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Influence of Zinc Oxide Nanoparticles on the Productivity, Mineral Element Accumulation, and Fruit Quality of Tomato (*Solanum lycopersicum* L.)

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ABSTRACT

Foliar application of zinc oxide nanoparticles (ZnO-NPs) is a promising strategy in modern agriculture. This method has shown significant potential in enhancing tomato yields, improving fruit quality, and increasing nutrient uptake. An experiment was conducted in cocopeat media under glasshouse conditions at Ladang 15, Universiti Putra Malaysia (UPM) in 2020 to evaluate the effectiveness of various doses of ZnO-NPs on plant growth, yield, nutrient uptake, and fruit quality in terms of profitability. A total of ten treatments were evaluated, consisting of five levels of ZnO-NPs (0 ppm, 25 ppm, 50 ppm, 75 ppm, and 100 ppm) and two tomato varieties (MARDI Tomato 1 and MARDI Tomato 3). The experiment utilized a split-plot design with four replications. The results indicated that the application of 100 ppm ZnO-NPs produced the maximum measures of plant growth and fruit quality, including the highest number of primary branches per plant (27.75), leaf area (27.80 cm²), photosynthetic rate (33.05 µmol/m²/s), stomatal conductance (1.01 mol/m²/s), fruit length (4.55 cm), fruit diameter (4.33 cm), number of fruits per plant (52.75), fruit yield (53.85 t/ha), ascorbic acid content (26.13 mg/100 g), zinc content in fruits (52.25 mg/kg), total zinc uptake (102.34 mg/plant), and a benefit-cost ratio of 3.39. Moreover, among the tested varieties, MT3 outperformed MT1. Therefore, a foliar application of 100 ppm ZnO-NPs is recommended as the optimal dose for tomato cultivation. This

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approach promotes healthier plants and superior fruit quality and supports more sustainable and productive agricultural practices while minimizing environmental harm. Additionally, further research is necessary to explore higher dosages of ZnO-NPs in tomato production to establish the best dose for optimizing output.

1 Introduction

Tomato (*Solanum lycopersicum* L.) is one of the most widely cultivated and consumed vegetables globally. It is renowned for its high yield and substantial contribution to human nutrition (Hanif et al. 2023). The fruit is rich in vitamins (B, C, K, A, and E), carotenoids, and essential minerals such as potassium and phosphorus, making it a valuable source of nutrients (Ali et al. 2021). Additionally, widespread tomato cultivation and consumption significantly contribute to economic growth in many regions worldwide (Angyu and Kwon-Ndung 2024). However, tomato production faces numerous challenges, both biological and environmental. Among these, nutrient deficiencies stand out as a major factor that can adversely affect plant growth, fruit quality, and yield (Fu et al. 2020; Wang et al. 2023). Nanotechnology has brought revolutionary changes across various fields, including agriculture. Nanoparticles (NPs), which have at least one dimension in the nanoscale (1 to 100 nanometers), exhibit unique properties due to their increased surface area and significant effects (Kwon-Ndung et al. 2019; Ahsan et al. 2025).

Among these nanoparticles, zinc oxide nanoparticles (ZnO-NPs) have garnered considerable attention for their potential to enhance plant growth, nutrient uptake, and stress tolerance (Pinela et al. 2022; Wang et al. 2023). Zinc (Zn) is a vital micronutrient for plants, playing crucial roles in numerous physiological processes, including enzyme activation, protein synthesis, chlorophyll formation, pollen development, and the maintenance of biological membrane integrity (Quddus et al. 2020; Kondak et al. 2022). Zinc deficiency can lead to stunted growth, reduced yield, and diminished fruit quality in crops like tomatoes (Quddus et al. 2022a). ZnO-NPs have emerged as a promising solution to overcome Zn deficiency in plants (Wang et al. 2023). Their unique properties, such as high surface area and reactivity, facilitate efficient Zn delivery to plants (Ahmed et al. 2023).

Several studies have reported that ZnO-NPs can improve plant growth, nutrient uptake, and yield in various crops (Chanu and Upadhyaya 2019; Su et al. 2019; Huang et al. 2020; Khan et al. 2021; Wang et al. 2023; Ahsan et al. 2025). Using zinc oxide nanoparticles presents a significant opportunity to address challenges posed by a rapidly growing global population (Jampílek and Král'ová 2021). Continued research and development are key to realizing the full economic benefits of ZnO-NPs while ensuring their safe and responsible usage, paving the way for innovative applications and sustainable growth (Ahsan et al. 2025). Studies have shown that ZnO-NPs positively impact tomato plants, leading to increased growth, improved fruit quality, and enhanced stress tolerance. Pérez Velasco et al. (2020) reported significant plant height, stem diameter, and fruit weight improvements. Furthermore, ZnO-NPs have been found to increase protein content and mitigate the negative effects of salt stress. However, it is crucial to consider factors like plant age, nanoparticle dose, and type, as these can influence the extent of benefits (Faizan et al. 2021). For instance, ZnO-NPs at 50 ppm significantly enhanced the nutritional quality of tomatoes by increasing antioxidant enzyme activities and total soluble solids by 26.92%. They also showed potential in mitigating tomato mosaic virus through improved growth, photosynthesis, and antioxidant production (Gutiérrez-Miceli et al. 2021; Sofy et al. 2021). Foliar spraying with 100 ppm ZnO-NPs significantly improved tomato plant growth, as evidenced by increased fresh and dry weights of leaves and roots, along with enhanced levels of sucrose, starch, and glucose (Sun et al. 2020). Foliar applications of ZnO-NPs are preferred over soil applications because they can rapidly correct deficiencies, minimize toxicity, and prevent nutrient immobilization within the soil, as highlighted by Abdelaziz et al. (2021). While high concentrations of ZnO-NPs (400-800 mg/L) can adversely affect seed germination and plant growth, lower concentrations (up to 200 mg/L) have been shown to enhance growth and stimulate antioxidant enzyme activity (Tondey et al. 2021; Włodarczyk and Smolińska 2022). Consequently, ZnO-NPs are pivotal in boosting tomato productivity and promoting sustainable agricultural practices by reducing soil degradation and minimizing the environmental and economic risks associated with excessive fertilizer use (Benavides-Mendoza et al. 2023). Nevertheless, the specific effects of ZnO-NPs on tomato growth, productivity, mineral element accumulation, and fruit quality remain an active area of research (Pérez Velasco et al. 2020; Sofy et al. 2021). Given the circumstances, choosing the ideal foliar dose of zinc oxide nanoparticles (ZnO-NPs) is necessary to enhance tomato growth, yield, and quality. This study conducts comprehensive research on how ZnO-NPs influence various aspects of tomato growth, fruit quality, yield, and the accumulation of essential minerals. By understanding these effects, we can better assess the potential benefits of using ZnO-NPs in tomato cultivation, ultimately contributing to sustainable agriculture and a secure food supply. Therefore, this study aims to evaluate the influence of zinc oxide nanoparticles on the productivity, mineral element accumulation, and fruit quality of selected tomato varieties.

2 Materials and Methods

2.1 Experimental site and design

The experiment was conducted in cocopeat media at the glasshouse (8D) in the Agro-Tech Unit, Ladang 15, Faculty of Agriculture, Universiti Putra Malaysia (UPM), Serdang, Selangor, from March 2020 to August 2020. The experimental site is located in Malaysia's lowlands at a latitude of 2059'22.6" N and a longitude of 101042'82.2" E. The average daytime temperature was 30.28°C (33.38°C inside the glasshouse), and the relative humidity averaged 88.58% (83.92% inside the glasshouse), indicating high ambient temperatures and humidity levels (Shamshuddin et al. 2020; Ahmed et al. 2023). The experiment utilized a split-plot design with four replications. It involved 10 treatments consisting of five levels of zinc oxide nanoparticles (ZnO-NPs): 0 ppm, 25 ppm, 50 ppm, 75 ppm, and 100 ppm, in combination with two tomato varieties, MARDI Tomato 1 and MARDI Tomato 3. The selected varieties were V1 (MT 1) and V2 (MT 3). The treatments were labeled as T1 (0 ppm), T2 (25 ppm), T3 (50 ppm), T4 (75 ppm), and T5 (100 ppm). Tomato varieties were allocated to the main plots, while the zinc oxide nanoparticles were applied to each variety as sub-plot treatments.

