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REVIEW ARTICLE

Nano-chelates and their role in boosting the productivity of cereals and vegetable crops

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Abstract

Nano-chelates are considered as a potential application that can increase cereals and vegetable production. The nano-chelates applied via foliar and soil methods, including iron, zinc and potassium. Overall, which determined that the application of nano-chelate fertilisers contributed to significant increases in plant growth parameters (e.g., plant height, leaf area, chlorophyll, yield) when applied to the cereals like wheat, rice as well as the vegetables like lettuce, cucumber and pepper. Nano-chelates helps in increase the nutrient uptake effectiveness and also it helps in improved concentrations of necessary micronutrients in the tissues of the studied plants were associated with improved physiological functions including rates of photosynthesis and increased activities of antioxidant enzymes. In cereals, nano-chelates contributed to higher grain yield and protein content that contributes to resistance against abiotic stresses including drought and heavy metals. In vegetables, the use of nano-chelated fertilisers benefitted vegetative growth biomass and accumulation of nutrients required by the plants, but they also assisted with increased plant defences against both biotic and abiotic stresses that can negatively affect plant health and productivity. Their nanoscale size ensures targeted delivery and rapid assimilation within chloroplasts, improving photosynthetic performance. Such mechanisms explain the observed rise in chlorophyll levels and overall metabolic efficiency in crops. Additionally, nano-chelates aid in food safety and health by helping to reduce the accumulation of toxic elements such as arsenic and cadmium in plant edible tissues. These collective findings support the notion that nano-chelates could be sustainable methods to increase crop yield and nutritional quality.

Keywords: enzyme activation; iron; micronutrients; nano-chelates; sustainable; zinc

Introduction

Nano-chelates are micronutrients bound to ligands and hybridized/functionalized at the nanoscale by design; they are more bioavailable, more mobile, and enhance uptake in plants. In agriculture, nano-chelates will provide a new class of agro-inputs characterised as nano-fertiliser and designed to enhance nutrient use efficiency with minimise losses and enhance plant performance. There are a number of nano-fertilisers, but those that can be described as nano-chelates will involve essential micronutrients (e.g., iron (Fe), zinc (Zn), manganese (Mn), copper (Cu), etc. bound with organic or inorganic ligand and formulated at the nanoscale (1). Essentially, this new approach will deliver the benefits of traditional chelation (i.e., prevention of nutrient loss and fixation within the soil) with the benefits of nanoparticles (i.e., increased surface area, a high level of reactivity and functionalised for better interactions with plants) (2).

Nano-chelates is low bioavailability material due to soil interactions and plants may not be able to uptake micronutrients, especially in alkaline or calcareous soils where elements such as iron and zinc may precipitate or be fixed. Chelating agents allow nutrients to remain in a soluble and plant-available form, but the bioavailability and uptake efficiency of nutrients are at least partly enhanced when nutrient-chelates are delivered at the nanoscale. This can more easily pass through plate layers or stomatal openings and absorbed faster as small particles (3). Nano-chelates combine short and long term controlled-release behaviour, which allows nutrients to be delivered at a controlled rate and time, ideally with less frequent applications for reduced labour costs. The slow yet controlled delivery of nutrients ideally coincides during the growth phases of plants and it improving physiological functions of enzyme activation, chlorophyll development and overall optimised root and shoot development (4). The effective delivery using nano-chelates results mitigating the potential effects of toxicity or leaching and eco-friendly and cost effective.

The function of nano-chelates is more significant when the agricultural sector continues to determine options to achieve climate-resilient and resource conserving farming. A potentially nutrient delivery system embodies sustainable resource management, include nano-chelated nutrients, that helps in managing inputs for net goods return while also maintaining stewardship for the environment (5). The advantages of nano-chelated nutrients can improve photosynthesis, antioxidant enzyme activity and tolerance to abiotic stresses such as drought and salinity and its benefits for crop quality, such as grain protein content in cereals and nutrient density in vegetables, may provide a positive influence in plant growth and vegetables (6).

