



Effect of zinc oxide (ZnO) nanoparticles on morphological traits, yield and uptake in tomato (*Solanum lycopersicum*) and bell pepper (*Capsicum annuum*)

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Received: 22 September 2024; Accepted: 27 November 2025

ABSTRACT

Zinc, an essential micronutrient, is extensively studied for its potential application as a nano-fertiliser in agriculture. Zinc oxide (ZnO) nanoparticles are known to boost root contact and nutrient mobilisation in the rhizosphere by releasing bioavailable Zn²⁺ ions, improving nutrient uptake and overall plant vigour. The present study was carried out for two consecutive years during rainy (*khari*) season of 2020–22 at Dr Yashwant Singh Parmar University of Horticulture and Forestry, Nauni, Solan, Himachal Pradesh to investigate the optimum concentration of zinc as nano-fertiliser by examining its effect on morphological characteristics, yield and nutrient uptake in tomato (*Solanum lycopersicum* L.) and bell pepper (*Capsicum annuum* L.). The pot experiments comprised of seven treatments set up in a completely randomised design (CRD) with three replications for both crops. Treatment combinations consisted of three concentrations of ZnO nanoparticles i.e. 50, 100, and 150 mg/L; which was applied as seed treatment [T₂ (50 mg/L), T₄ (100 mg/L) and T₆ (150 mg/L)] and foliar application [T₃ (50 mg/L), T₅ (100 mg/L) and T₇ (150 mg/L)] with T₁ taken as control. Recommended dose of nutrients was applied, through integration of vermicompost and chemical fertilisers. ZnO nanoparticles @50 mg/L through foliar spray significantly enhanced various growth attributes as compared to control, viz. plant height (28% and 65%), root length (67% and 71%), number of primary branches, plant biomass, fruit yield (approx. 2–3 fold increase) and nutrient uptake in tomato and bell pepper, respectively. Whereas, seed treatment @50 mg/L significantly increased nutrient content in plants. Overall, the results concluded that application of ZnO nanoparticles @50 mg/L emerged as a promising nano-fertiliser strategy for enhancing morphological traits, yield and uptake in tomato and bell pepper.

Keywords: Chemical fertilisers, Growth, Uptake, Vermicompost, Yield, ZnO

Tomato (*Solanum lycopersicum* L.) and bell pepper (*Capsicum annuum* L.) are widely grown as commercial crops by large number of small and marginal farmers in mountainous regions of north-western Himalayas, particularly in Himachal Pradesh (Kalia *et al.* 2021). These crops are grown in both open fields and protected conditions, have longer harvest duration, gave higher off-season productivity, adapted to wider climate and soil suitability. The protected cultivation technique is well established and proved to raise the economic standard of farmers in this region.

Zinc oxide (ZnO) nanoparticles are known to improve agronomic conditions by addressing micronutrient deficiencies, fertiliser inefficiency, and soil deterioration. Their high surface reactivity and controlled release

characteristics significantly enhance Zn bioavailability, thereby mitigating the limitations associated with the poor uptake of conventional zinc fertilisers. Studies conducted by Bhardwaj *et al.* (2024) also showed that through better nutrient usage, ZnO nanoparticles successfully enhances performance in tomato and bell pepper. The application of urea with ZnO nanoparticles improves nitrogen utilisation (Amin *et al.* 2023). Also, foliar application of ZnO nanoparticles in rice improved yield, grain zinc content, and nitrogen metabolism (Wang *et al.* 2023). Slow-release nano-fertilisers can minimise amount of fertiliser usage besides reducing environmental pollution (Sadak and Bakry 2020). The use of nano-fertilisers represents an advanced approach to plant nutrition, delivering nutrients in a precise and controlled manner due to their nanoscale properties, improve nutrient-use efficiency and uptake, while reducing losses to the environment and minimising the negative impacts associated with conventional fertilisers (Aparanjitha *et al.* 2023).

Studies also revealed that ZnO nanoparticles at low concentration promote beneficial soil microorganisms, which

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aid in nutrient cycling and soil health (Strekalovskaya *et al.* 2024). Whereas, high ZnO nanoparticles concentrations not only impair plant growth or quality, but they disturb soil stability, which may have negative environmental effects (Zhang *et al.* 2024a). Furthermore, the growing release of ZnO nanoparticles into the environment poses a serious issue since it may lead to increased phytotoxic effects (Samuditha *et al.* 2024). The potential toxicity of ZnO nanoparticles on plants can be reduced while limiting adverse effects by employing strategies such as dose optimisation, controlled release systems, nanoparticle surface modifications, and combination with other treatments (Verma *et al.* 2024).

ZnO nanoparticles, commonly used in agriculture, have the potential to enhance the agricultural productivity (Zhou *et al.* 2023). Despite results from various research studies revealed that ZnO nanoparticles enhanced physiological and growth parameters of Solanaceae crops, there are currently not enough investigations that particularly describes about their ideal concentration and effective application method. The main goal of this study was to analyse the diverse roles played by ZnO nanoparticles in crop growth and development. The present study aimed to check the efficacy of ZnO nanoparticles by utilising pot experiment trials under protected conditions and to investigate the optimum concentration, method of application and effectiveness of ZnO nanoparticles on morphological traits, yield, nutrient accumulation and uptake in tomato and bell pepper.