2.2 Plant and planting materials

High-yielding tomato varieties MT-1 and MT-3 were sourced from the Malaysian Agricultural Research and Development Institute (MARDI). The seeds were initially germinated in trays filled with a mixture of peat moss and bio-soil in a 3:1 ratio. After three weeks, the healthiest seedlings were carefully transplanted into black poly bags measuring 18 inches by 18 inches, each filled with 3 Kg of coco peat. Each bag was equipped with 32 drainage holes to ensure optimal water management. The seedlings were placed 60 cm apart within rows and 75 cm between adjacent rows to maintain adequate spacing. The initial nutrient composition of the planting medium was methodically assessed using the methodology established by Keeney and Nelson (1982), and the results are presented in Table 1.

2.3 Agronomic management

In this study, tomato plants received three liquid fertilizers applied at different growth stages: seedling, vegetative, and fruiting. A 20g fertilizer blend composed of N (13%), P (40%), K (13%), B (0.01%), Cu (0.003%), Fe (0.025%), Mn (0.013%), Mo (0.0018%), and Zn (0.004%) was dissolved in 20 liters of water. This initial solution was applied twice weekly at 250 mL per plant during seedling. A second fertilizer blend, with the same NPK and micronutrient content as the seedling stage, was also prepared at 20g per 20 liters. This solution was applied twice weekly at 300 mL per plant during the vegetative stage. At the fruiting stage, a third fertilizer blend was created, containing N (13%), P (7%), K (20%), Ca (8%), Mg (2%), B (0.025%), Cu (0.01%), Fe (0.085%), Mn (0.045%), Mo (0.0038%), and Zn (0.025%). This blend was prepared at a rate of 35g per 20 liters and was applied twice weekly at 500 mL per plant. The tomato plants were vertically staked with plastic sticks to minimize root disturbance and prevent damage. Regular weeding and irrigation were performed as needed, and notably, the study period was free from any disease outbreaks or insect infestations.

2.4 Synthesis method of zinc oxide nanoparticles (ZnO-NPs)

To synthesize zinc oxide (ZnO) nanoparticles, we added 2 ml of 0.01% Polyvinyl Alcohol (PVA) to a 1 M zinc sulfate heptahydrate solution. This was followed by a dropwise addition of 2 M sodium hydroxide. The mixture was stirred for 18 hours, resulting in the formation of a white precipitate. This precipitate was filtered, washed, dried at 100°C, and calcined for three hours at 450°C. The structural properties of the ZnO nanoparticles were analyzed using Field Emission Scanning Electron Microscopy (FESEM) (Figure 1a) and X-ray diffraction (XRD) (Figure 1b), as described by Mohan and Renjanadevi (2016). For the foliar treatments, we applied various doses of ZnO nanoparticle fertilizer at three stages of tomato growth: (i) before flower initiation, (ii) after fruit set (when the fruit reached the marble size), and (iii) 20 days after the second spray. Each plant received 1000 ml of water, divided into three sprays: 300 ml for the first two stages and 400 ml for the third spray.

2.5 Measurement of growth and yield parameters

After the experiment, plant height was measured using a wooden meter ruler, and leaf area was calculated with a leaf area meter (LI-3000, Li-COR) in cm². The number of branches and total fruits were counted weekly. We recorded the total fruit weight per plant (in kg) and total yield (in t/ha) up to the final harvest (Cox 1995). Chlorophyll content was measured at the vegetative, flowering, and mature stages using a SPAD meter (SPAD-502, Konica Minolta). The experimental plot setup is illustrated in Figure 2.

Table 1 Initial nutrient status of the media in the experimental pot

Properties and Unit	pH	Total C (%)	Total N (%)	Total S (%)	K	Ca	Mg	Cu	Mn	B	Zn
					mg/kg						
Value	6.8	41.06	0.28	0.09	2917	603	205	0.8	24.9	11.4	14.7

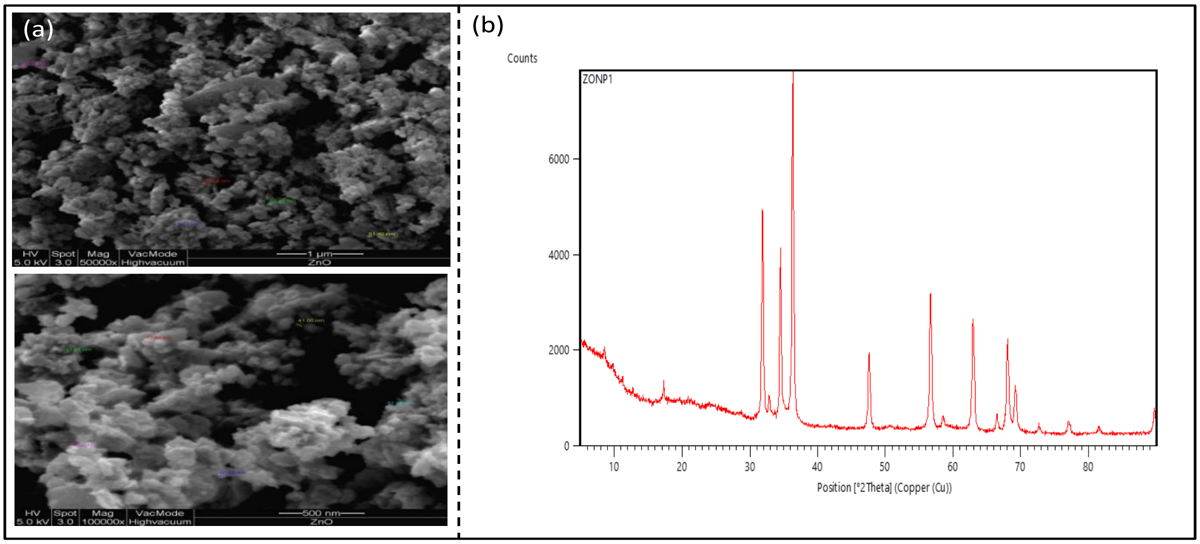

Figure 1 (a) Represent the Scanning Electron Microscope (SEM) image of the zinc oxide nanoparticles (ZnO-NPs)' size (40-55 nm), (b) XRD spectrum of zinc oxide nanoparticle prepared using Poly Vinyl Alcohol (PVA).

Figure 2 The image of the experimental plot

2.6 Measurement of photosynthetic parameters

The gross photosynthetic rate (PN), leaf stomatal conductance (GS), and transpiration rate of 5-week-old plant leaves were measured in the morning using a portable gas exchange system (LI-6400, LI-COR, Lincoln, NE, USA).

2.7 Determination of total carbon, total N, and sulfur in leaves and fruits of tomatoes

Samples of tomato fruits and leaves were collected from various pots and stored separately in paper bags. The paper bags containing the samples were placed in an oven set to 70°C for 72 hours or until they reached a constant weight. After drying, the plant samples were crushed and sieved through a 4 mm sieve. The total amounts of carbon, nitrogen, and sulfur were measured using a Leco TruMac CNS analyzer. For the analysis, 0.2–0.3 g of the air-dried sample was placed in a ceramic boat and combusted at 1350°C with helium, compressed air, and 99.99% pure oxygen. The gases produced, CO_2, NO_2, and SO_2, were used to identify the total carbon, nitrogen, and sulfur contents, respectively. The total carbon and nitrogen contents were recorded as percentages (Ahmed et al. 2023).

2.8 Determination of P, K, Mg, B, Fe, and Zn in leaves and fruits of tomatoes

The total concentrations of phosphorus (P), potassium (K), magnesium (Mg), boron (B), iron (Fe), and zinc (Zn) were determined using an ICP-Optical Emission Spectrometer, following the dry ashing method based on Cottenie's theory (Cottenie 1980). A 2–3 g air-dried sample was dried at 60°C for 24 hours, then ashed at 300°C for 1 hour and at 550°C for 8–9 hours. After cooling, 2 mL of concentrated hydrochloric acid (HCl) and water were added, and the sample was heated for 15–20 minutes. Once cooled, 10 mL of 20% nitric acid (HNO_3) was added, and the sample was placed in a water bath for 1 hour. Finally, the sample was filtered through Whatman filter paper No. 2, diluted to a final volume of 100 mL with distilled water, and analyzed for P, K, Mg, B, Fe, and Zn concentrations using the PerkinElmer Optima 8300 ICP-Optical Emission Spectrometer.

2.9 Determination of quality parameters

Tomato fruits were manually harvested at the red ripe stage to assess their quality performance. For the experiment, we selected fruits of uniform size and colour that were undamaged and free from disease and bruises, following the guidelines established by Beckles (2012). Total Soluble Solids (TSS), firmness, and Titratable Acidity (TA) were measured immediately in the fresh fruit, while the physicochemical properties were analyzed in refrigerated samples (Ahmed et al. 2023).

2.9.1 Total Soluble Solid (TSS)

A digital pocket refractometer (model PAL1, ATAGO, Tokyo, Japan) was used to measure tomato fruits' soluble solids. Fresh tomato juice was placed on the refractometer's glass lens using a garlic pestle, a kitchen tool. The total soluble solids (TSS) were expressed as a percentage of Brix (% Brix) (Nirupama Pila et al. 2010).