The nano-chelates can be used in foliar spray or as a soil amendment. The application of nano-chelated iron or zinc in cereals may enhance plant vigour, flowering and grain formation (7). In vegetable crops, nano-chelates have shown to improve root growth, nutrient content and fruit quality (8). This review paper focus on the efficacy of nano-chelates in the clinical long-term impacts on soil ecology, establishing standard doses, regulation and the challenge of balancing high crop productivity with sustainable practices in global agriculture. It is possible that some solutions may come from the advancements in the science of agriculture and that nano-chelates will be a primary factor in these advancements, specifically in the area of nutrient management.

Properties of nano-chelates

Surface area and surface energy

The physiological process of nano-chelates in plant was presented in Fig 1. Nano-chelates possess a very high surface area-to-volume ratio, enhancing their reactivity and interaction with plant roots and leaves. The increased surface energy improves nutrient solubility and facilitates faster absorption and translocation within plant tissues (8, 9).

Quantum mechanical effects

At the nanoscale, quantum effects alter the electronic and optical properties of micronutrients, improving redox potential and enabling controlled nutrient release. This leads to enhanced metabolic activity and better stress tolerance in plants (10, 11).

Geometry and atomic exposure

The unique geometry and high atomic exposure of nano-chelates allow more active sites for plant interaction. This structural advantage promotes efficient chelation, minimizing nutrient loss and improving bioavailability (12, 13).

Structural influence on catalytic properties

The structural configuration of nano-chelates enhances their catalytic behaviour in enzymatic and metabolic reactions. They stimulate key physiological processes like chlorophyll formation, photosynthesis and antioxidant defence, leading to improved plant growth and productivity (14, 15).

Impact of nano-based fertilisers on growth and physiology of cereals and vegetables

Effects of nano-based fertilisers on growth and physiological traits in cereals like rice, maize, wheat and vegetable crops like potato, lettuce, okra has presented in Table 1.

Plant height and shoot growth

Nano-chelated micronutrients have consistently increased plant height across vegetable and cereal crops. In tomato, foliar-applied nano-iron significantly improved shoot biomass and plant height compared to conventional treatments (16, 17). Lettuce treated with ZnO (zinc oxide) nanoparticles (18–140 nm at 200 ppm) showed enhanced shoot biomass and height without phytotoxicity (18). The ZnO nanoparticles (50–100 mg/L) improved height in brinjal (19) and tomato (20), while salt-stressed tomato treated with ZnO nanoparticles (75–150 mg/L) exhibited a 354 % increase in height (21). In cereals, nano-chelated micronutrients at 20 ppm significantly increased shoot length (22), with similar effects seen in rice and maize with 4_3 (Iron ferric oxide) and ZnO nanoparticles and in sweet corn with nano-Zn (23).