MATERIALS AND METHODS

Experimental site: The present study was carried out during rainy (*kharif*) season of 2020–22 at Dr Yashwant Singh Parmar University of Horticulture and Forestry, Nauni, Solan (30°52' N, 77°11' E; with an elevation of 1175 m amsl), Himachal Pradesh. The pot experiment comprised of seven treatments and three replications set up in a completely randomised design (CRD) conducted in protected conditions. The experimental area falls under sub-temperate, sub-humid, agro-climatic zone-II of Himachal Pradesh. During the experiment, day/night temperatures were maintained at 22–30°C and 18–24°C, respectively with relative humidity at 55–75%, monitored daily using a digital thermometer and hygrometer.

Layout and experimental design: Potting mixture was prepared by mixing farm yard manure, sand and unsterilised soil in the ratio of 1:1:2 on volume basis. The potting mixture was analysed for various properties and nutrient contents before the execution of experiment. The potting mixture was neutral in reaction, normal EC value and available NPK was medium in range. All treatments adhered to the recommended practices for managing fertilisers, controlling weed and plant protection. Recommended dose of nutrients (RDN) as per package of practices of vegetable crops for the cultivation of tomato and bell pepper in mid-hill conditions are Nitrogen: 100 kg/ha, Phosphorus: 75 kg/ha and Potassium: 55 kg/ha (Anonymous 2014).

In this study, recommended nutrients (Nitrogen: 0.45 g/pot; Phosphorus: 0.33 g/pot and Potassium: 0.24 g/pot)

were supplied to all treatments by using integration of vermicompost and chemical fertilisers (Urea, Single super phosphate and Muriate of potash); and their quantity was computed in 50:50 ratio on nitrogen equivalence basis. On the basis of 10 kg of potting mixture in each pot, quantity of nutrient sources was calculated and doubled which further mixed in pots before transplantation of seedlings. One month old healthy seedlings of tomato variety 'Solan Lalima' and bell pepper variety 'California Wonder' were selected for experiment with 4–5 leaves at the time of transplanting.

ZnO nano-powder (Sigma-Aldrich, Saint Louis, MO 63103, USA) with particle size <50 nm (Brunauer-Emmett-Teller) and purity >97% was used in study. Nano-powder was first dispersed in ethanol to reduce aggregation and then mixed with distilled water to prepare the aqueous suspension. Despite these steps, some agglomeration may still occur due to the inherent tendency of ZnO nanoparticles to cluster. Three concentrations of ZnO nanoparticles were taken for this experiment i.e. 50, 100 and 150 mg/L which were applied to plants by 2 ways i.e. through seed treatment and foliar application. The treatments were T₁, Control (No application of ZnO nanoparticles); T₂, Seed treatment of ZnO nanoparticles @50 mg/L; T₃, Foliar application of ZnO nanoparticles @50 mg/L; T₄, Seed treatment of ZnO nanoparticles @100 mg/L; T₅, Foliar application of ZnO nanoparticles @100 mg/L; T₆, Seed treatment of ZnO nanoparticles @150 mg/L; and T₇, Foliar application of ZnO nanoparticles @150 mg/L. In seed treatment, seeds were dipped for overnight in respective concentration of ZnO nanoparticles; and in treatments comprising foliar applications, three sprays with respective concentration of ZnO nanoparticles were applied at the intervals of 15 days after transplanting in both crops. Foliar application of ZnO nanoparticles was done by using knapsack sprayer with a hollow-cone nozzle (150–250 µm droplet size). Approximately 25 mL of solution was applied per plant to uniformly wet the foliage without runoff, with spraying conducted in the early morning (07:00–09:00 AM). Recommended doses of nutrients were applied to all treatments through integration of chemical fertilisers and vermicompost.

Observations: All of the plant growth attributes were recorded after third picking of both crops. Digestion of the samples was carried out by method laid down by Piper (1966) for P, K, Zn, Cu, Fe and Mn. The total nitrogen was analysed by Micro-Kjeldahl's method (AOAC 1980), total phosphorus was estimated by Vanado-molybdate phosphoric yellow colour method (Jackson 1973). Total potassium was estimated in flame photometer (Jackson 1967). The estimation of Zn, Cu, Fe and Mn was carried out on Atomic Absorption Spectrophotometer (Vogel 1978). Nutrient uptake by plant was calculated using the following formula:

$$\text{Nutrient uptake (g/plant)} = \frac{\text{Nutrient content (\%)} \times \text{Dry matter yield (g/plant)}}{100}$$

Statistical analysis: The data generated from two-year

pot experiments of both crops were appropriately computed, tabulated and analysed by applying completely randomised design (CRD) (Panse and Sukhatme 2000) and analysis of variance (ANOVA) was used to determine significance at $p \leq 0.05$ using Microsoft Excel and OPSTAT packages (Sheron *et al.* 1998). The least significant difference (LSD) was determined among the factors at $p \leq 0.05$. The significant difference between mean value of treatments were separated using Duncan's Multiple Range Test (DMRT) at 5% level did significance. Alphabetic letters signify statistical difference between the mean. Means followed by the same letter do not differ significantly from one another and if the mean value had different letters, they were significantly different ($p \leq 0.05$).