2.9.2 Firmness

The firmness of the tomato fruits was measured using a Universal Testing Machine (Model 5543, load frame, Instron Corp., Norwood, MA, USA). The machine was equipped with a 6 mm diameter cylindrical probe and operated at a 20 mm/min speed. The measurements were recorded in Newtons (N) using Instron Merlin software, version M12-13664-EN (Kumah et al. 2011).

2.9.3 Titratable Acidity (TA)

Titratable acidity was measured using a titration method. To prepare the sample, 10g of tomato fruit pulp was homogenized with 20 mL of distilled water. This mixture was then filtered and combined with phenolphthalein. The solution was titrated with 0.1 N NaOH until a persistent pink colour, indicating a pH of 8.1, was achieved. As Mohammadi-Aylar et al. (2010) described, the volume of NaOH used was recorded, and the results were expressed as the percentage of citric acid per 100 g of fresh weight.

$$\text{Titratable acidity (\%)} = (\text{Titer vol. (ml)} \times \text{normality NaOH}(0.1) \times \text{vol. made up (20 ml)} \times 64\ \text{g(equivalent wt. of citric acid)} \times 100)/(\text{Wt. of sample (5 g)} \times \text{vol. of sample for titration (5 ml)} \times 1000)$$

2.9.4 Antioxidant properties

2.9.4.1 Ascorbic acid

The ascorbic acid content was measured using a direct colourimetric method with 2,6-dichlorophenol-indophenol (DCPIP) dye, as Ding and Mashah (2016) outlined. To extract the ascorbic acid, 2 grams of tomato fruit were mixed with 20 mL of 2% metaphosphoric acid (HPO_3). The mixture was then filtered, and the volume was adjusted by adding more 2% HPO_3. An aliquot of 0.5 mL of the extract was combined with 3 mL of 2% HPO_3 and 2 mL of DCPIP dye. The absorbance was measured at 518 nm using a UV spectrophotometer. Based on a standard curve, the ascorbic acid content in the tomato fruit was expressed as mg/g of fresh weight.

$$\text{AA (in mg/g FM)} = \frac{\text{Cppm x V}}{\text{W}}$$

Here, Cppm = Conc. of sample soln. as ppm computed from the standard curve

V = Final vol. made up in liter (0.04 L)

W= Fresh wt. of the samples (g)

2.9.4.2 Lycopene

Lycopene content was measured using slightly modified techniques developed by Nagata and Yamashita (1992). Approximately 1g of the sample was dissolved in a mixture of 10 to 20 mL of acetone and hexane in a 4:6 ratio. The pigments were extracted and homogenized with a mortar and pestle, after which the supernatant was separated. The optical density of the supernatant was measured using a UV spectrophotometer at wavelengths of 663, 645, 505, and 453 nm. The amount of lycopene was then calculated using the following equation:

$$\text{Lycopene (mg/100g)} = -0.0458A_{663} + 0.204A_{645} + 0.372A_{505} - 0.0806A_{453}$$

A_{663}, A_{645}, A_{505}, and A_{453} are the absorbance at 663 nm, 645 nm, 505 nm, and 453 nm of each other. Data obtained as mg/100 mL were converted as data mg/100 mL × sample volume = data mg/100 g.

The total N contents of the tomato dry fruit were multiplied by the constant food factor of 6.25 to estimate the protein content (Hiller et al. 1948).

2.10 Calculation of nutrient uptake

The nutrient content was multiplied by the dry weight of the tomato plant portion (oven-dry weight) to calculate nutrient uptake (Sharma et al. 2012):

$$\text{Nutrient uptake} = \frac{\text{Nutrient concentration (\%)} \times \text{Dry weight (g)}}{100}$$

2.11 Calculation of apparent zinc recovery efficiency (AZnR)

Baligar et al. (2001) calculated the apparent zinc recovery efficiency based on dry weight. The following equation is provided:

$$\text{AZnR} = \frac{\text{Nutrient uptake (mg/plant)} - \text{control value}}{\text{Applied zinc (mg/plant)}} \text{x } 100$$

2.12 Cost and Return Analysis

In the experiment, the variable cost for each treatment was calculated by adding the costs of labour and inputs. Each treatment's tomato fruit yield was expressed in tons per hectare (t ha^{-1}). To determine the gross return, we multiplied the yield by the current unit price of tomatoes. It is important to note that the net house and experimental land rent were excluded from this calculation. Subsequently, we calculated the gross margin by subtracting the variable cost from the gross return. The benefit-cost ratio (BCR) was then calculated using the formula provided by Quddus et al. (2023): BCR = GR ÷ TVC, Where GR= Gross return and TVC= Total variable cost

2.13 Statistical analysis

The statistical analysis focused on growth, yield, yield-contributing characteristics, quality attributes, and nutrient content data. This analysis was conducted using SAS software (version 9.4) and ANOVA. A significance level of 0.05 ($p < 0.05$) was set for Tukey's Honestly Significant Difference (HSD) test, which was employed to compare the means.

3 Results and Discussion

3.1 The growth parameters

3.1.1 Varietal effect on growth traits

Growth traits, such as the number of primary branches per plant and leaf area, showed significant variation among different tomato varieties, while plant height did not exhibit any notable differences (Table 2). The MT3 variety demonstrated superior characteristics, with an average of 24.05 branches per plant and a leaf area of 22.91 cm² compared to the MT1 variety. The greater number of branches and larger leaf area in MT3 may be attributed to genetic differences and favourable environmental conditions, which enhance nutrient uptake. Tujuba and Ayana (2020) similarly observed that the number of branches varies among different tomato cultivars, linking this variation to genetic differences.

3.1.2 Effect of ZnO-NPs on growth parameters

The growth parameters of plant height, number of primary branches per plant, and leaf area were significantly influenced by

Table 2 Effects of foliar application of zinc oxide nanoparticles on growth parameters of tomato varieties

Treatment	Plant height (cm)	No. of primary branch/plant	Leaf area (cm^2)
MT1	116.40 ±2.62^{a}	20.75 ±1.05^{b}	19.49 ±1.19^{b}
MT3	119.25 ±2.72^{a}	24.05 ±1.48^{a}	22.91 ±1.53^{a}
Level of sig.	ns	*	**
MSD value	11.99	3.13	1.54
CV (%)	8.06	12.00	8.53
T_1	105.13 ±2.55^{b}	14.00 ±0.53^{c}	12.58 ±0.37^{d}
T_2	112.75 ±2.85^{ab}	19.63 ±0.82^{b}	16.61 ±0.58^{c}
T_3	121.25 ±4.25^{a}	24.63 ±1.13^{a}	23.54 ±1.41^{b}
T_4	124.00 ±4.13^{a}	26.00 ±1.38^{a}	25.48 ±0.89^{ab}
T_5	126.00 ±2.27^{a}	27.75 ±1.52^{a}	27.80 ±1.07^{a}
Level of sig.	**	**	**
MSD value	13.99	3.96	2.66
CV (%)	8.06	12.00	8.53
(V*T)	ns	ns	ns

Means in a column that includes the same letters are not statistically different at the 5% level using Tukey's HSD test, MSD = Minimum significant difference, CV = Coefficient of variation, sig.= significance, T_1: 0 ppm, T_2: 25 ppm, T_3: 50 ppm, T_4: 75 ppm and T_5: 100 ppm of ZnO-NPs. ns indicated non-significant at $p>0.05$, *indicated significant at $p\leq0.05$ and ** indicated significant at $p\leq0.01$, ± standard error mean (n=4)according to ANOVA.

various levels of foliar-applied zinc oxide nanoparticles (ZnO-NPs) (Table 2). The maximum plant height of 126.00 cm was achieved with a treatment of 100 ppm ZnO-NPs (T5), representing a 20% increase over the control group. This height was superior to the results from treatments T_1 and T_2 but similar to those from T_3 and T_4. Zinc oxide nanoparticles (ZnO-NPs) may enhance plant growth, particularly height, by potentially releasing essential nutrients crucial for crop development, increasing chlorophyll content, and promoting active photosynthesis (Khanm et al. 2018; Mi et al. 2023). This finding aligns with Sun et al. (2020), who reported the highest plant height with 100 mg/L ZnO-NPs. Additionally, 50 ppm ZnO-NPs led to a 30.1% increase in shoot length (Faizan and Hayat 2019), while treatment of 100 ppm ZnO-NPs resulted in a 16% increase in wheat plant height (Munir et al. 2018; Ahmed et al. 2023). Plants treated with 100 ppm ZnO-NPs (T_5) showed the most vigorous branching, with an average of 27.75 branches per plant, followed closely by those treated with 75 ppm (T_4) and 50 ppm (T_3). In contrast, the control treatment resulted in the fewest branches, averaging just 14 per plant. This significant increase in branching among the ZnO-NPs-treated plants suggests that these nanoparticles stimulate new branch development by interacting with the plant's growth-regulating tissues and triggering important metabolic processes, as previously noted by Faizan and Hayat (2019) and Wang et al. (2024).