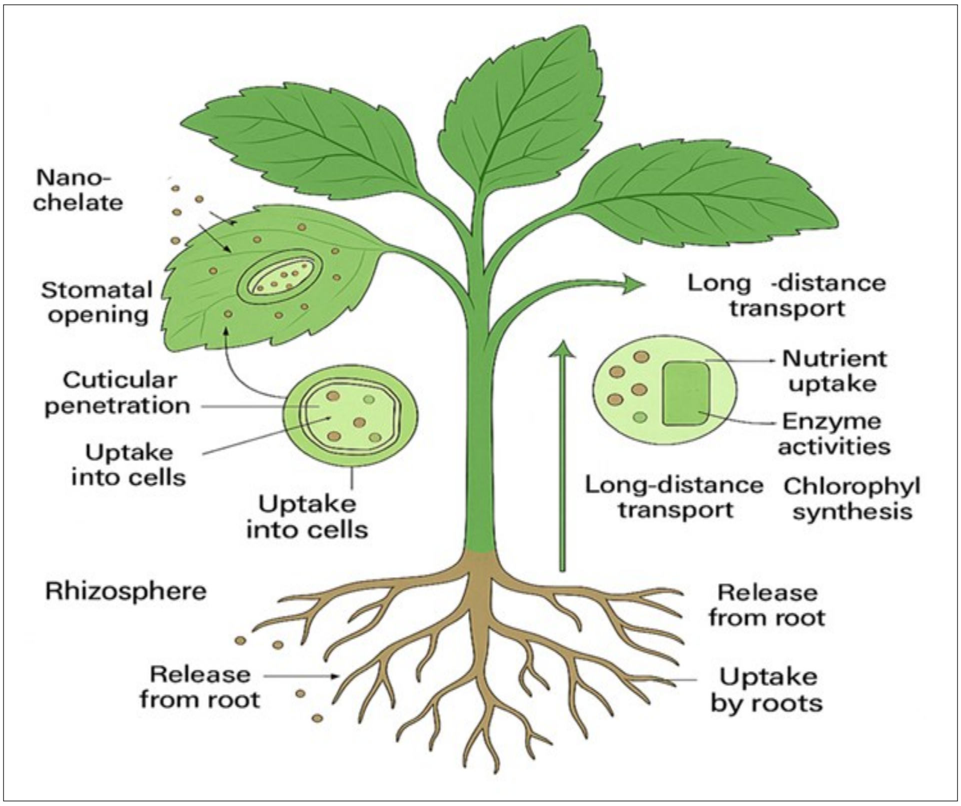

Fig. 1. Plant physiological responses to nano-chelated nutrient application.

Stem diameter and internodal growth

Nano NPK formulations (4 mL/L) combined with zinc (Zn) and iron (Fe) (1 g/4 L) improved stem diameter and internodal length in okra (24). Maize stem diameter increased with nano-chelated zinc and sweet corn with nano-Zn (25).

Leaf development and canopy traits

Lettuce and cowpea treated with nano-chelated micronutrients showed a significant increase in leaf number (29). Nano-chelated iron improved leaf length in lettuce under cadmium stress and nano-chelated zinc enhanced leaf length in maize. Nano-Zn fertilisers increased leaf area in snap beans, lettuce and tomato (27). Similar enhancements occurred in drought-stressed wheat treated with copper and zinc nanoparticles (28).

Fresh and dry biomass gains were observed in lettuce treated with ZnO and Fe nanoparticles under chromium stress, with increases of 58–76 % in shoots and 45–70 % in roots (29). Nano-NPK plus micronutrients improved foliage number and branching in okra (30).

Root development

Iron(III) oxide (Fe_2O_3) and ZnO nanoparticles promoted root elongation and biomass in rice and maize. In mung bean, kinetin-capped ZnO nanoparticles enhanced root length and root activity under drought stress (31). Sweet corn treated with nano-Zn also showed improved root length.

Photosynthetic pigments and gas exchange

Nano-chelated micronutrients increased chlorophyll a, chlorophyll b and total chlorophyll in vegetables and cereals. Lettuce under cadmium stress treated with nano-chelated iron recorded higher chlorophyll content (32). Zinc oxide nanoparticles improved chlorophyll concentration in maize and nano-Fe_3O_4 enhanced chlorophyll levels in *Vigna radiata* by up to 28 % (33) because nano-chelated micronutrients enhance chlorophyll synthesis by improving nutrient uptake and photosynthetic efficiency in vegetables and cereals. Their application, such as nano-Fe and ZnO nanoparticles, significantly increases chlorophyll content even under stress conditions, promoting better plant growth. Similar effects were seen with nano-Zn in sweet corn and in snap beans with nano-Zn fertiliser (33).