RESULTS AND DISCUSSION

Growth analysis: The growth parameters of plants were recorded significantly maximum in treatment comprising foliar application of ZnO nanoparticles @50 mg/L. The highest value of plant height (216.33 and 72.00 cm), root length (28.17 and 14.85 cm), number of primary branches (6.67 and 5.67), plant biomass (172.67 and 87.00 g/plant) and fruit yield (1.61 and 1.48 kg/plant), respectively for tomato and bell pepper was recorded under treatment T₃ (Table 1). These results were supported by the findings of Faizan *et al.* (2021) who concluded that exogenously applied ZnO nanoparticles have showed positive impact on tomato plants by enhancing growth and yield characteristics, thus advantageous for progressive growth and development. ZnO nanoparticles at optimum dosages lead to increase in plant growth by influencing at the physiological, biochemical, and molecular levels (Lv *et al.* 2022). Foliar-applied ZnO nanoparticles improve plant growth and yield through a variety of metabolic processes by enhancing photosynthesis, antioxidant defense, and metabolic efficiency by increasing the activity of zinc-dependent enzymes such as carbonic anhydrase and superoxide dismutase (Chen *et al.* 2024). Additionally, ZnO nanoparticles promote balanced growth and effective grain or fruit filling by improving the transfer of nutrients and carbohydrates from source leaves to sink tissues (Zhang *et al.* 2021). They also affect hormone metabolism, especially auxin biosynthesis, which promotes branching, internode elongation, root growth, and successful reproduction that affects biomass accumulation, reproductive development, and crop output, making ZnO nanoparticles a powerful tool for targeted nutrients delivery.

On the other hand, all assessed growth characteristics were significantly reduced when 150 mg/L of ZnO nanoparticles were applied. The inhibitory effects of high nanoparticle concentrations on important zinc-dependent enzymatic activities might be responsible for this reduction which include impaired photosynthesis, disrupted carbohydrate metabolism, oxidative stress accumulation, and general metabolic imbalance, all of which reduced vegetative growth and biomass accumulation (Rajput *et al.* 2021). Similar results were also noted by Akanbi-Gada *et al.* (2019) that decreased root uptake with increasing ZnO

nanoparticles concentrations was due to the production of oxidative stress, which further markedly inhibited the activity of stress-regulating enzymes in the roots. Likewise, application of high dose of ZnO nanoparticles might also led to the aggregation of nanoparticles that settle out of solution due to gravity and increasing the size of nanoparticles, reducing their mobility in the soil.

ZnO nanoparticles can positively affect plant development at optimum dosage and have the potential to replace traditional zinc fertilisers. ZnO nanoparticles have received increased attention due to their long-term solubility (Pullagurala *et al.* 2018) which impacts plant nutrient availability by providing a consistent supply of Zn²⁺ ions, altering soil chemical interactions, and influencing nutrient uptake through competitive or inhibitory pathways. Controlled dissolution improves plant nutrition and growth, but excessive ion release can cause nutritional imbalances and toxicity. In addition, integration of organic manures (vermicompost) and chemical fertilisers offer sustained soil fertility, progressive nutrient release and may also increase the activity of beneficial microbes. Their use reduces the negative effects of agricultural activities on the environment while promoting healthy plant development, which leads to increased yields (Hui *et al.* 2023). It was also concluded by Brar *et al.* (2025) that the combined application of organic manure, chemical fertilisers and nanoparticles improved plant growth characteristics in cabbage.

Several studies also revealed the concentration dependent effectiveness of ZnO nanoparticles on various agricultural crops. Application of ZnO nanoparticles at concentrations between 75 and 150 mg/L under salt stress in tomato lead to significant increase in plant growth parameters (Ahmed *et al.* 2024). Furthermore, it was noted that ZnO nanoparticles can be extremely beneficial even at low concentrations of 2.6 mg/L that improve plant health and yield, and other parameters such as increased oil content and head diameter in sunflower (Kolencik *et al.* 2020). In present study, rise in photosynthetic pigment contents by the application of ZnO nanoparticles, might be responsible for the increment in morphological traits and yield of both solanaceous crops. Our results were also supported by findings of Ahmed *et al.* (2023), who noted the maximum values of growth, physiological, yield, and quality characteristics in tomato when ZnO nanoparticles were applied through foliar application.