Moreover, leaf area also showed significant variation among the different treatments. Plants treated with 100 ppm ZnO-NPs exhibited the largest leaf area (27.80 cm²), followed closely by those treated with 75 ppm ZnO-NPs (T_4). The control group demonstrated the smallest leaf area at 12.58 cm². This increase in leaf area can be attributed to the vital role of zinc in plant growth. Zinc is actively involved in essential metabolic processes, including carbohydrate and protein synthesis, as well as the production of auxin, a plant hormone that stimulates cell expansion and differentiation, ultimately resulting in larger leaf size (Vasconcelos et al. 2011; Saleem et al. 2022; Kondak et al. 2022; Ahsan et al. 2025). These findings mirror the observations of Faizan and Hayat (2019), who reported a substantial 24.1% increase in leaf area when plants were treated with 50 ppm ZnO-NPs compared to the control treatment.

3.2 The physiological characteristics

3.2.1 Varietal effect on physiological traits

Physiological traits, such as leaf stomatal conductance, varied significantly among the different tomato varieties, while chlorophyll content, photosynthetic rate, and transpiration rate did not show any significant differences (Table 3). The variety MT3 exhibited higher stomatal conductance (0.86 mol/m²/s) than MT1

Table 3 Effects of foliar application of zinc oxide nanoparticles on physiological growth of tomato varieties

Treatment	Chlorophyll content in leaf (SPAD)	Photosynthesis rate ($\mu mol/m^2/s$)	Stomatal conductance ($mol/m^2/s$)	Transpiration rate ($mmol/m^2/s$)
MT1	46.00 ±1.32^a	26.44 ±1.09^a	0.78 ±0.04^b	12.43 ±0.58^a
MT3	49.69 ±1.69^a	28.95 ±1.38^a	0.86 ±0.04^a	13.37 ±0.60^a
Level of sig.	ns	Ns	**	ns
MSD value	6.10	2.55	0.02	1.51
CV (%)	7.40	10.68	8.98	8.35
T_1	38.94 ±1.01^c	20.12 ±0.55^c	0.56 ±0.02^d	8.70 ±0.27^c
T_2	44.25 ±1.71^b	24.66 ±0.79^b	0.72 ±0.03^c	11.85 ±0.37^b
T_3	49.55 ±1.74^a	29.22 ±0.82^a	0.89 ±0.03^b	14.25 ±0.39^a
T_4	51.85 ±1.52^a	31.45 ±0.96^a	0.94 ±0.03^{ab}	14.48 ±0.48^a
T_5	54.63 ±1.40^a	33.05 ±1.87^a	1.01 ±0.04^a	15.22 ±0.45^a
Level of sig.	**	**	**	**
MSD value	5.22	4.36	0.11	1.59
CV (%)	7.40	10.68	8.98	8.35
(V*T)	ns	Ns	ns	ns

Means in a column that include the same letters are not statistically different at the 5% level using Tukey's HSD test, MSD = Minimum significant difference, CV = Coefficient of variation, sig.= significance, T_1: 0 ppm, T_2: 25 ppm, T_3: 50 ppm, T_4: 75 ppm and T_5: 100 ppm of ZnO-NPs, ns indicated non-significant at $p>0.05$, * indicated significant at $p\leq0.05$ and ** indicated significant at $p\leq0.01$, ± standard error mean (n=4) according to ANOVA.

(0.78 mol/m²/s). This difference may reflect variations in growth and yield potential due to genetic and environmental factors (Ben-Rouina et al. 2006; Isah et al. 2014; Dong et al. 2025). Additionally, the variety MT3 demonstrated superior nutrient uptake compared to MT1. This finding is consistent with Olaniyi et al. (2010) and Ahmed et al. (2023), who noted enhanced physiological growth attributes in the UC82B variety.

3.2.2 Effect of ZnO-NPs on physiological parameters

Physiological parameters such as leaf chlorophyll content, photosynthetic rate, stomatal conductance, and transpiration rate in tomatoes were significantly influenced by the foliar application of various levels of ZnO nanoparticles.

3.2.2.1 Chlorophyll Content

The highest chlorophyll content observed was 54.63 SPAD in the treatment with 100 ppm ZnO-NPs (T_5). This was comparable to the 75 ppm treatment (T_4) and the 50 ppm treatment (T_3) but significantly higher than the control group, which had a chlorophyll content of 38.94 SPAD. These results are consistent with previous research by Sun et al. (2020) and Faizan and Hayat (2019), who found a 32.1% increase in chlorophyll content with 50 ppm ZnO-NPs compared to the control group.

3.2.2.2 Photosynthetic Rate

The highest photosynthetic rate recorded was 33.05 µmol/m²/s with the application of 100 ppm ZnO nanoparticles (ZnO-NPs). This rate was statistically similar to those observed at 75 ppm and 50 ppm but significantly higher than the rates at 25 ppm and the control group, which had a rate of 20.12 µmol/m²/s. This improvement aligns with the findings of Sofy et al. (2021), who noted that nanoparticles enhance key processes such as carbohydrate and protein metabolism and cell wall development (Jabri et al. 2022). However, the results of this study contradict those of Faizan and Hayat (2019), who observed a substantial 35% increase in the photosynthetic rate with the application of 50 ppm ZnO-NPs, followed by 100 ppm ZnO-NPs. Munir et al. (2018) also reported a significant 58% improvement in the photosynthetic rate in wheat plants treated with 100 mg/L ZnO-NPs. Rehman et al. (2023) also corroborated similar findings in tomatoes.

3.2.2.3 Stomatal Conductance

The maximum stomatal conductance of 1.01 mol/m²/s was achieved with 100 ppm of ZnO nanoparticles (T_5). This level was comparable to that observed with 75 ppm (T_4) but was significantly higher than the measurements taken with 50 ppm (T_3) and the control group (T_1). This finding is consistent with the research conducted by Munir et al. (2018), which reported a 102% increase in stomatal conductance in wheat treated with 100 mg/L of ZnO nanoparticles.

3.2.2.4 Transpiration Rate

The highest transpiration rate recorded was 15.22 mmol/m²/s with the application of 100 ppm ZnO nanoparticles (T_5), while the control group (T_1) exhibited the lowest transpiration rate. This result supports the established role of zinc in enhancing the production of carbonic anhydrase, an essential enzyme for CO_2 transport during photosynthesis (Saleem et al. 2022; Alloway 2008). The improvement in transpiration is likely due to increased nitrogen accumulation, higher stomatal density, and greater leaf area, all of which are positively influenced by zinc (Jabri et al. 2022; Rehman et al. 2023). Additionally, this finding is supported by Munir et al. (2018), who reported a 62% increase in transpiration in wheat treated with 100 mg/L ZnO nanoparticles.

3.3 The yield and yield contributing characters

3.3.1 Varietal effect on yield and yield contributing characters

Tomato yield and characteristics, such as fruit length, individual fruit weight, and total yield, varied significantly among the varieties, with no differences in fruit diameter or the number of fruits per plant (Table 4). The MT3 variety had the highest fruit length (4.14 cm), individual fruit weight (43.79 g), number of fruits per plant (46.10g), and total yield (2.09 kg per plant), representing a 22.2% increase over MT1. These differences likely stem from genetic factors and better nutrient uptake (Quddus et al. 2022b). Similar results were noted by Razzaque et al. (2016) in mungbean varieties.

3.3.2 Effect of ZnO-NPs on yield and yield contributing characters

Tomato yield and yield contributing characters were significantly enhanced by the different levels of ZnO-NPs (Table 4). ZnO-NPs in previous research were demonstrating their positive influence on plant growth and development (Ahsan et al. 2025; Wang et al. 2023).

3.3.2.1 Fruit length and diameter

The treatment with 100 ppm ZnO nanoparticles (T_5) resulted in the largest fruits, measuring 4.55 cm in length and 4.33 cm in diameter. This size was statistically comparable to the fruits from the 75 ppm ZnO nanoparticles treatment (T_4). In contrast, the control treatment (T_1) produced the smallest fruits, with a length of 3.16 cm and a diameter of 3.02 cm. Zinc is essential for various plant processes, including RNA metabolism, carbohydrate and protein synthesis, DNA replication, fruit set, and the development of fruit characteristics (Quddus et al. 2020). This finding is consistent with the observation by Kumar et al. (2017), which noted that combining 150 ppm ZnO and FeO nanoparticles resulted in the largest fruit sizes.

