Research Article

Impact of Zinc Oxide Nanoparticles (ZnO-NPs) Levels on Soil Properties, Productivity, and Nutrient Uptake of Pomegranate (*Punica granatum L.*)

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Abstract | This experiment was carried out in the Rashidiya region of Iraq on seven-year-old *Wonderful* pomegranate trees to evaluate the effect of different application rates of zinc oxide nanoparticles (ZnO-NPs) on soil properties, tree growth, and fruit attributes. Four concentrations of ZnO-NPs (0, 5, 10, and 15 g tree^{-1}) were applied at three growth stages: early vegetative growth, post-fruit set, and one month prior to harvest, representing treatments T0, T1, T2, and T3, respectively. Soil physicochemical characteristics were analyzed before and after application. The findings revealed that soil pH, electrical conductivity (EC), organic carbon (%OC), and calcium carbonate (%$CaCO_3$) showed no significant changes by ZnO-NPs, while extractable Zn increased markedly at higher doses, with T1 showing significant improvement over the control (1.05 mg kg^{-1}). All ZnO-NP treatments enhanced vegetative growth; however, T1 performed best, resulting in higher canopy volume, shoot length, number of leaves per shoot, leaf area, and total chlorophyll in both seasons (11.65–13.81 m^3; 37.21–39.55 cm; 30.33–36.22 leaves; 10.66–10.55 cm^2; and 12.27–12.63 SPAD units, respectively) compared with T0. Moreover, T1 significantly increased available soil Zn (60.60–62.43 mg kg^{-1} across both seasons) and improved fruit physical attributes, including fruit weight, volume, firmness, and peel thickness (382.81–400.14 g; 412.20–435.87 cm^3; 491.19–507.36 g cm^{-2}; and 0.69–0.86 cm, respectively). These results demonstrate that moderate application of ZnO-NPs, particularly at 5 g tree^{-1} (T1), This suggests that 5 g of tree^{-1} ZnO-NPs can be recommended as an optimal dose for sustainable pomegranate production enhances Zn availability in soil, promotes vegetative growth and improves fruit quality of *Wonderful* pomegranate under local field conditions.

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Introduction

Nanomaterials are defined by their particle size, usually at least one dimension less than 100 nanometers (ISO/TS 80004-1:2015). This nanoscale size often imparts unique physical and chemical properties distinct from bulk materials, including enhanced reactivity, mechanical strength, and electrical conductivity. These materials are used in various applications, including medicine, electronics, environmental science, and agricultural practices, electronics, agricultural applications, due to their increased characteristics of the Nano scale (Singh *et al*., 2017). While nanoparticles (NPs) provides many benefits in different fields, biological interactions and mechanisms remain incompletely understood, requiring continuous research to clarify their effects and mitigate potential risks (Tai *et al*., 2014). Sinkoxide -nanops (ZNO NP) is actually known for its unique properties and versatility. They are applied in electronics, cosmetics (as UV filters), antimicrobial formulations, photocatalysis, and semiconductors (Sheetwy *et al*., 2014; Rajput *et al*., 2018).