Nutrient accumulation and uptake: The sequence of data in Table 2 reflects significant statistical improvement in N (3.61 and 3.46%), P (0.75 and 1.62%) and K (4.62 and 11.48%) content in tomato and bell pepper in treatment comprised of 50 mg/L ZnO nanoparticles as seed treatment (T₂) over control. The significant increase in the total Fe (257.08 ppm) and Zn (26.17 ppm) contents was recorded under treatment T₃ and T₂, respectively. However, the total Mn content was recorded maximum in treatment T₆ and total Cu content remained non-significant under the influence of ZnO nanoparticles application in tomato. The maximum value of total Fe content (442.67 ppm) and Cu

Table 1 Effect of ZnO nanoparticles on morphological traits and fruit yield in tomato and bell pepper

Treatments	Plant height (cm)		Root length (cm)		Number of primary branches		Plant biomass (g/plant)		Fruit yield (kg/plant)	
	Tomato	Bell pepper	Tomato	Bell pepper	Tomato	Bell pepper	Tomato	Bell pepper	Tomato	Bell pepper
T ₁	168.83 ± 1.17g	43.67 ± 1.17g	16.87 ± 0.24f	8.67 ± 0.14g	2.00 ± 0.29d	3.67 ± 0.44a	81.33 ± 0.17g	56.83 ± 0.60g	0.49 ± 0.01f	0.32 ± 0.03f
T ₂	194.83 ± 0.88d	57.50 ± 0.50d	19.97 ± 0.24d	11.85 ± 0.20d	3.17 ± 0.17c	4.17 ± 1.20a	138.33 ± 1.83d	74.67 ± 0.73d	1.01 ± 0.03d	0.81 ± 0.08cd
T ₃	216.33 ± 0.88a	72.00 ± 0.50a	28.17 ± 0.24a	14.85 ± 0.20a	6.67 ± 0.17a	5.67 ± 0.17a	172.67 ± 1.17a	87.00 ± 0.58a	1.61 ± 0.07a	1.48 ± 0.10a
T ₄	187.83 ± 0.88e	54.00 ± 0.50e	18.80 ± 0.32e	10.95 ± 0.29e	3.17 ± 0.33c	3.50 ± 0.58a	121.33 ± 1.17e	71.67 ± 0.60e	0.91 ± 0.03d	0.68 ± 0.08de
T ₅	209.33 ± 0.88b	67.50 ± 0.50b	26.00 ± 0.32b	13.87 ± 0.25b	4.83 ± 0.17b	4.00 ± 0.50a	160.33 ± 1.17b	82.83 ± 1.30b	1.40 ± 0.03b	1.24 ± 0.10b
T ₆	179.83 ± 0.88f	50.00 ± 0.50f	18.10 ± 0.32e	9.92 ± 0.26f	1.50 ± 0.29d	4.00 ± 0.29a	94.33 ± 1.17f	63.67 ± 0.44f	0.74 ± 0.04e	0.56 ± 0.01e
T ₇	202.83 ± 0.88c	62.17 ± 0.73c	21.90 ± 0.32c	12.87 ± 0.22c	3.83 ± 0.17c	3.50 ± 0.50a	149.33 ± 1.17c	80.17 ± 0.60c	1.17 ± 0.03c	1.01 ± 0.06c
Mean	194.26	58.12	21.40	11.85	3.60	4.07	131.10	73.83	1.05	0.87
LSD ($p \leq 0.05$)	2.84	2.05	0.89	0.70	0.72	NS	3.70	2.27	0.12	0.22
SEM±	0.93	0.67	0.29	0.23	0.24	0.61	1.21	0.74	0.04	0.07

Treatment details are given under Materials and Methods.

content (42.17 ppm) was recorded in T₃ and Zn (84.00 ppm) content in T₂ under bell pepper. Whereas, total Mn content remained non-significant by the application of ZnO nanoparticles (Table 3).

The highest NPK and Zn contents in tomato and bell pepper were recorded in treatment comprising 50 mg/L ZnO nanoparticles as seed treatment (T₂). The maximum total Fe content was recorded under treatment comprising 50 mg/L ZnO nanoparticles as foliar spray. The increase in macronutrient contents could be attributed to increased microbial biomass or activity near growing roots supplemented by organic matter, which was further enhanced by seed treatment of ZnO nano-particles. Similarly, studies conducted by Zhang *et al.* (2024b), also reported that apart from their direct physiological effects on plants,

nanoparticles frequently cause significant changes in the soil's physicochemical environment, such as changes in pH, redox potential, nutrient speciation, and ion exchange capacity, as well as pronounced restructuring of rhizosphere microbial communities. These changes can affect microbial diversity, functional guild composition, enzymatic activity, and biogeochemical cycling processes, which collectively shape nutrient availability and plant-soil interaction. Tondey *et al.* (2021) also concluded in their studies that application of ZnO nanoparticles by seed treatment resulted in a greater total potassium content in maize plants. Liang *et al.* (2021) similarly affirmed that there was an increase in Fe absorption by foliar application of ZnO quantum dots ranging from 50–200 mg/L in lettuce plants. Seed treatment (T₂) increased Zn content, reflecting a strong seed-priming effect. This

