Journal of Applied Horticulture, 28(2): 552-558, 2026
https://doi.org/10.37855/jah.2026.v28i02.86
Journal of Applied Horticulture
ISSN: 0972-1045

The impact of foliar spraying with ZnO NPs fertilizer on the growth and yield of three cucumber hybrids planted in plastic houses

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Abstract

The experiment was carried out in a plastic house located in the Al-Azawiyah area of Babylon Province to evaluate the growth and yield of three cucumber hybrids: Grow Imp. F1, Princestar RZ F1, and Wazir F1. The plants were sprayed with zinc oxide nanoparticles (ZnO NPs, 20-50 nm) at four suspension concentrations (0, 2, 4, and 6 mg L^{-1} based on total ZnO mass, corresponding to 0, 1.61, 3.21, and 4.82 mg L^{-1} elemental Zn equivalent) during the 2025 growing season. The study followed a factorial experiment within a randomized complete block design (RCBD) with three replications. ANOVA indicated significant effects of hybrid, ZnO NPs concentration, and their interaction on measured growth and yield traits ($P < 0.05$ *to* $P < 0.001$). Grow Imp. F1 demonstrated superior vegetative growth, recording significantly higher plant height (262.86 cm), number of leaves (leaves $plant^{-1}$) (59.71 leaves), leaf area (8402 cm^2 $plant^{-1}$), and vegetative dry weight (35.42 g). Conversely, Wazir F1 exhibited superior reproductive performance, producing significantly higher fruit length (15.75 cm), number of fruits (35.13 fruits $plant^{-1}$), fruit weight (107.26 g), and total yield per plant (3.779 kg) compared to the other hybrids. All vegetative growth traits, fruit characteristics, and yield parameters were significantly higher with foliar application at 6 mg L^{-1} of ZnO NPs as compared to the control treatment. The interaction showed that Grow Imp. F1 at 6 mg L^{-1} achieved the maximum vegetative growth parameters (plant height 303.87 cm, 69.42 leaves $plant^{-1}$, leaf area 9414 cm^2 $plant^{-1}$, and shoot dry weight 47.33 g). In contrast, Wazir F1 at 6 mg L^{-1} recorded the highest reproductive output (fruit length 17.33 cm, 40.97 fruits $plant^{-1}$, fruit weight 111.20 g, and total yield per plant of 4.556 kg).

Key words: Cucumber, *Cucumis sativus* L., ZnO NPs, plastic houses, hybrids

Introduction

Cucumber (*Cucumis sativus* L.) is an important vegetable crop of the Cucurbitaceae family. It is consumed fresh or processed as pickles. In Iraq, cucumber is widely cultivated for its economic and nutritional values and used in salads and different dishes. Cucumber is grown under open-field and protected conditions (especially in plastic houses), and production in Iraq was 2607.4 kg $dunum^{-1}$ in 2023 (Central Statistical Organization, 2023).

Judicious nutrient management is essential to maintain cucumber growth and productivity, especially in protected cultivation. Foliar fertilisation is an effective way to apply nutrients directly to plant tissues and can help address nutrient fixation and low availability in the soil. This is especially important in alkaline soils where nutrients may be precipitated, adsorbed, oxidised or incorporated into compounds which reduce their availability to plant roots (Abu Dhahi, 2002). Zinc (Zn) is an essential micronutrient that plays a key role in enzymatic activities, auxin synthesis, protein formation, and photosynthetic efficiency (Broadley *et al*., 2012). Zinc fertilisation has been found to increase Zn concentration and uptake and improve crop productivity, including chilli yield (Rajendiran *et al*., 2024).

The development of nano-fertilizers offers a promising strategy to enhance nutrient-use efficiency and minimize the ecological drawbacks of over-applying conventional agrochemicals (Chhipa, 2017; Al-Shahbani *et al.,* 2026). Recent mechanistic reviews demonstrate that foliar uptake of metallic nanoparticles proceeds primarily through cuticular micropores and stomatal pathways, facilitating targeted cellular delivery (Hong *et al.,* 2021). Foliar application of zinc oxide nanoparticles (ZnO NPs) may potentially enhance Zn availability, cuticular penetration, and uptake efficiency compared to conventional ionic salts and chelated fertilizers due to its high surface-area-to-volume ratio and distinct physical properties (García-López *et al.,* 2019; Ahmed *et al.,* 2023b; Shahein *et al.,* 2025). Foliar application of nano-zinc, alone or combined with biofertilizers or nano-iron, has been reported to improve plant growth, fruit number, fruit weight, and nutrient availability in tomato (Hashim *et al.,* 2026). Similarly, ZnO NPs have been reported to improve plant height, leaf area, chlorophyll content, fruit characteristics and yield of tomato under greenhouse conditions (Ahmed *et al*., 2023a). Hussein and Khalaf (2022) evaluated higher application rates up to 150 mg L^{-1} of ZnO NPs in combination with methionine, observing distinct vegetative and reproductive responses in greenhouse cucumber. Foliar application of nano-calcium and nano-silicon was also found to enhance vegetative growth, nutrient accumulation, fruit characteristics and total fruit weight of cucumber grown in plastic houses (Mahdy *et al*., 2024).

The choice of hybrid is as important for cucumber growth and yield as nutrient management. Vegetative growth, fruit characteristics and productivity may differ considerably among hybrids. Karima produced greater plant height, leaf number and

vegetative dry matter than Grass, while Grass produced longer and heavier fruits and higher yield per plant (Hussein and Atallah, 2017). Hussein and Mohammed (2023) also noted significant differences among cucumber hybrids, with Super Faris showing better vegetative growth, while Jamila produced longer and heavier fruits and a higher yield per plant. The results suggest that cucumber hybrids can respond differently to nutritional treatments and that the interaction between hybrid and fertilisation is an important factor to consider for improving production.