Photosynthetic rate and stomatal conductance

Sodium-alginate–encapsulated Fe_2O_3 nanoparticles with soil yeast inoculum improved photosynthetic rate, stomatal conductance and chlorophyll content in lettuce. Nano-Fe_3O_4 (magnite) also improved photosynthetic efficiency, stomatal conductance and transpiration in *V. radiata* (34). The ZnO nanoparticles enhanced gas exchange in maize grown in cadmium-contaminated soils.

Biochemical properties

Protein content

Across cereal and vegetable crops, multiple studies have demonstrated that nano-chelated fertilisers significantly enhance protein content, though the magnitude and location of these effects vary by crop type and application method. In cereals, foliar nano-ZnO applied at flowering increased soluble protein content by 5–13 % over controls and was linked to improved carbohydrate metabolism and grain quality (35), while nano-chelated iron in paddy boosted grain protein by 13 % compared to synthetic fertilisers, alongside higher macronutrient levels of N, P and K. Similarly, zinc chitosan nanoparticles in durum wheat produced grain protein levels comparable to conventional zinc sulfate ($ZnSO_4$) despite using ten times less zinc, also achieving a 36 % increase in grain zinc content. Foliar ZnO application in rice further enhanced leaf and grain nitrogen content by 10.7–24.7 % from heading to maturity and ZnO seed priming in wheat elevated protein by 59 % in leaves and 63 % in root. In vegetables, comparable improvements were noted, with nano-chelated iron increasing protein levels in lettuce under stress (36) and intercropping cowpea and maize treated with iron and zinc nano-chelates raising cowpea seed protein by 28.6 % over controls (37). Bio-nano-fertilisers of ZnO and Fe_2O_3 combined with PGPR and microalgae improved soluble protein in tomato and broccoli seedlings more effectively than uncoated nanoparticles, while foliar ZnO and Fe_3O_4 nanoparticles enhanced leaf and seed protein in cucumber (36). In chickpea, nano-chelated zinc and iron significantly increased seed protein fractions compared to mineral and conventional chelated forms (37). Overall, while cereals generally exhibited protein enhancements concentrated in grains contributing directly to grain quality and nutritional enrichment vegetables tended to show increases in leaves and seeds, improving physiological performance, stress resilience and biomass accumulation.

Table 1. Effects of nano-based fertilisers on growth and physiological traits in cereals and vegetable crops

Traits	Crops	Nano treatment	Effects/outcomes	References
Germination and seedling vigour	Rice, maize, mung bean, okra	Nano-fertilisers, Cu/Ni/Co oxide + vermicompost	↑ Germination %, ↑ vigour index, ↑ okra germination (~167 %), vigour (95 %)	(14, 16)
Plant height and shoot growth	Tomato, lettuce, brinjal, cereal crops	Nano-Fe, ZnO nanoparticles (18 –150 mg/L)	↑ Plant height (up to 354 % in salt-stressed tomato), ↑ shoot biomass	(17, 18)
Stem diameter and internodal growth	Okra, maize, sweet corn	Nano-NPK + Zn, Fe, nano-Zn	↑ Stem diameter, ↑ internode length	(19, 20)
Leaf development	Lettuce, cowpea, maize, snap beans	Nano-chelated Fe, Zn, Cu; ZnO nanoparticles	↑ Leaf number, length, area	(21, 22)
Canopy biomass	Lettuce, okra	ZnO, Fe nano-particles; nano-NPK + micronutrients	↑ Fresh/dry shoot and root biomass, ↑ foliage number and branching	(23, 24)
Root development	Rice, maize, mung bean, sweet corn	Fe_2O_3, ZnO nanoparticles; kinetin-capped ZnO	↑ Root length and biomass	(25, 26)
Chlorophyll content	Vegetables, cereals, *V. radiata*	Nano-chelated Fe, Zn, Fe_3O_4, ZnO nanoparticles	↑ Chlorophyll a, b, total chlorophyll	(27, 28)
Photosynthetic rate and gas exchange	Lettuce, *V. radiata*, maize	Fe_2O_3 nanoparticles (encapsulated), nano-Fe_3O_4, ZnO	↑ Photosynthetic rate, stomatal conductance, transpiration	(11, 22, 29)