Table 2 Effect of ZnO nanoparticles on macronutrient content in tomato and bell pepper

Treatments	Total N (%)		Total P (%)		Total K (%)	
	Tomato	Bell pepper	Tomato	Bell pepper	Tomato	Bell pepper
T ₁	2.85 ± 0.01d	2.46 ± 0.04f	0.63 ± 0.00e	0.84 ± 0.09c	3.53 ± 0.06e	9.48 ± 0.07c
T ₂	3.61 ± 0.01a	3.46 ± 0.04a	0.75 ± 0.00a	1.62 ± 0.08a	4.62 ± 0.05a	11.48 ± 0.07a
T ₃	3.39 ± 0.01b	3.28 ± 0.05b	0.69 ± 0.02b	1.27 ± 0.09b	4.42 ± 0.06b	10.74 ± 0.08b
T ₄	3.11 ± 0.16c	2.62 ± 0.04e	0.65 ± 0.01de	0.92 ± 0.05c	3.79 ± 0.04d	9.68 ± 0.07c
T ₅	3.19 ± 0.01c	2.92 ± 0.04d	0.65 ± 0.00cd	1.02 ± 0.09c	4.10 ± 0.02c	9.67 ± 0.10c
T ₆	3.27 ± 0.01bc	3.06 ± 0.04c	0.68 ± 0.00b	0.97 ± 0.09c	4.48 ± 0.05ab	10.38 ± 0.07b
T ₇	3.24 ± 0.01bc	2.99 ± 0.04cd	0.67 ± 0.00bc	0.97 ± 0.07c	4.44 ± 0.04b	9.53 ± 0.49c
Mean	3.23	2.97	0.67	1.08	4.20	10.13
LSD ($p \leq 0.05$)	0.19	0.12	0.02	0.24	0.14	0.61
SEM±	0.06	0.04	0.01	0.08	0.05	0.20

Treatment details are given under Materials and Methods.

Table 3 Effect of ZnO nanoparticles on micronutrient content in tomato and bell pepper

Treatments	Total Fe (ppm)		Total Mn (ppm)		Total Cu (ppm)		Total Zn (ppm)	
	Tomato	Bell pepper	Tomato	Bell pepper	Tomato	Bell pepper	Tomato	Bell pepper
T ₁	227.25 ± 0.63c	215.33 ± 1.20f	106.33 ± 1.59c	206.17 ± 3.90a	26.67 ± 1.20a	31.50 ± 0.87c	14.83 ± 0.60e	53.00 ± 0.29e
T ₂	247.42 ± 0.98b	424.50 ± 3.06b	126.67 ± 2.40ab	234.17 ± 0.73a	31.00 ± 1.26a	36.33 ± 0.83bc	26.17 ± 0.17a	84.00 ± 1.61a
T ₃	257.08 ± 0.87a	442.67 ± 0.17a	123.67 ± 7.82b	198.00 ± 6.76a	29.50 ± 1.26a	42.17 ± 1.30a	23.00 ± 0.50b	78.00 ± 1.04b
T ₄	246.92 ± 0.36b	323.67 ± 1.42d	121.33 ± 8.29bc	200.00 ± 30.31a	30.00 ± 1.89a	38.00 ± 3.01ab	16.00 ± 0.50e	60.50 ± 0.76d
T ₅	256.25 ± 1.01a	380.67 ± 5.05c	127.67 ± 4.23ab	215.33 ± 4.91a	31.17 ± 2.74a	38.83 ± 1.17ab	19.00 ± 0.29d	69.50 ± 1.04c
T ₆	236.42 ± 0.74d	268.50 ± 3.12e	140.50 ± 3.33a	212.33 ± 4.19a	30.17 ± 1.86a	37.17 ± 1.92abc	22.17 ± 0.44b	72.17 ± 0.93c
T ₇	242.75 ± 0.63c	268.00 ± 2.75e	127.50 ± 3.75ab	209.17 ± 4.42a	31.67 ± 1.17a	37.50 ± 2.75ab	20.50 ± 0.29c	71.17 ± 0.83c
Mean	244.87	331.90	124.81	210.74	30.02	37.36	20.24	69.76
LSD ($p \leq 0.05$)	2.23	8.64	15.59	NS	NS	5.77	1.30	3.06
SEM±	0.78	2.82	5.09	12.2	1.71	1.89	0.42	0.99

Treatment details are given under Materials and Methods.

likely stems from enhanced metabolic and transport activities that improve Zn mobilisation, root uptake, and translocation. Such responses aligned with nanoparticle-based priming, which can modify ion homeostasis and strengthen early nutrient uptake. Seed priming generally boosts nutrient availability by stimulating early root growth, increasing absorption efficiency, and accelerating metabolic processes that mobilise essential minerals from the rhizosphere. Studies conducted by Rai-Kalal and Jajoo (2021) reported that priming seeds with ZnO nanoparticles have been demonstrated to increase Zn content in seeds, contributing to better seedling growth and yield in wheat.