Table 4 Effects of foliar application of zinc oxide nanoparticles on yield and yield attributes of tomato varieties

Treatment	Fruit length (cm)	Fruit diameter (cm)	Individual fruit weight (g)	No. of fruits/plant	Yield (kg/plant)	Yield (t/ha)
MT1	3.69 ±0.10[b]	3.70 ±0.11[a]	39.30 ±1.83[b]	42.20 ±1.77[a]	1.71 ±0.14[b]	34.28 ±2.77[b]
MT3	4.14 ±0.17[a]	3.94 ±0.13[a]	43.79 ±2.22[a]	46.10 ±1.99[a]	2.09 ±0.18[a]	41.87 ±3.51[a]
Level of sig.	**	ns	**	ns	*	**
MSD value	0.22	0.34	1.58	4.03	0.24	4.89
CV (%)	7.49	7.06	7.04	7.55	10.81	10.07
T_1	3.16 ±0.10[c]	3.02 ±0.07[c]	27.23 ±0.72[d]	31.75 ±1.03[d]	0.87 ±0.04[d]	17.33 ±0.80[d]
T_2	3.48 ±0.09[c]	3.55 ±0.09[b]	37.33±0.98[c]	39.50 ±1.31[c]	1.48 ±0.08[c]	29.53 ±1.51[c]
T_3	4.05 ±0.12[b]	4.05 ±0.12[a]	45.26 ±1.50[b]	47.50 ±1.21[b]	2.16 ±0.12[b]	43.18 ±2.33[b]
T_4	4.35 ±0.18[ab]	4.16 ±0.11[a]	47.14 ±1.69[ab]	49.25 ±1.71[ab]	2.33 ±0.12[b]	46.50 ±2.43[b]
T_5	4.55 ±0.19[a]	4.33 ±0.11[a]	50.77 ±1.65[a]	52.75 ±1.68[a]	2.69 ±0.16[a]	53.85 ±3.20[a]
Level of sig.	**	**	**	**	**	**
MSD value	0.43	0.40	4.31	4.91	0.30	6.06
CV (%)	7.49	7.06	7.04	7.55	10.81	10.07
(V*T)	ns	ns	ns	ns	ns	ns

Means in a column that includes the same letters are not statistically different at the 5% level using Tukey's HSD test, MSD = Minimum significant difference, CV = Coefficient of variation, sig.= significance, T_1: 0 ppm, T_2: 25 ppm, T_3: 50 ppm, T_4: 75 ppm and T_5: 100 ppm of ZnO-NPs. ns indicated non-significant at $p>0.05$, * indicated significant at $p\leq0.05$ and ** indicated significant at $p\leq0.01$, ± standard error mean (n=4) according to ANOVA.

3.3.2.2 Individual fruit weight

Applying 100 ppm ZnO nanoparticles (ZnO-NPs) resulted in the heaviest individual fruit, weighing 50.77 grams. This weight was significantly greater than that of other treatments and closely matched the 75 ppm ZnO-NPs treatment results. This finding is consistent with previous research highlighting the positive effects of ZnO-NPs on fruit weight. For instance, Ahmed et al. (2023) reported the highest fruit weight in tomatoes treated with 100 ppm ZnO-NPs, while Kumar et al. (2017) observed similar results with a combination of 150 ppm ZnO-NPs and FeO-NPs. Prasad et al. (2012) also found that 125 ppm ZnO-NPs significantly enhanced peanut shoot growth, pod size, and overall yield compared to chelated zinc sulfate.

3.3.2.3 Number of fruits per plant

The highest number of fruits per plant (52.75) was achieved by applying 100 ppm ZnO-NPs (T_5). This result was significantly higher than those from other treatments and was comparable to the 75 ppm ZnO-NPs treatment (T_4). In contrast, the control treatment (T_1) had the lowest fruit count, recording only 31.75 fruits. These findings align with previous studies. For instance, Faizan and Hayat (2019) reported a 21.1% increase in fruit numbers with sequential foliar sprays of 50 ppm and 100 ppm ZnO-NPs. Additionally, Kumar et al. (2017) found the highest fruit count per plant using 150 ppm ZnO-NPs in combination with FeO-NPs. Similarly, Ahmed et al. (2023) observed comparable results with 100 ppm ZnO-NPs in tomato plants.

3.3.2.4 Overall yield

The foliar application of 100 ppm ZnO nanoparticles (T_5) produced the highest yield, averaging 2.69 kg per plant and 53.85 tons per hectare. This yield was significantly greater than all other treatments, with a remarkable 210% increase. This finding is consistent with the research by Seleiman et al. (2023), which reported optimal maize yields at a concentration of 100 mg/L ZnO nanoparticles. Zinc plays a critical role in various metabolic processes, as highlighted by Quddus et al. (2022b), and positively influences fruit set, number, length, diameter, and dry fruit weight, as noted by Mubashir et al. (2023). Meanwhile, foliar spraying with 50 ppm resulted in a 19.4% yield increase over the control. Faizan and Hayat (2019) concluded that combining 150 ppm ZnO nanoparticles with FeO nanoparticles enhanced fruit yield. However, the 100 ppm concentration consistently demonstrated the most significant impact, resulting in a 185% increase in wheat grain yield compared to the control, as documented by Munir et al. (2018).

Table 5 Effects of foliar application of zinc oxide nanoparticles on the quality attributes of tomato varieties

Treatment	TSS (^{0}Brix)	Firmness (N)	Titratable acidity (%)	Ascorbic acid (mg/100g)	Lycopene content(µg/100g)	Protein content (%)
MT1	6.58 ±0.21^a	11.45 ±0.56^b	0.64 ±0.03^a	21.30 ±0.86^a	211.50 ±7.77^b	13.55 ±0.61^a
MT3	6.87 ±0.23^a	12.86 ±0.57^a	0.67 ±0.04^a	23.20 ±1.02^a	232.55 ±10.87^a	13.96 ±0.66^a
Level of sig.	ns	**	ns	ns	*	ns
MSD value	0.48	0.52	0.05	3.35	15.14	1.04
CV (%)	6.82	7.48	10.69	9.45	8.65	8.28
T_1	5.25 ±0.13^c	8.25 ±0.35^d	0.83 ±0.03^a	16.00 ±0.46^c	167.63 ±5.11^c	8.75 ±0.23^c
T_2	6.35 ±0.18^b	11.17 ±0.40^c	0.77 ±0.03^{ab}	20.50 ±0.71^b	195.88 ±4.53^c	14.00 ±0.41^b
T_3	7.10 ±0.19^a	13.15 ±0.42^b	0.67 ±0.03^{bc}	24.00 ±0.85^a	227.00 ±7.17^b	14.63 ±0.38^{ab}
T_4	7.35 ±0.21^a	13.61 ±0.64^{ab}	0.59 ±0.02^c	24.63 ±0.92^a	245.38 ±8.76^b	15.47 ±0.39^{ab}
T_5	7.58 ±0.18^a	14.62 ±0.46^a	0.45 ±0.02^d	26.13 ±1.04^a	274.25 ±11.14^a	15.94 ±0.41^a
Level of sig.	**	**	**	**	**	**
MSD value	0.68	1.34	0.10	3.10	28.30	1.68
CV (%)	6.82	7.48	10.69	9.45	8.65	8.28
(V*T)	ns	ns	ns	ns	ns	ns

Means in a column that includes the same letters are not statistically different at the 5% level using Tukey's HSD test, MSD = Minimum significant difference, CV = Coefficient of variation, sig.= significance, T_1: 0 ppm, T_2: 25 ppm, T_3: 50 ppm, T_4: 75 ppm and T_5: 100 ppm of ZnO-NPs. ns indicated non-significant at p>0.05, * indicated significant at p≤0.05 and ** indicated significant at p≤0.01, ± standard error mean (n=4) according to ANOVA.

3.4 Quality parameters

3.4.1 Varietal effect on quality traits

The quality traits of tomatoes, such as fruit firmness and lycopene content, showed significant variations between the two varieties examined. However, no significant differences were observed in total soluble solids (TSS), titratable acidity, ascorbic acid, and protein content (Table 5). The tomato variety MT3 had higher fruit firmness, measuring 12.82 N, and a greater lycopene content of 232.55 µg/100 g than the MT1 variety. MT3 displayed superior nutritional characteristics, likely due to genetic and environmental factors. Similar findings were reported by Quddus et al. (2020) and Razzaque et al. (2016) in their studies on mungbean varieties.