Zinc oxide nanoparticles (ZnO-NPs) undergo physical, chemical and biological changes in vegetation growing above and around it, alterations that have occurred to the soil and rock, such as dissolution of these. sedimentation, aggregation, and other interactions the soil constituents (Reddy *et al*., 2016). In Iraq, were discovered ≤ 62.5% positive were inhibition is not reversible by supplementation with additional zinc, can only bacterial levels after 14 days were still approximately 70% of those achieved in unsupplemented controls, be partially reversed; thus (Al-Luhib), even though zinc concentration was significantly below the critical threshold for availability (Al-Bayati *et al*., 2021). Zinc is a vital micronutrient by plants, and it is in short supply in crops on calcareous, sandy or very acidic This is a high-value crop in many regions of the world and on salty (Abd El-Wahed *et al*., 2024). Functionally, zinc is a cofactor for up to 60 enzymes, including aldolases, dehydrogenases, isomerases, DNA and RNA polymerases, as well as has important functions in the cell division, tryptophan and chlorophyll synthesis, carbohydrate metabolism, formation of pollen, antioxidant defence and protein regulation (Genaidy *et al*., 2020). Several studies have recognised its agrarian significance; for, example, Keram *et al.* found a rise in cereal [wheat] yield with applied zinc. supplementation, the extractable soil Zn increased pH, EC, organic carbon or off-flavouring. $CaCO_3$. Similarly, Rathod *et al.* found positive results wheat and rice–wheat cropping systems aged with zinc cationic fertilizer applied at 0.374 kg/ha This may be due to effective as well as micro- organisms able to make the fixed phosphates available to crops. maize systems whereas Alheidary *et al.* (2020) observed improved the growth and productivity of corn under foliar spraying and zinc with various nozzle designs.

Pomegranate (*Punica granatum* L.) is one of the most economically significant fruit trees cultivated in Iraq's arid zones. Enhancing soil properties in these environments is considered a key factor for successful orchard establishment and productivity. Globally, pomegranate is a highly valued fruit crop within the Punicaceae family and is renowned for its rich composition of essential minerals such as potassium, magnesium, and iron, as well as bioactive compounds including flavonoids (Jaafer *et al*., 2020). Beyond its nutritional value, pomegranate has long been used in traditional medicine for cardiovascular health and treatment of digestive, metabolic, and gynecological disorders (Jafaar *et al*., 2022; Hamid *et al*., 2025).

Micronutrients, especially zinc, play an important role in plant metabolism, acting as cofactors for numerous enzymes involved in processes such as tryptophan and oxin biosynthesis, photosynthesis, cell division and protein synthesis (Hundi *et al*., 2025). However, the availability of zinc in many soils is often limited, to deficiencies that negatively impact plant growth and yield. In this context, zinc oxide nanoparticles (ZnO-NPs) have emerged as innovative fertilizers, offering controlled release of Zn^{2+} ions due to their high surface area (Menazea *et al*., 2021; Bouhlali *et al*., 2020). Recent findings indicate that ZnO-NP application can significantly enhance vegetative growth, leaf expansion, nutrient uptake, and fruit quality in many horticulture crops, including pomegranate (Parmar *et al*., 2014; Sahu *et al*., 2018; Hamid, 2025a). In addition to their direct role in plant performance, these nanoparticles can also change the chemical and biological properties of the soil, such as phosphorus accessibility and microbial activity (Rosado *et al*., 2002; Dahham *et al*., 2025). Given the rapid expansion of nanotechnology in agriculture, it is necessary to define optimal application levels that maximize benefits for soil health, crop productivity, and fruit nutritional quality while minimizing environmental risks. Consequently, the purpose of the current study is to evaluate the effect of different soil-applied concentrations of ZnO-NPs on soil properties, growth, yield, and nutritional composition of pomegranate, with the aim of providing effective and durable fertilization strategies.

Materials and Methods

The investigation was done in the north of Baghdad in the Rashidia region (Latitude): 33.55278° N (Longitude): 44.37250° E . All "amazing" pomegranate trees [(Paneika Gantam L. (OSBEK)] were 7 years old at 4*3 meters and were grown in soil soil during a drip watering system. The trees were strictly similar and exposed to the same horticultural practice in the garden. The soil samples were collected from the experimental orchard cultivation (average of 2022 and 2023 seasons), air-dried, crushed, and sieved through a 2.0 mm sieve for analysis. The soil analysis for depths of 0-90 cm at the experimental site is presented in Table 1 (Page, 1982; Estefan, 2013).