The NPK uptake of plants was increased as the growth progressed along with the application of 50 mg/L ZnO nanoparticles as foliar application. The nano-fertilisers had a significant effect on these parameters with maximum NPK uptake i.e. 5.85, 1.18 and 7.63 g/plant, respectively recorded under the treatment T₃ in tomato. The highest N and K uptake (2.84 and 9.35 g/plant) was noted in T₃; however, highest P uptake (1.22 g/plant) was recorded under T₂ in bell pepper (Table 4). The higher nutrient uptake in the treatment consisted of 50 mg/L ZnO nanoparticles as foliar spray was attributable to improved root system development, which increased root length, thereby, boosting nutrient uptake. Morsy *et al.* (2017), Khati *et al.* (2018) and Chanu and Upadhyaya (2019) also reported that ZnO application boosted nutrient uptake efficiency in tomato and beans. These findings were consistent with those reported by Liang *et al.* (2021) on lettuce plants.

These findings offer practical value for farmers and agronomists seeking cost-effective ways to improve yields, especially in zinc-deficient soils or areas with micronutrient imbalances. Foliar application of ZnO nanoparticles enables

precise Zn delivery, higher nutrient-use efficiency, and reduced losses from soil fixation, often requiring lower doses than conventional fertilisers while producing stronger physiological benefits. This can enhance crop quality, raise yields, and lower input costs. The results support incorporating nano-based micronutrient formulations into nutrient-management programmes, particularly for high-value field and horticultural crops. Overall, the study highlighted ZnO nanoparticles as an advanced agronomic tool for improving crop performance through better nutrient delivery. Further field-scale trials and economic analyses are needed to assess long-term sustainability and develop best-practice recommendations.

ZnO nanoparticles can partially replace conventional zinc fertilisers by improving zinc-use efficiency and supporting plant growth, yield, and biofortification at lower application rates. Their high surface area and controlled release reduce leaching losses and enhance root uptake, as shown in rice, tomatoes, and other vegetables. However, their narrow effective dosage range, higher production costs, and potential phytotoxic or environmental risks limit broad adoption. Economically, ZnO nanoparticles are most suitable for high-value or biofortified crops, with combined use alongside conventional Zn sources offering the most practical approach.

Based on the findings, foliar application of ZnO nanoparticles at 50 mg/L is recommended for improving growth, yield, and nutrient uptake in tomato and bell pepper. However, further field trials are necessary to validate these findings under different soil and climatic conditions. The widespread use of ZnO nanoparticles in agriculture is constrained by high costs, application challenges, and potential environmental risks such as phytotoxicity and

Table 4 Effect of ZnO nanoparticles on nutrient uptake in tomato and bell pepper

Treatments	Nutrient uptake (g/plant)					
	N		P		K	
	Tomato	Bell pepper	Tomato	Bell pepper	Tomato	Bell pepper
T ₁	2.31 ± 0.00f	1.39 ± 0.03e	0.51 ± 0.00f	0.48 ± 0.05d	2.87 ± 0.06e	5.38 ± 0.06e
T ₂	4.99 ± 0.07bc	2.58 ± 0.04b	1.04 ± 0.02b	1.22 ± 0.07a	6.39 ± 0.11b	8.56 ± 0.08b
T ₃	5.85 ± 0.04a	2.84 ± 0.05a	1.18 ± 0.02a	1.10 ± 0.08a	7.63 ± 0.14a	9.35 ± 0.12a
T ₄	3.77 ± 0.17d	1.87 ± 0.04d	0.78 ± 0.02d	0.66 ± 0.04bcd	4.60 ± 0.09c	6.92 ± 0.10d
T ₅	5.11 ± 0.05b	2.42 ± 0.05c	1.05 ± 0.01b	0.84 ± 0.08b	6.58 ± 0.07b	8.01 ± 0.19c
T ₆	3.08 ± 0.04e	1.94 ± 0.01d	0.64 ± 0.01e	0.62 ± 0.05cd	4.22 ± 0.06d	6.60 ± 0.01d
T ₇	4.83 ± 0.05c	2.39 ± 0.05c	1.00 ± 0.01c	0.78 ± 0.06bc	6.63 ± 0.09b	7.71 ± 0.31c
Mean	4.28	2.21	0.89	0.81	5.56	7.51
LSD ($p \leq 0.05$)	0.23	0.13	0.04	0.20	0.28	0.47
SEM±	0.08	0.04	0.01	0.06	0.09	0.14

Treatment details are given under Materials and Methods.

shifts in soil microbial communities. Optimising dosage and integrating ZnO nanoparticles with conventional fertilisers are essential for safe and effective use. Future research should clarify how these nanoparticles interact with soil microbes, including impacts on diversity, functional groups, and nutrient cycling. Long-term, multi-location studies are needed to evaluate cumulative effects on crop productivity, plant health, and soil fertility. Comparative assessments of agronomic efficiency, bioavailability, and economic feasibility across soils and cropping systems will further guide optimised strategies for sustainably integrating nanofertilisers into agroecosystems.