3.4.2 ZnO-NPs effect on quality traits

The foliar application of ZnO-NPs significantly affected the total soluble solids (TSS), firmness, titratable acidity, ascorbic acid, lycopene, and protein content of tomatoes (Table 5).

3.4.2.1 Total soluble solids (TSS)

The highest total soluble solids (TSS) value of 7.58 was achieved with 100 ppm ZnO nanoparticles (T_5). This result was similar to other treatments, except for the 25 ppm ZnO nanoparticles (T_2) and the control (T_1), which recorded the lowest TSS at 5.25. Zinc enhances photosynthesis and sugar content while reducing acidity (Ahmed et al. 2023; Włodarczyk et al. 2024). Additionally, Gutiérrez-Miceli et al. (2021) found that ZnO nanoparticles at a concentration of 50 ppm improved TSS by 26.92% compared to the control.

3.4.2.2 Fruit firmness

The highest fruit firmness, measured at 14.62 N, was observed in the treatment with 100 ppm ZnO nanoparticles (T_5). This significantly differed from the treatments with 50 ppm ZnO nanoparticles (T_3) and 25 ppm ZnO nanoparticles (T_2). The control treatment (T_1) exhibited the lowest firmness at 8.25 N. It is suggested that zinc may play a role in the synthesis of cell wall components, which could enhance tomato fruits' firmness and shelf life. This observation is supported by Siva Prasad et al. (2021).

3.4.2.3 Titratable acidity

Titratable acidity decreased as the levels of ZnO nanoparticles (ZnO-NPs) increased. The lowest acidity (0.45%) was recorded with 100 ppm of ZnO-NPs (T5), while the control group (T_1) exhibited the highest acidity at 0.83%. These results are consistent with the findings of previous researchers (Ahmed et al. 2021; Ahmed et al. 2023; Włodarczyk et al. 2024).

3.4.2.4 Ascorbic acid

The highest ascorbic acid (26.13 mg/100 g) was found in the treatment with 100 ppm ZnO-NPs (T_5). This level was not significantly different from the other treatments, except for the one with 25 ppm ZnO-NPs (T_2). The control group (T_1) had the lowest ascorbic acid content, at 16.00 mg/100 g. Włodarczyk et al. (2024) reported that foliar application of ZnO-NPs at 150 ppm could increase the amount of ascorbic acid in tomato fruits.

3.4.2.5 Lycopene content

The maximum lycopene content recorded was 274.25 µg/100 g, achieved with 100 ppm ZnO-NPs (T_5), significantly higher than in other treatments. The second highest content was 245.38 µg/100 g, observed with 75 ppm ZnO-NPs (T_4), closely followed by 50 ppm ZnO-NPs (T_3). The control group (T_1) had the lowest lycopene content at 167.63 µg/100 g. Zinc is critical for photosynthesis and associated enzymatic activities, which help increase sugar content and reduce acidity (Jabri et al. 2022; Włodarczyk et al. 2024). Applying ZnO-NPs at 100 ppm led to a 113.1% increase in lycopene content (Raliya et al. 2015). Additionally, ZnO-NPs at 150 ppm also exhibited the highest levels of lycopene and beta-carotene compared to the control (Włodarczyk et al. 2024). Sofy et al. (2021) observed significant improvements in growth indices, quality traits, and antioxidant levels by applying 100 ppm ZnO-NPs.

3.4.2.6 Protein content

The highest protein content (15.94%) was observed in the treatment with 100 ppm of ZnO nanoparticles (T_5), which was significantly different from the treatment with 25 ppm of ZnO nanoparticles (T_2). In contrast, the control treatment (T_1) showed the lowest protein content at 8.75%. The presence of zinc nutrition played a significant role in enhancing the protein levels in tomatoes, a conclusion supported by the findings of Quddus et al. (2020).

3.5 Nutrient contents in leaves

Significant differences in macronutrient content in tomato leaves were observed between plants treated with zinc oxide nanoparticles (ZnO-NPs) and those not (Table 6). While no significant differences were found among the various tomato varieties, the MT3 variety consistently showed higher nutrient levels, followed by the MT1 variety. In the case of ZnO-NPs, the highest nitrogen content (29.15 g/kg) was recorded at a concentration of 100 ppm (T_5), significantly greater than all other treatments. The control group (T_1) had the lowest nitrogen content. Similarly, higher levels

Table 6 Effects of foliar application of zinc oxide nanoparticles on nutrient contents in leaves of tomato varieties

Treatment	Nitrogen (N)	Phosphorus (P)	Potassium (K)	Sulphur(S)	Boron (B)	Zinc (Zn)
	(g/kg)				(mg/kg)	
MT1	23.30 ±1.24[a]	9.52 ±0.72[a]	22.11 ±1.27[a]	10.72 ±0.52[b]	54.12 ±2.46[a]	503.02 ±57.03[a]
MT3	23.68 ±1.22[a]	10.05 ±0.76[a]	23.15 ±1.24[a]	11.07 ±0.55[a]	55.36 ±2.27[a]	515.52 ±58.82[a]
Level of sig.	ns	ns	ns	**	ns	ns
MSD value	1.82	0.71	2.21	0.20	3.93	53.53
CV (%)	8.24	8.97	8.62	8.40	8.75	7.51
T_1	14.05 ±0.41[c]	4.95 ±0.13[e]	13.63 ±0.41[d]	7.02 ±0.28[d]	39.95 ±1.26[d]	20.10 ±0.58[d]
T_2	23.90 ±0.63[b]	7.97 ±0.22[d]	21.00 ±0.93[c]	11.03 ±0.45[c]	51.95 ±1.49[c]	551.10 ±13.55[c]
T_3	24.35 ±0.75[b]	10.05 ±0.30[c]	23.71 ±0.68[bc]	11.63 ±0.46[b]	52.70 ±1.42[c]	625.65 ±15.78[b]
T_4	26.00 ±0.73[b]	11.99 ±0.38[b]	26.08 ±0.74[ab]	11.94 ±0.48[b]	61.00 ±1.74[b]	636.90 ±14.53[b]
T_5	29.15 ±0.81[a]	13.97 ±0.38[a]	28.72 ±0.73[a]	12.87 ±0.48[a]	68.10 ±1.83[a]	712.60 ±18.12[a]
Level of sig.	**	**	**	**	**	**
MSD value	2.85	1.29	2.87	0.46	7.06	54.20
CV (%)	8.24	8.97	8.62	8.40	8.75	7.51
(V*T)	ns	ns	ns	ns	ns	ns

Means in a column that includes the same letters are not statistically different at the 5% level using Tukey's HSD test, MSD = Minimum significant difference, CV = Coefficient of variation, sig.= significance, T1: 0 ppm, T2: 25 ppm, T3: 50 ppm, T4: 75 ppm and T5: 100 ppm of ZnO-NPs. ns indicated non-significant at $p>0.05$, * indicated significant at $p\leq0.05$ and ** indicated significant at $p\leq0.01$, ± standard error mean (n=4) according to ANOVA.

of phosphorus (13.97 g/kg), potassium (28.72 g/kg), boron (68.10 mg/kg), and zinc (712.60 mg/kg) were also observed in the 100 ppm ZnO-NPs treatment (T_5), while the control had the lowest values for these nutrients. Regarding sulfur content, the highest level (12.87 g/kg) was found in plants treated with 75 ppm ZnO-NPs (T_4), 83% higher than in the control group. Ahmed et al. (2023) obtained similar findings with 100 ppm zinc oxide nanoparticles, reporting the highest contents of nitrogen, phosphorus, potassium, sulfur, boron, and zinc.

3.6 Nutrient contents in fruits

The macronutrient content, specifically nitrogen (N), phosphorus (P), potassium (K), and sulfur (S) in the fruits of two tomato varieties was significantly affected by the foliar application of zinc oxide nanoparticles (ZnO-NPs) (Table 7). The highest nitrogen content (25.50 g/kg) was observed with the application of 100 ppm ZnO-NPs (T_5). This result was similar to those obtained with 75 ppm ZnO-NPs (T_4) and 50 ppm ZnO-NPs (T_3). In contrast, the control group (T_1) exhibited the lowest nitrogen content. A similar trend was noted for phosphorus, potassium, and sulfur content. The highest levels were recorded with the 100 ppm ZnO-NPs treatment (T_5), and it was reported that 12.29 g/kg phosphorus, 25.53 g/kg potassium, and 11.14 g/kg sulphur. These values were statistically similar to those from the 75 ppm ZnO-NPs treatment (T_4), while the control group showed the lowest levels. Micronutrient content in the tomato fruits was also significantly influenced by varying levels of zinc oxide nanoparticles (Table 7). The highest zinc content at 52.25 mg/kg was recorded with the 100 ppm ZnO-NPs treatment (T_5), which was significantly greater than other treatments, except for the 75 ppm ZnO-NPs treatment (T_4). The control group had the lowest zinc content at 18.68 mg/kg. Previous studies have indicated that increased application of zinc can lead to higher phosphorus content in tomato leaves and fruits. Additionally, higher zinc levels may influence potassium levels (Islam et al. 2018; Kaya and Higgs 2002; Quddus et al. 2020). Adequate zinc application also enhances boron uptake, helping to mitigate deficiencies (Jabri et al. 2022; Rengel et al. 1998).