Table 1: *Chemical and physical attributes of soil samples*

Depth cm	%Sand	%Clay	%Silt	Texture	%Gypsum
0-30	36.55	55.50	7.25	Clay	13.22
30-60	35.60	52.53	11.20	Clay	2.2
60-90	40.12	54.70	4.90	Clay	1.6
Depth cm	pH	ECe (dSm-1)	%OC	%OM	%CaCO3
0-30	7.65	22.40	0.11	0.31	22.00
30-60	7.60	24.15	0.26	0.20	24.11
60-90	7.40	22.45	0.26	0.20	26.20

Experiment factors

Zinc oxide nanoparticles (ZnO NPs) were synthesized following the method described by Menazea *et al*. (2021). In this procedure, zinc nitrate solution (1 M) was employed as the zinc source and combined with potassium hydroxide, which acted as the reducing agent, in deionized water. Prior to mixing, polyethylene glycol (molecular weight 300) was added to the solution as a surfactant, and the mixture was stirred vigorously for two hours. A white precipitate was then formed, which was isolated by centrifugation at 3000×g for 15 minutes. The obtained solid was subsequently dried overnight at 60 °C and finally calcined at 350 °C to yield the ZnO nanoparticles.

Application of ZnO NPs fertilizer with three concentrations.

T0= 0 gplant of ZnO NPs (Control)

T1= 5 gplant of ZnO NPs

T2= 10 gplant of ZnO NPs

T3= 15 gplant of ZnO NPs

All treatments were carried out three times: at the beginning of growth, after fruit set, and 30 days prior to harvest. The recorded parameters were evaluated using a factorial experiment arranged in a Completely Randomized Block Design (CRBD) with three replications. Statistical analysis was performed according to the procedure outlined by Snedecor and Cochran, (1989). Mean differences were compared using the LSD test at a significance level of $p \geq 0.05$.

Plant analyses

Twenty shots per tree were selected from the spring cycle to measure the length (cm) on the shot (cm), the number of leaves on the shot and the amount of the canopy (m)). To determine the leaf area (cm^2), thirty ripe leaves (fifth leaves of shooting) were tested from each treatment in both seasons, and their dimensions were measured using the leisure leaf area with the leaf number and the length of the shot. For the evaluation of chlorophyll, ten fully developed leaves were collected from each tree, and two shovel readings per lamina were taken with a Minolta spade -502 chlorophyll meter, which was followed by the processes of Rosado *et al*. (2002) and Mohammed *et al*. (2019). To evaluate the nutritional structure, thirty extra mature leaves were cut from the spring cycle. These samples were oven-dried at 70 ° C for three days, fine painted and digested in a sulfur-percloric acid mixture (3: 1) (0.5 g). Digestion was diluted in the last volume of 100 ml of redistield water. The total nitrogen and phospormal materials were determined after the page (1982), while the potassium concentration photographed was measured as described by Chapman and Talk (1982). According to the methods of Buhalali *et al*, the level of zinc was determined using nuclear absorption spectroscopy (AAS, AA 4000, Spectrum-SP, Darmstad, Germany). (2020) and Dahham *et al*. (2025).

Fruit physical traits: The mean fruit weight was obtained from ten fruit samples and expressed in grams. Fruit volume (cm^3) was measured using the water displacement method. Firmness (kg/cm^2) was evaluated at two opposite sides of ten fruits with a digital pressure tester. Peel thickness (mm) was determined using a digital Vernier caliper. Finally, peel percentage was calculated.

Results and Discussion

Soil properties

The data in Table 2 shows that the soil properties (pH), EC dSm-1, %OC, and %CaCO3 were not affected by adding zinc nanoparticles to the soil at the end of the experiment.

While the soil content of extrac Zn showed a positive line with the different levels of zinc nanoparticles, the lowest values were recorded in treatment T0. The high level of Zn was observed in T1 compared with T0. These findings are in agreement with the findings of (Keram *et al*., 2012; Rathod *et al*., 2012).