REFERENCES

- Ahmed M, Marrez D A, Rizk R, Zedan M, Abdul-Hamid D, Decsi K, Kovacs G P and Toth Z. 2024. The influence of zinc oxide nanoparticles and salt stress on the morphological and some biochemical characteristics of *Solanum lycopersicum* L. plants. *Plants* **13**(10): 1418.
- Ahmed R, Uddin M K, Quddus M A, Samad M Y A, Hossain M M and Haque A N A. 2023. Impact of foliar application of zinc and zinc oxide nanoparticles on growth, yield, nutrient uptake and quality of tomato. *Horticulturae* **9**(2): 162.
- Akanbi-Gada M A, Ogunkunle C O, Vishwakarma V, Viswanathan K and Fatoba P O. 2019. Phytotoxicity of nano-zinc oxide to tomato plant (*Solanum lycopersicum* L.): Zn uptake, stress enzymes response and influence on non-enzymatic antioxidants in fruits. *Environmental Technology and Innovation* **14**: 100325.
- Amin S, Aziz T, Zia-ur-Rehman M, Saleem I, Rizwan M, Ashar A, Mussawar H A and Maqsood M A. 2023. Zinc oxide nanoparticles coated urea enhances nitrogen efficiency and zinc bioavailability in wheat in alkaline calcareous soils. *Environmental Science and Pollution Research* **30**(27): 70121–30.
- Anonymous. 2014. *Package of Practices for Vegetable Crops*, pp. 8, 24. Directorate of Extension Education, Dr Y S Parmar University of Horticulture and Forestry, Nauni, Solan, Himachal Pradesh.
- AOAC. 1980. *Official Methods of Analysis*, 13th edn, pp. 1018.
- Horowitz W (Ed). Association of Official Analytical Chemists, Benjamin Franklin Station, Washington DC.
- Aparanjitha R, Imran G and Mondal K. 2023. Nano fertilisers: Revolutionizing agriculture for sustainable crop growth. *Agriculture Archives* **2**(3): 6–9.
- Bhardwaj G, Brar P S, Chauhan A and Bhardwaj M. 2024. Comparison of fruit and quality parameters of tomato and capsicum by using different amount of nano ZnO through foliar and seed application. *Journal of Plant Nutrition* **47**(19): 3767–76.
- Brar P S, Bhardwaj G, Kaushal R, Bhardwaj R K, Singh U and Sharma U. 2025. Growth response of cabbage (*Brassica oleracea*) to TiO₂ nanoparticles exposure in Inceptisol of north-western mid-hills of Himachal Pradesh. *The Indian Journal of Agricultural Sciences* **95**(7): 821–26.
- Chanu T T and Upadhyaya H. 2019. Zinc oxide nanoparticle-induced responses on plants: A physiological perspective. (*In*) *Nanomaterials in Plants, Algae, and Microorganisms*, Vol. 2, pp. 43–64. Academic press, London.
- Chen H, Song Y, Wang Y, Wang H, Ding Z and Fan K. 2024. ZnO nanoparticles: Improving photosynthesis, shoot development, and phyllosphere microbiome composition in tea plants. *Journal of Nanobiotechnology* **22**(1): 389.
- Faizan M, Bhat J A, Chen C, Alyemini M N, Wijaya L, Ahmad P and Yu F. 2021. Zinc oxide nanoparticles (ZnO-NPs) induce salt tolerance by improving the antioxidant system and photosynthetic machinery in tomato. *Plant Physiology and Biochemistry* **161**: 122–30.
- Hui N, Deepak S and Maisnam G. 2023. Impact of different organic manures on growth and yield of tomato (*Solanum lycopersicum* L.). *International Journal of Applied Science and Engineering* **11**: 12.
- Jackson M L. 1967. *Soil Chemical Analysis*. Prentice Hall of India Private Limited, New Delhi.
- Jackson M L. 1973. *Soil Chemical Analysis*, pp. 111–26. Prentice Hall of India Pvt. Ltd., New Delhi.
- Kalia P, Kathuria K, Kumar K and Farooq M S. 2021. Price spread and marketing efficiency of capsicum: A study of kandaghat block of Solan district in Himachal Pradesh (India). *Asian Journal of Dairy and Food Research* **40**(2): 225–28.
- Khatai P, Bhatt P P, Kumar N R and Sharma A. 2018. Effect