3.7 Total Nutrient uptake by plant

A significant difference was observed in the macronutrient content of two tomato varieties following the foliar application of ZnO nanoparticles (ZnO-NPs) (Figure 3a). The maximum nitrogen uptake by the plants measured 7.18 g per plant with the application of 100 ppm ZnO-NPs (T_5), significantly higher than all other treatments. In contrast, the minimum nitrogen uptake of 1.70 g per plant was recorded in the control treatment (T_1). The foliar application of zinc improved nitrogen uptake and accumulation, ultimately increasing plant production (Grzebisz et al. 2008; Jabri

Table 7 Effects of foliar application of zinc oxide nanoparticles on nutrient contents in fruits of tomato varieties

Treatment	Nitrogen (N)	Phosphorus (P)	Potassium (K)	Sulphur(S)	Boron (B)	Zinc (Zn)
	(g/kg)				(mg/kg)	
MT1	21.68 ±0.97^{a}	9.03 ±0.62^{a}	19.83 ±1.16^{a}	9.24 ±0.53^{b}	26.84 ±1.71^{a}	42.65 ±2.86^{a}
MT3	22.34 ±1.05^{a}	9.24 ±0.65^{a}	20.49 ±1.18^{a}	9.57 ±0.53^{a}	27.82 ±1.75^{a}	42.93 ±2.95^{a}
Level of sig.	ns	ns	ns	**	ns	ns
MSD value	1.66	0.89	1.47	0.04	3.00	3.17
CV (%)	8.28	10.37	9.13	8.98	8.50	7.32
T_1	14.00 ±0.37^{c}	5.80 ±0.15^{c}	11.19 ±0.33^{d}	5.35 ±0.21^{d}	13.65 ±0.38^{d}	18.68 ±0.44^{d}
T_2	22.40 ±0.66^{b}	6.36 ±0.16^{c}	19.81 ±0.54^{c}	9.75 ±0.43^{c}	26.80 ±0.77^{c}	45.40 ±1.15^{c}
T_3	23.40 ±0.62^{ab}	9.61 ±0.46^{b}	21.30 ±0.66^{bc}	10.23 ±0.41^{bc}	30.00 ±0.89^{bc}	46.53 ±1.21^{bc}
T_4	24.75 ±0.62^{ab}	11.62 ±0.33^{a}	22.96 ±0.62^{ab}	10.58 ±0.44^{b}	32.20 ±0.93^{ab}	51.10 ±1.20^{ab}
T_5	25.50 ±0.65^{a}	12.29 ±0.33^{a}	25.53 ±0.70^{a}	11.14 ±0.45^{a}	34.00 ±0.96^{a}	52.25 ±1.20^{a}
Level of sig.	**	**	**	**	**	**
MSD value	2.68	1.40	2.64	0.50	3.42	4.62
CV (%)	8.28	10.37	9.13	8.98	8.50	7.32
(V*T)	ns	ns	ns	ns	ns	ns

Means in a column that includes the same letters are not statistically different at the 5% level using Tukey's HSD test, MSD = Minimum significant difference, CV = Coefficient of variation, sig.= significance, T_1: 0 ppm, T_2: 25 ppm, T_3: 50 ppm, T_4: 75 ppm and T_5: 100 ppm of ZnO-NPs. ns indicated non-significant at $p>0.05$, * indicated significant at $p\leq0.05$ and ** indicated significant at $p\leq0.01$, ± standard error mean (n=4) according to ANOVA.

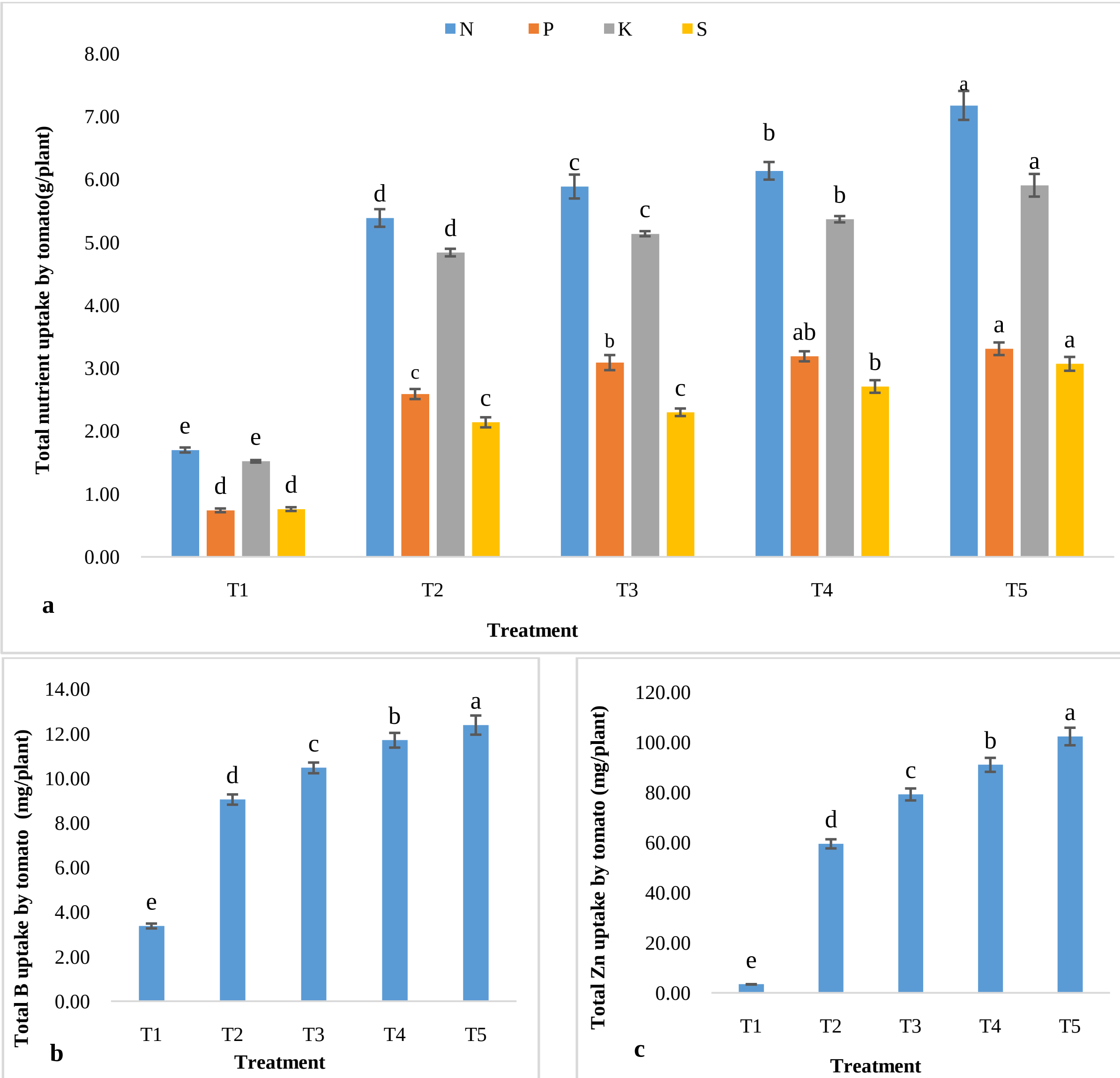

Figure 3 Effects of zinc oxide nanoparticles on (a) total uptake of N, P, K, S, (b) total B uptake, and (c) total Zn uptake by tomato, Error bar represents the ±standard error mean (n=4). Mean values on the bar followed by a different letter (s) are significantly different from each other at a 5% level of significance by Tukey's HSD test, T_1: 0 ppm, T_2: 25 ppm, T_3: 50 ppm, T_4: 75 ppm and T_5: 100 ppm of ZnO-NPs.

et al. 2022). Regarding phosphorus uptake, the highest level was also found in the 100 ppm ZnO-NPs treatment (T_5), and it was reported at 3.31 g per plant, similar to the 75 ppm ZnO-NPs treatment (T_4). The lowest phosphorus uptake (0.74 g per plant) was noted in the control treatment (T_1). Similarly, the highest total potassium and sulfur uptake was seen in the T_5 treatment (100 ppm ZnO-NPs), with values significantly different from all other treatments, while the control group (T_1) exhibited the lowest results. The highest boron uptake of 12.39 mg per plant also occurred in the T_5 treatment (100 ppm ZnO-NPs) and was significantly higher than all other treatments, with the control group again showing the lowest uptake. Additionally, zinc uptake peaked in the T5 treatment at 102.34 mg per plant, significantly different from the other treatments. The lowest zinc uptake (1.32 mg per plant) was recorded in the control (T_1). Ahmed et al. (2023) similarly reported the highest uptake of zinc and boron from applying 100 ppm ZnO-NPs to tomatoes.