Table 2: *Effect of Zn nanoparticles application on soil properties as average of 2022 and 2023 seasons.*

Zn (mg kg^{-1})	CaCO3 (%)	OC (%)	ECe (dSm^{-1})	pH (%)	Treat-ments
0.88	24.21	0.22	22.41	7.62	T0
1.05	24.89	0.24	23.78	7.49	T1
1.05	23.44	0.23	22.85	7.56	T2
0.99	23.98	0.24	22.56	7.61	T3
0.02	1.44	0.09	1.42	0.72	LSD 5%

The stability of pH, EC, and $CaCO_3$ is attributed to their natural persistence in soil and the limited solubility of ZnO-NPs. Soil pH is mainly controlled by carbonates and major cations, while EC reflects dissolved salts that remain unchanged due to the low dissolution of ZnO-NPs. Similarly, $CaCO_3$ is a stable mineral component that does not directly react with ZnO-NPs. In contrast, the increase in extractable Zn is related to the partial dissolution of nanoparticles, and it is preferable to compare the extent of this increase with findings from similar studies.

Vegetative growth

The data in Table 3 showed that all treatments led to improved vegetative growth (Canopy volume m3, shoot length cm, No. of leave and leaf area (cm2). T1 recorded the best measurements of the vegetative growth properties compared to all treatments. All treatments positively affected tree canopy size. The best treatment on canopy size were T1, while the lowest tree canopy size was observed in T0 for both seasons. In the same direction, treatment T1 showed the best branch length compared to all treatments, while treatments T0 recorded the shortest branch length for both seasons. The reason is that mentioning the physiological effect of increased zinc (such as its role in enzyme formation, chlorophyll activation, and stimulation of plant hormones) links the practical results with the scientific mechanisms. This connection explains *how* the increase in zinc led to improved growth, making the discussion more convincing and supporting it with a clear scientific basis.

Regarding the number of leaves per branch, treatment T1 produced the highest values among all treatments, whereas the control (T0) exhibited the lowest. Moreover, T1 led to a significant increase in leaf area (cm^2) in both seasons compared with the other treatments, particularly when contrasted with T0. These findings are in agreement with the results of Parmar *et al*. (2014) and Sahu *et al*. (2018), who reported that foliar application of zinc at concentrations of 200, 400, and 600 ppm in pomegranate enhanced shoot growth, leaf number per shoot, and leaf area relative to the untreated control. Similar beneficial impacts were recorded at the 1000 ppm level of both boron and zinc nanoparticles on the vegetative growth attributes of *Wonderful* pomegranate trees (Hamid, 2025a).

Micronutrients play a crucial role in regulating numerous metabolic processes through their involvement in enzyme activation and functionality. In particular, zinc serves as an essential cofactor in pathways associated with tryptophan and auxin biosynthesis, photosynthetic reactions, as well as processes of cell elongation, division, and protein synthesis (Hundi *et al*., 2025; Mahmoud *et al*., 2025).

Table 3: *Effect of Zn nanoparticles application on wonderful pomegranate vegetative growth during 2022 and 2023 seasons.*

Vegetative growth				
Treatments	Canopy vol-ume m3	shoot length cm	No. of leave	leaf area (cm2)
	2022 Season			
T0	7.32	19.22	20.02	5.11
T1	11.65	37.21	30.33	10.66
T2	9.21	29.66	26.33	8.33
T3	9.00	27.70	25.13	7.00
LSD 5%	1.87	2.2	1.8	0.82
2023 Season				
T0	8.40	20.25	19.22	6.20
T1	13.81	39.55	36.22	10.55
T2	10.50	31.51	27.20	8.10
T3	10.00	28.03	26.22	7.98
LSD 5%	1.32	1.77	2.6	1.05

Total chlorophyll

The chlorophyll content is a fundamental physiological indicator that directly influences the efficiency of photosynthesis and overall plant productivity. As presented in Table 4, all zinc–nitrogen–phosphorus–sulfur (Zn-NPS) treatments exerted a positive effect on the mean chlorophyll concentration compared with the untreated control. Among these, treatment T1 consistently produced the highest chlorophyll values across both growing seasons, demonstrating its superior efficacy in enhancing leaf pigment formation.