- of nanozeolite and plant growth promoting rhizobacteria. *Biotechnology* **8**: 141–53.
- Kolencik M, Ernst D, Urik M, Durisova L, Bujdos M, Sebesta M, Dobrocka E, Ksinan S, Illa R, Qian Y, Feng H, Cerny I, Holisova V and Kratosova G. 2020. Foliar application of low concentrations of titanium dioxide and zinc oxide nanoparticles to the common sunflower under field conditions. *Nanomaterials* **10**(8): 1619.
- Liang Z, Pan X, Li W, Kou E, Kang Y, Lei B and Song S. 2021. Dose-dependent effect of ZnO quantum dots for lettuce growth. *ACS Omega* **6**: 10141–49.
- Lv W, Geng H, Zhou B, Chen H, Yuan R, Ma C, Liu R, Xing B and Wang F. 2022. The behaviour, transport, and positive regulation mechanism of ZnO nanoparticles in a plant-soil-microbe environment. *Environmental Pollution* **315**: 120368.
- Morsy N M, Shams A S and Abdel-Salam M A. 2017. Zinc foliar spray on snap beans using nano-Zn with N-soil application using mineral, organic and biofertiliser. *Middle East Journal of Agriculture Research* **6**(4): 1301–12.
- Panse V G and Sukhatme P V. 2000. *Statistical Methods for Agricultural Workers*, pp. 359. Indian Council of Agricultural Research, New Delhi.
- Piper C S. 1966. *Soil and Plant Analysis*, pp. 368. Hans Publication, Bombay.
- Pullagurala V L R, Adisa I O, Rawat S, Kim B, Barrios A C, Medina-Velo I A, Hernandez-Viezcas J A, Peralta-Videa J R and Gardea-Torresdey J L. 2018. Finding the conditions for the beneficial use of ZnO nanoparticles towards plants- A review. *Environmental Pollution* **241**: 1175–81.
- Rai-Kalal P and Jajoo A. 2021. Priming with zinc oxide nanoparticles improve germination and photosynthetic performance in wheat. *Plant Physiology and Biochemistry* **160**: 341–51.
- Rajput V D, Minkina T, Fedorenko A, Chernikova N, Hassan T, Mandzhieva S, Sushkova S, Lysenko V, Soldatov M A and Burachevskaya M. 2021. Effects of zinc oxide nanoparticles on physiological and anatomical indices in spring barley tissues. *Nanomaterials* **11**(7): 1722.
- Sadak M S and Bakry B A. 2020. Zinc oxide and nano ZnO oxide effects on growth, some biochemical as pects, yield quantity, and quality of flax (*Linum uitaissimum* L.) in absence and presence of compost under sandy soil. *Bulletin of the National Research Centre* **44**: 1–12.
- Samuditha P S, Adassooriya N M and Salim N. 2024. Assessing phytotoxicity and tolerance levels of ZnO nanoparticles on *Raphanus sativus*: Implications for widespread adoptions. *Beilstein Journal of Nanotechnology* **15**: 115–25.
- Sheron O P, Tonk D S, Kaushik L S, Hasija R C and Pannu R S. 1998. Statistical software package for agricultural research workers. (In) Hooda D S and Hasija R C (Eds), *Recent Advances in Information Theory, Statistics and Computer Application*, pp. 139–43. Department of Mathematics and Statistics, Chaudhary Charan Singh Haryana Agricultural University, Hisar, Haryana.
- Strekalovskaya E I, Perfilova A I and Krutovsky K V. 2024. Zinc oxide nanoparticles in the “soil-bacterial community-plant” system: Impact on the stability of soil ecosystems. *Agronomy* **14**(7): 1588.
- Tondey M, Kalia A, Singh A, Dheri G S, Taggar M S, Nepovimova E, Krejcar O and Kuca K. 2021. Seed priming and coating by nano-scale zinc oxide particles improved vegetative growth, yield and quality of fodder maize (*Zea mays*). *Agronomy* **11**: 1–16.
- Verma N, Kaushal P and Sidhu A K. 2024. Harnessing biological synthesis: Zinc oxide nanoparticles for plant biotic stress management. *Frontiers in Chemistry* **12**. <https://doi.org/10.3389/fchem.2024.1432469>
- Vogel A. 1978. *Textbook of Quantitative Inorganic Analysis*, 4th edn. Longman, London.
- Wang R, Mi K, Yuan X, Chen J, Pu J, Shi X, Yang Y, Zhang H and Zhang H. 2023. Zinc oxide nanoparticles foliar application effectively enhanced zinc and aroma content in rice (*Oryza sativa* L.) grains. *Rice* **16**: 36.
- Zhang H, Wang R, Chen Z, Cui P, Lu H, Yang Y and Zhang H. 2021. The effect of zinc oxide nanoparticles for enhancing rice (*Oryza sativa* L.) yield and quality. *Agriculture* **11**(12): 1247.
- Zhang H, Zhao X, Bai J, Tang M, Du W, Lv Z, Siddique K H M and Mao H. 2024a. Effect of ZnO nanoparticle application on crop safety and soil environment: A case study of potato planting. *Environmental Science: Nano* **11**(1): 351–62.
- Zhang H, Zheng T, Wang Y, Li T and Chi Q. 2024b. Multifaceted impacts of nanoparticles on plant nutrient absorption and soil microbial communities. *Frontiers in Plant Science* **15**. <https://doi.org/10.3389/fpls.2024.1497006>
- Zhou X Q, Hayat Z, Zhang D D, Li M Y, Hu S, Wu Q, Cao Y F and Yuan Y. 2023. Zinc oxide nanoparticles: Synthesis, characterisation, modification, and applications in food and agriculture. *Processes* **11**(4): 1193.