation, heralding a new era of precision and sustainability in crop nutrition.

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Authors' contributions

Writing original draft and resources collection were done by SR. Conceptualization, supervision, validation and resources were contributed by IRC. The visualization process was carried out by SBK, AG, JP, DM, SKS and SM. All authors read and approved the final manuscript.

Compliance with ethical standards

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