Amino acid composition

In terms of amino acid composition, nano-chelated fertilisers also showed marked effects across cereal crops, with the nature of changes depending on nanoparticle type and concentration. In wheat, Fe_2O_3 nanoparticles (50–500 mg/kg) improved cysteine and tyrosine levels in the grain, whereas copper(II) oxide (CuO) treatments altered the profile by increasing some amino acids while decreasing others; notably, titanium-di-oxide (TiO_2) nanoparticles consistently enhanced overall amino acid content while modifying protein composition toward improved nutritional balance (38). In another wheat study, the application of 25 ppm Cu and Fe nanoparticles increased the abundance of proteins involved in glycolysis and the tricarboxylic acid cycle, coupled with higher sugar levels and superoxide dismutase (SOD) activity, indicating strengthened carbohydrate metabolism and stress mitigation (39). For vegetables, Fe_3O_4-coated nanoparticles applied to cucumber grown in acidic nutrient solutions improved chlorophyll content and catalase activity while enhancing antioxidant enzyme levels and iron assimilation, which indirectly supports amino acid synthesis (40). Sodium-alginate–encapsulated Fe_2O_3 nano-chelates used in lettuce enhanced photosynthetic rate, stomatal conductance and chlorophyll content, all physiological factors that can promote amino acid production. Across both cereals and vegetables, these studies indicate that while cereals experienced more direct shifts in grain amino acid profiles and energy metabolism–related proteins, vegetables tended to benefit from physiological and enzymatic changes that support amino acid biosynthesis and overall protein quality under varied environmental conditions.

Carbohydrate metabolism

In cereals, nano-ZnO application in rice improved amylose content and overall carbohydrate metabolism while Cu and Fe nanoparticle treatments in wheat increased sugar levels and enzymes central to carbohydrate breakdown and energy production (41). In vegetables, nano-chelated iron increased soluble sugar content in lettuce and bio-nano-fertiliser applications in tomato and broccoli enhanced biomass production through improved carbohydrate metabolism (42). The key difference lies in the fact that cereals exhibited carbohydrate changes mainly in grains, influencing starch quality, whereas vegetables showed changes primarily in leaves, contributing to growth and biomass.

Antioxidant enzyme activity and stress response

In cereals, Cu and Fe nanoparticle applications in wheat increased SOD activity, supporting stress mitigation (43), while ZnO nanoparticle seed priming elevated proline levels and enhanced osmotic adjustment under stress. In vegetables, Fe_3O_4-coated nanoparticles in cucumber enhanced catalase and other antioxidant enzymes, while combined ZnO and Fe_3O_4 nanoparticle applications improved antioxidant activity in cucumber leaves (44). Nano-chelated zinc and iron also increased antioxidant enzyme activity in chickpea. Overall, cereals tended to exhibit antioxidant enhancement linked to osmo protection and metabolic enzymes, whereas vegetables showed stronger associations with detoxification enzymes and photosynthetic stability.

Nutrient assimilation and mineral biofortification

Cereal studies reported increased nutrient uptake, with rice and wheat showing higher N, P and K concentrations, greater leaf and grain nitrogen content and improved zinc biofortification. Vegetable crops such as lettuce exhibited increased mineral nutrient concentrations throughout the plant, whereas chickpea showed improved mineral biofortification (45). In cereals, micronutrient enhancement was mainly confined to the edible grains, while in vegetables, nutrient enrichment occurred across the whole plant, contributing to improved growth and physiological performance.

Impact of nano-based fertilisers yield parameters

Effects of nano-based fertilisers on yield attributes like grain weight, total yield, total straw production in cereals and vegetable crops has presented in Table 2.