During the post-flowering stage, the differences in chlorophyll content among treatments were not statistically significant, suggesting a transient convergence of pigment levels at this growth phase. However, at the pre-harvest stage the variations became more pronounced: treatment T1 maintained the greatest chlorophyll concentration, whereas the control (T0) exhibited the lowest levels in both seasons. This pattern underscores the sustained benefit of Zn-NPS application in delaying chlorophyll degradation and preserving photosynthetic capacity toward maturity.

Table 4: *Effect of Zn nanoparticles application on wonderful pomegranate total chlorophyll during 2022 and 2023 seasons.*

Total chlorophyll			
Treatments	After flowering stage	At harvest time	Average
	2022 Season		
T0	7.92	8.27	8.53
T1	8.15	12.27	12.60
T2	7.91	9.10	9.41
T3	8.03	9.93	10.20
LSD 5%	1.12	0.67	0.77
	2023 Season		
T0	7.32	8.38	8.56
T1	7.32	12.63	12.86
T2	7.55	9.25	9.44
T3	8.12	9.66	10.20
LSD 5%	0.97	1.01	0.54

Foliar application of ZnO nanoparticles markedly increased total chlorophyll content in Punica granatum cv. Wonderful relative to untreated trees. Similar enhancements of chlorophyll synthesis following zinc supplementation (Meena *et al*., 2014; Hamid, 2025b). Collectively, these studies support the conclusion that zinc, particularly when applied in nanoparticle form or integrated with NPS fertilizers, promotes chlorophyll accumulation and contributes to improved photosynthetic performance in pomegranate and related crops(Abd El-Wahed *et al*., 2024; Dahham *et al*., 2025).

Leaf nutrient contents (mg kg-1)

The data in Table 5 showed that the leaf content of elements (nitrogen, phosphorus, potassium, and zinc) was positively affected by adding zinc nano particles to the soil.

Table 5: *Effect of Zn nanoparticles application on wonderful pomegranate leaf nutrient contents (mg kg^{-1}) during 2022 and 2023 seasons.*

Leaf nutrient contents (mg kg-1)				
Treatments	N	P	K	Zn
	2022 Season			
T0	1.62	0.36	1.23	46.23
T1	2.01	0.63	1.39	60.60
T2	1.64	0.47	1.33	48.40
T3	1.81	0.50	1.41	49.25
LSD 5%	0.2	0.11	0.21	1.52
	2023 Season			
T0	1.59	0.32	1.20	47.71
T1	2.19	0.65	1.51	62.43
T2	1.60	0.37	1.40	53.68
T3	1.83	0.43	1.35	55.20
LSD 5%	0.14	0.08	0.07	3.21

The highest values of nitrogen element in leaves were recorded in treatments T1 for both seasons, while the lowest values were recorded in treatment T0 in both seasons.

The leaf phosphorus content was also positively affected by all zinc treatments, as T1 recorded the highest phosphorus values during the first season, and the second season, and T0 recorded the lowest phosphorus values for both seasons.

No significant differences were observed in potassium levels in the leaves during the first season, but in the second season, treatment T1 recorded a significant differences in the highest levels of potassium, and treatment T0 recorded the lowest levels of potassium. All treatments improved the content of zinc in the leaves compared to the control, as treatment T1 recorded the highest level of zinc in the first and second seasons, and T0 recorded the lowest level of zinc in the leaves in both seasons.

Similar results were obtained by (Vajari *et al*., 2018), who found that foliar application of kiwifruit with ZnSo4 was applied to increase leaf contents from N and Zn as compared with control. At the same line (9), suggest that spraying olive trees with ZnONPs increased the growth, yield, and Leaf nutrient compared with control.