3.8 Apparent zinc recovery efficiency of tomato

Tomatoes' apparent zinc recovery efficiency was affected by the foliar application of zinc oxide nanoparticles (ZnO-NPs) (Figure 4). Applying 75 ppm ZnO-NPs (T_4) resulted in the highest apparent zinc recovery efficiency at 7.05%, while the treatment

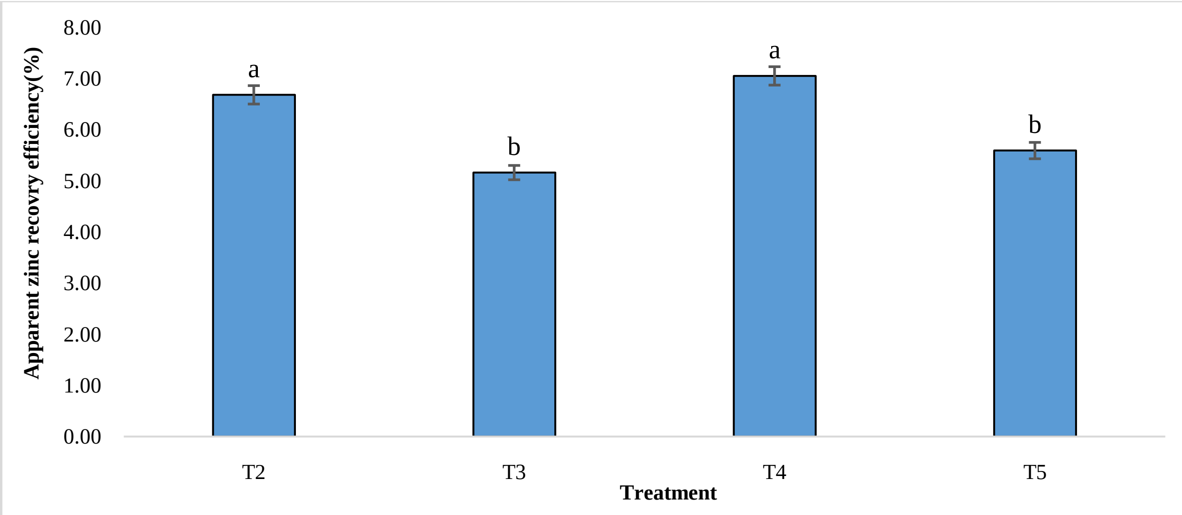

Figure 4 Effect of zinc oxide nanoparticles on apparent zinc recovery efficiency of tomato, error bar represents the ±standard error mean (n=4), Mean values on bar followed by uncommon letter (s) are significantly different from each other at 5% level of significance by Tukey's HSD test, T_1: 0 ppm, T_2: 25 ppm, T_3: 50 ppm, T_4: 75 ppm and T_5: 100 ppm of ZnO-NPs.

Table 8 Effect of different doses of zinc oxide nanoparticles on the cost and return of tomato

Treatment	Gross return (US Dollar/ha)	Total variable cost (US Dollar/ha)	Gross margin (US Dollar/ha)	Benefit-cost ratio(BCR)	% increased of BCR over control
T_1	20,796	17,045	3,751	1.22	-
T_2	35,436	17,545	17,891	2.02	65.57
T_3	51,816	18,045	33,771	2.87	135.25
T_4	55,800	18,545	37,255	3.01	146.72
T_5	64,620	19,045	45,575	3.39	177.87

T_1: 0 ppm, T_2: 25 ppm, T_3: 50 ppm, T_4: 75 ppm and T_5: 100 ppm of ZnO-NPs, Output: Price of fresh tomato fruit = 1.2 dollar/kg, Input: Seed price = 300 dollar/kg, cost of other fertilizer = 650 $, total cost for seed germination tray = 595 $/ha, price of bio soil + peat moss = 600 $/ha, price of coco peat = 125 dollar/ton (total need 60 ton), total cost of Poly bag = 1200 $/ha, Labour cost =1200 $/ha, price of plastic stick= 5000 $/ha, price of zinc oxide nanoparticles = 1000 US dollar/kg, 1 US dollar = 4.16 Ringgit (Malaysian currency), Fresh tomato price was considered based on current farm gate price.

with 50 ppm ZnO-NPs (T_3) yielded the lowest efficiency. As the supply of nutrients like zinc increases, nutrient usage efficiency often decreases (Saleem et al. 2022; Elia and Conversa 2012). Biological factors and varying nutrient recovery rates may influence tomatoes' absorption capacity for nutrients. Several factors significantly affect crop productivity, including seasonal variability, the growing environment, and fertilizer management practices. These factors can interact in complex ways, leading to apparent nutrient recovery efficiency inconsistencies. Consequently, the amount of fertilizer applied to a crop does not always result in increased yields. Other elements, such as weather conditions, soil type, and the timing and method of fertilizer application, also play crucial roles in determining how much of the applied nutrients are absorbed and utilized by the plants. This variability in nutrient recovery efficiency underscores the importance of considering multiple factors when deciding fertilizer management practices (Baligar et al. 2001). The high apparent zinc recovery efficiency observed in tomatoes at 75 ppm ZnO-NPs is attributed to increased zinc absorption. However, it is necessary to acknowledge that nutrient use efficiency (NUE) in crops can be influenced by various factors, including environmental conditions and the fertilizer application rate, as demonstrated by Quddus et al. (2022b).

3.9 Cost and return analysis

Cost and return analysis is a crucial factor in determining farmers' technology adoption, as Maroušek and Maroušková (2021) emphasized. The foliar application of 100 ppm ZnO nanoparticles (T_5) yielded the highest gross return of US$64,620 per hectare, followed by the application of 75 ppm ZnO nanoparticles (T_4) (Table 8). This gross return was 211% higher than the control treatment (T_1). Additionally, the benefit-cost ratio of 3.39 achieved with the 100 ppm ZnO nanoparticles application was 177.78%

higher than that of the control. The observed increase in gross return and the favourable benefit-cost ratio can likely be attributed to the positive effects of the ZnO nanoparticles application, although the exact mechanisms remain unidentified.

Conclusion

The foliar application of zinc oxide nanoparticles (ZnO-NPs) has shown significant positive effects on tomato plants' growth, yield, quality, and nutrient uptake. The experiment indicated that applying 100 ppm of ZnO-NPs resulted in the highest values for key growth and yield parameters, such as the number of primary branches, leaf area, photosynthetic rate, fruit size, number of fruits per plant, and overall fruit yield. Additionally, this treatment led to increased nutrient content and enhanced nutrient uptake. The nutritional quality of tomato fruit, including ascorbic acid levels, was most positively impacted by the 100 ppm ZnO-NPs application. This treatment also resulted in a better benefit-to-cost ratio. Moreover, the MARDI Tomato-3 (MT3) variety outperformed MARDI Tomato-1 (MT1) in most of the evaluated parameters. These findings suggest that a concentration of 100 ppm ZnO-NPs is optimal for improving both the productivity and quality of tomatoes and providing a potential alternative to excessive chemical fertilizer use. This approach could help minimize environmental impacts and contribute to food security and nutritional enhancement. Further research is necessary to investigate the effects of higher doses of ZnO-NPs on tomato fruit yield to determine the optimal dosage for maximizing production.

Author Contributions

Conceptualization, R.A., M.K.U., M.A.Q., and M.A.M.H.; methodology, R.A., M.A.Q., M.K.U. and M.A.M.H.; formal analysis, R.A., M.K.U. and M.A.Q.; data curation: R.A. and M.A.Q.; statistical analysis, R.A., M.A.Q. and M.K.U.; writing—original draft preparation, R.A. and M.A.Q.; writing—review and editing, M.K.U., M.A.Q. and M.A.M.H.; visualization: R.A., M.A.M.H. and M.A.Q.; supervision, M.K.U., M.A.Q. and M.A.M.H. All authors have read and agreed to the published version of the manuscript.

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Conflict of interest

The authors have no conflict of interest.

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