Grain weight

In cereals, nano-ZnO seed priming and foliar application increased 1000-kernel weight substantially. For example, maize treated with 800 ppm nano-ZnO recorded a kernel weight of 30.8 g (27), while similar treatments yielded 29.66 g per 100 grains. Wheat under low-dose 12 kg/ha ZnO nanoparticles exhibited a 78.7 % increase in 1000 -grain weight (47). However, when NPK was partially replaced with nano-chelated micronutrients, wheat grain yield improved but 1000-kernel weight decreased by 3.7–13.1 %. In vegetables, nano-Zn foliar spray in snap bean increased 1000-seed weight compared to controls, while kinetin-capped ZnO nanoparticles in mung bean also enhanced 1000-seed weight under drought stress.

Grain/seed yield

Maize showed a higher grain yield gains with nano-ZnO, achieving 8.75 t/ha and 71.29 qt/ha. In wheat, yields increased by 106.1 % to 5320 kg/ha under low-dose ZnO nanoparticles. In rice, nano-Zn with green manuring enhanced grain yield beyond conventional treatments and maize under saline stress treated with nano-Zn and nano-Si showed yield increases of up to 106 %. Vegetables also saw strong responses, such as increased seed yield in amaranth with biosynthesized Zn nanoparticles, cucumber with ZnO and Fe_3O_4 nanoparticles, green bean with nano-ZnO foliar sprays (47) and mung bean with kinetin-capped ZnO nanoparticles.

Straw/biomass yield

Stover yields in maize reached 11.14 t/ha with nano-ZnO seed priming combined with foliar application and wheat straw yield increased by 88.5 % to 9719 kg/ha under low-dose ZnO nanoparticles. On the other hand, higher straw yields in Basmati rice where recorded in the application of nano-Zn and green manuring. In vegetables, nano-Zn foliar spray in snap bean improved biological yield, Zn and Fe nanoparticles in beans increased biomass yield and sweet corn recorded fodder yields of 20.4 t/ha under foliar Zn (48).

Harvest index and biological yield

Nano-Zn with green manuring improved harvest index in rice compared to conventional treatments. Partial replacement of NPK with nano-chelated micronutrients in wheat maintained high yields despite lower chemical inputs. In vegetables, nano-chelated Fe in tomato improved harvest index compared to chelated Fe, while bell pepper yield gains from nano-Zn and Fe were mainly due to increased fruit count and weight (49).

Yield component traits

Nano-ZnO increased kernel rows per cob and cob weight in maize, with foliar application outperforming controls by 42 % and $ZnSO_4$ by 15 %. In vegetables, nano-chelated micronutrients improved pod number and fruit size in multiple species (50). Sweet corn cob yield reached 15.5 t/ha under foliar Zn application.

Table 2. Effects of nano-based fertilisers on yield attributes in cereals and vegetable crops

Parameter	Crops	Nano treatment	Effects	References
Protein content	Rice, wheat, durum wheat, lettuce, cowpea, tomato, broccoli, cucumber, chickpea	Nano-ZnO, nano-Fe, Zn chitosan nanoparticles, bio-nano-fertilisers	Increased protein levels	(37, 41)
Amino acid composition	Wheat, cucumber	Fe_2O_3, CuO, TiO_2, Fe_3O_4 nano-particles	Improved amino acid profiles	(38, 41)
Carbohydrate metabolism	Rice, wheat, lettuce, tomato, broccoli	Nano-ZnO, Cu, Fe nano-particles	Enhanced sugars and starch	(19, 31)
Antioxidant enzymes	Wheat, cucumber	Cu, Fe, Zn, Fe_3O_4 nanoparticles	Increased antioxidant activity	(33, 37)
Nutrient assimilation	Rice, wheat, lettuce, chickpea	Nano-Zn, nano-chelated Fe, Zn	Better nutrient uptake	(29, 44)
Grain/seed yield	Maize, wheat, rice, amaranth, cucumber, mung bean	Nano-ZnO, nano-Si, biosynthesized Zn nanoparticles	Increased yield	(31, 46)
Biomass yield	Maize, wheat, rice, snap bean, sweet corn	Nano-ZnO, nano-Fe	Higher biomass production	(21, 32)
Harvest index and yield traits	Rice, wheat, tomato, bell pepper	Nano-Zn, nano-chelates	Improved harvest index and yield	(26, 45)

Economic benefits of nano-chelates in crops

The economic benefits of nano-chelates in various vegetable and cereal crops were presented in Table 3.