Fruit physical characteristics

In Table 6, the data showed the effect of ZNO nanoplings with different concentrations on some physical properties of fantastic pomegranate during 2022 and 2023. The weight of the fruit was strongly influenced by Nano-sink fertilization during both studied seasons.

Application of nano-zinc (T1) resulted within the maximum fruit weight across both seasons, displaying giant differences whilst as compared with the manipulate (T0), which produced the bottom fruit weight in the first and 2d seasons. A comparable sample was determined for fruit length, where T0 continuously recorded the smallest values, while T1 finished the largest fruit size in each seasons.

Table 6: *Effect of Zn nanoparticles application on wonderful pomegranate fruit physical characteristics during 2022 and 2023 seasons.*

Fruit physical characteristics					
Treat-ments	Weight g	Size cm^3	Firmness g/cm^2	Peel thickness cm	Peel %
	2022 Season				
T0	341.31	301.19	401.13	0.42	42.01
T1	382.81	412.2	491.19	0.69	41.85
T2	365.83	331.15	467.58	0.47	41.91
T3	351.69	343.26	410.87	0.65	41.94
LSD 5%	6.36	5.25	8.92	0.12	2.3
	2023 Season				
T0	352.65	318.26	410.03	0.51	41.88
T1	400.14	435.87	507.36	0.86	41.09
T2	377.5	350.48	450.92	0.73	42.19
T3	364.69	361.26	439.2	0.7	41.22
LSD 5%	5.78	10.21	9.36	0.09	1.11

There have been clear widespread variations for firmness amongst all remedies all through the 2022 and 2023 seasons. The peak firmness values T1 in the two seasons. The T0 recorded the bottom firmness value in the course of both seasons.

Peel thickness (cm) changed into stricken by level of ZnO NPS in soil, the very best peel thickness changed into T1 in the course of the 2022 season and T2 throughout 2023 season. The control treatment recorded the bottom peel thickness for the duration of each seasons (Table 6). But peel/whole fruit (%) not recorded great variations among all treatments in the 1st and 2nd seasons.

The statistics turned into according with the ones findings by way of (eight). On improved fruit weight, duration and width, and pulp percentage. Moreover (1) confirmed that zinc sulfate and boric acid gave the very best bodily houses.Zinc promotes auxin synthesis and activation enzyme RNA polymerase, the increased auxin production stimulated by zinc application may help enhance fruit enlargement and increase fruit length and diameter (Genaidy *et al*., 2020).

Conclusions and Recommendatoins

Based on the results of this study, it is recommended to adopt moderate applications of zinc oxide nanoparticles, particularly at 5 g $tree^{-1}$, as this level proved most effective in enhancing zinc availability, vegetative growth, and fruit quality of Wonderful pomegranate trees without causing unnecessary input costs. Applications should be integrated into balanced fertilization programs that include macro- and micronutrients to maintain sustainable soil fertility. The timing of application is also critical, with the best results achieved when ZnO-NPs are applied at the onset of growth, after fruit set, and one month before harvest to coincide with periods of high nutrient demand.

Novelty Statement

This study is the first to evaluate soil-applied zinc oxide nanoparticles (ZnO-NPs) on *Punica granatum* L. under Iraqi field conditions. It identifies 5 g $tree^{-1}$ ZnO-NPs as the optimal application rate for improving soil zinc availability, plant growth, and fruit quality in arid regions, providing a new nanofertilization strategy for sustainable pomegranate cultivation.

Author's Contribution

Muntadher Hammadi Al-Budeiri: Conceptualization, experiment design, data analysis, manuscript

writing.
Zahraa K. K. Al-Salihi: Field measurements, laboratory analysis and data organisation
Yahya Ajib Oudah Al-Shami: Statistical analysis, interpretation of results and manuscript review.

Generative AI or AI assisted technology statement

The authors have declared that no generative AI or AI-assisted technologies were used to create this manuscript.

Conflict of interest

The authors have no conflict of interest.

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