Yield improvement and profitability

In cereal crops, nano-fertilisers such as nano-ZnO, nano-N, nano-P and nano-chelated micronutrients have shown substantial yield benefits. Application of nano-phosphorus resulted in a 17–44 % increase in wheat yield under semi-arid conditions, along with more than a 50 % enhancement in phosphorus use efficiency. Foliar applications of nano-N, nano-Zn and nano-Cu in transplanted rice produced the highest net return of ₹64711/ha and a benefit-cost ratio (BCR) of 2.17 when combined with 50 % N (51). Higher wheat yield could be maintained using only 75 % of conventional NPK when supplemented with nano-N and nano-P, leading to reduced costs and greater profitability. In vegetables, similar benefits were observed. The applications of nano-chelated iron improved marketable yield of tomato and increasing BCR through reduced fertiliser use. On the other hand, the nano-Zn foliar sprays on beans enhanced pod weight and number, boosting farmers' net income. The okra yields improved with nano-fertilisers, making them more profitable than conventional fertilisation practices (52).

Fertiliser cost reduction and nutrient use efficiency

In cereal crops, nano-fertilisers have demonstrated the potential to lower input costs by enhancing nutrient uptake efficiency. Improved nutrient recovery and reduced leaching losses have resulted in higher economic returns compared with conventional fertilisers. Studies have reported more than a 30 % increase in nutrient use efficiency in rice and wheat, achieved with fewer applications and lower fertiliser doses without compromising yield, thereby improving return on investment. In maize, grain yield increases of around 30 % have been recorded alongside a reduction in fertiliser requirements.

In vegetable crops, ZnO nanoparticles applied in hydroponic lettuce systems enhanced nutrient uptake and photosynthetic activity, enabling a reduction in fertiliser inputs. Additionally, foliar application of ZnO nanoparticles in lettuce increased biomass production and antioxidant content, leading to extended shelf life and improved market value without increasing fertiliser use (53).

Added market value through quality enhancement

Quality improvements contribute directly to higher market prices. In cereals nano-Zn with green manuring in Basmati rice improved both grain yield and zinc biofortification, enhancing marketability. Whereas, the integrated nano-Zn and conventional Zn in wheat increased grain weight and yield while maintaining quality, optimizing inputs and profitability. In vegetables, improved lettuce shelf life and nutritional content with increased marketable value with nano applied fertiliser. The encapsulated Fe_2O_3 nanoparticles with yeast inoculants boosted lettuce biomass and quality, increasing profitability.

Stress tolerance and risk reduction

Nano-chelates provide economic benefits by reducing crop loss under stress conditions. In cereals, ZnO NP seed priming in fodder maize improved biomass and quality, ensuring better returns even under variable conditions. In vegetables, the ZnO nanoparticles enhanced drought tolerance in brinjal, improving productivity under stress. Combining biogenic Cu/Ni/Co oxide nanoparticles with vermicompost in okra boosted seed germination (167 %), vigour index (95 %) and seedling growth, minimizing nursery losses and ensuring better transplant success.

Integrated and sustainable approaches

Combining nano-fertilisers with sustainable practices amplifies benefits. The partial replacement of NPK with nano-chelated micronutrients in wheat maintained yields while lowering input costs and improving BCR. The nano-Zn with green manuring not only improved rice yield but also delivered nutritional benefits. In vegetables, integrating poultry manure with nano-fertilisers in cucumber under greenhouse conditions reduced chemical fertiliser dependency, cut cost per unit yield and increased profitability in protected cultivation systems.

Negative impacts of nano-chelates in agriculture

Nano-chelates improve nutrient efficiency, their overuse or uncontrolled application can cause several adverse effects. Excess accumulation of nanoparticles in soil may alter microbial diversity and enzyme activity, disrupting soil health and nutrient cycling. High concentrations can induce oxidative stress in plants, leading to cell membrane damage, chlorosis and reduced growth. Some metallic nanoparticles such as ZnO and Fe_3O_4, may persist in the environment, causing long-term toxicity and potential entry into the food chain. Additionally, their interactions with soil colloids and organic matter can influence nutrient bioavailability and ecosystem balance, raising concerns about sustainability and biosafety (53).

Table 3. Effects of nano-chelates on economic benefits in cereals and vegetable crops

Parameter	Crops	Nano treatment	Benefits	References
Yield and profitability	Wheat, rice, maize, tomato, beans, okra	Nano-ZnO, nano-N, nano-P, foliar sprays	Significant yield enhancement and improved economic returns	(24)
Cost reduction and efficiency	Rice, wheat, maize, lettuce	Nano-fertilisers, ZnO NPs, reduced NPK	Enhanced nutrient use efficiency and reduced input costs	(31)
Quality enhancement	Basmati rice, wheat, lettuce	Nano-Zn, Fe_2O_3 NPs	Improved crop quality and nutritional biofortification	(39)
Stress tolerance	Maize, brinjal, okra	ZnO NPs, biogenic oxide NPs	Increased stress resilience and seedling vigour	(45)
Sustainable practices	Wheat, rice, cucumber	Nano-chelates manure	Sustained productivity with optimized input use	(51)

Discussion

The application of nano-chelated fertilisers in contemporary agriculture offers an innovative way to tackle issues of low nutrient use efficiency, crop productivity and environmental sustainability. This review has provided strong evidence that demonstrates the extensive benefits of using nano-chelates for a wide array of cereal and vegetable crops. Due to their nanoscale size and greater surface area, nano-chelated micronutrients, such as zinc, iron, copper and manganese are able to significantly increase nutrient uptake, root and shoot growth, chlorophyll content and enzymatic activities which all help to spurt crop growth (54). Conversely, yield parameters such as grain weight, number of pods and stover production/ have shown significant improvements under nano-chelate treatments when compared to traditional fertilisers. Additionally, nano-chelates exhibit improvements to biochemical responses in terms of edible plant portions like increased protein, carbohydrate and antioxidant levels which are important factors for crop quality and human nutritional requirements (55). These gains were evident even under stress-based conditions such as drought and heavy metal contamination, whereby nano-chelates supported the plants physiological ability to cope with stress.

Conclusion

Nano-chelated fertilisers have the potential to reduce overall fertiliser requirements while maintaining or even enhancing crop yields, thereby improving the benefit–cost ratio from an economic standpoint. When crop performance equals or surpasses that of untreated controls, nano-chelated fertilisers can be considered both agronomically effective and economically viable for smallholder as well as commercial farming systems. Overall, nano-chelates represent a promising advancement in sustainable agriculture by helping to balance productivity with environmental stewardship. However, further long-term field evaluations and the development of appropriate regulatory frameworks are essential to better understand their interactions with soil ecosystems and to optimize their use across different agro-climatic conditions.

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Authors' contributions

TSP conducted the literature survey and contributed to drafting the sections on the effects of nano-chelates on the growth and yield of cereals and vegetables. RS contributed to the section comparing regular fertilisers and nano-chelates. TSP also supported the drafting and editing of the manuscript. JLP, SR and ASR participated in structuring the manuscript and reviewing critical references. RSP conceived the review topic, guided the overall structure and scientific direction, and coordinated the writing process. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interest to declare.

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