The alkaline and calcareous soils typical of central Iraq severely restrict Zn availability (DTPA-extractable Zn < 0.80 mg kg^{-1}), primarily due to elevated pH, high calcium carbonate content, and strong fixation mechanisms (Al-Kaysi, 2000; Rasheed *et al.,* 2017), necessitating targeted foliar interventions to maintain crop productivity. While elevated concentrations of ZnO NPs have previously been reported to induce phytotoxicity and early growth inhibition in crop plants (Lin and Xing, 2007), recent studies highlight that plant physiological responses are strongly dose-dependent (Gohar *et al.,* 2024). Evaluating lower, economically viable concentrations (0, 2, 4, and 6 mg L^{-1}) is therefore critical to optimize biological performance while minimizing cellular residue and potential ecotoxicological risks (Kah *et al.,* 2018). Furthermore, selecting the commercial hybrids Grow Imp. F1, Princestar RZ F1, and Wazir F1 provides an essential comparison across genotypes with contrasting vegetative vigor and reproductive yield potentials. Therefore, this study aimed to evaluate the impact of low-dose ZnO nanoparticle foliar sprays on the growth, yield components, and partial economic returns of these three cucumber hybrids under plastic-house conditions.

Materials and methods

The study was carried out in a non-heated plastic house under standard greenhouse conditions in the Al-Azawiya region, northern Babylon Province, Iraq, during the spring season of 2025. The experiment comprised twelve treatment combinations involving three cucumber hybrids (Factor A: Grow Imp. F1, Princestar RZ F1, and Wazir F1) and four concentrations of ZnO NPs fertilizer (Factor B: 0, 2, 4, and 6 mg L^{-1}). Foliar applications were carried out at flowering; the first application was when flowering had begun, the second 2 weeks after the first, and the third 2 weeks after the second application. The study used a 3 × 4 factorial design within a randomized complete block design (RCBD) with three replications, comprising 36 experimental units in total (3 hybrids × 4 Zn levels × 3 blocks). To minimize potential microclimatic gradients (such as longitudinal light and temperature variations within the non-heated plastic house), the experimental area was divided into three contiguous blocks oriented perpendicular to the main environmental gradient. Within each block, the 12 treatment combinations were randomly assigned to 4.0 m^2 plots (0.8 m width × 5.0 m length) using a computer-generated randomization procedure in GenStat.

Nanoparticle source and physicochemical characterization: Commercial-grade zinc oxide nanoparticles (ZnO NPs, purity ≥ 99%, Catalogue No. 544906, Sigma-Aldrich, Taufkirchen, Germany; CAS No. 1314-13-2) were used in this study. According to the manufacturer's Certificate of Analysis (CoA), the nominal specifications of the dry nano powder were: primary particle size distribution of 20–50 nm (determined by BET N_2 adsorption), specific surface area (SSA) of 30–50 m^2 g^{-1}, and true density of 5.606 g cm^{-3}. To independently verify these specifications prior to plant application, in-house physicochemical characterization was conducted. Transmission Electron Microscopy (TEM; JEOL JEM-2100F operating at 200 kV) confirmed a predominantly spherical to sub-hexagonal morphology with a mean primary core diameter of 28.4 ± 6.2 nm (distribution range: 20–48 nm). Powder X-ray Diffraction (XRD; Rigaku Ultima IV) verified a pure hexagonal wurtzite crystalline structure matching JCPDS Card No. 36-1451, with no detectable crystalline impurities. Upon dispersion in deionized water containing 0.05% (v/v) Tween-20 and probe sonication (40 kHz, 120 W for 30 min), Dynamic Light Scattering (DLS; Zetasizer Nano ZS, Malvern Instruments) revealed an average hydrodynamic diameter (Z-average) of 112.5 ± 8.4 nm with a Polydispersity Index (PDI) of 0.24 ± 0.02, reflecting mild colloidal aggregation in aqueous formulation. The surface charge (ζ-potential) of the spray suspension was +24.6 ± 1.8 mV, indicating moderate kinetic stability against rapid re-agglomeration during application.

Required quantities of dry ZnO NP powder were accurately weighed using a precision analytical balance (0.1 mg accuracy) based on total ZnO mass (0, 2, 4, and 6 mg L^{-1}, corresponding to 0, 1.61, 3.21, and 4.82 mg L^{-1} elemental Zn equivalent, respectively). The nanoparticles were dispersed in deionized water containing 0.05% (v/v) Tween-20 surfactant to reduce liquid surface tension and ensure uniform foliar wetting. To isolate the physiological effects of ZnO NPs from surfactant-induced penetration influences, Tween-20 concentration (0.05% v/v) was held constant across all treatment applications, including the control, as a strict experimental control parameter (Ragab and Turoop, 2022). Immediately prior to each of the three planned foliar spray applications, the suspensions were subjected to probe sonication (40 kHz, 120 W) for 30 minutes to break up agglomerates and ensure uniform particle dispersion. The resulting suspensions exhibited a neutral pH range of 6.8 to 7.1 and remained homogeneous without visible precipitation for over 3 hours post-sonication. All spray applications were completed within 45 minutes of sonication. Control plots received deionized water containing the identical 0.05% (v/v) Tween-20 concentration.

Before bed preparation, composite soil samples were collected from the 0–30 cm soil layer at randomly selected locations throughout the greenhouse. All samples were air-dried, ground and sieved through a 2 mm sieve before physical and chemical analysis (Table 1).

Soil pH was determined using a 1:2.5 soil-to-water suspension (Thomas, 1996), and ECe was measured using the saturated paste extract (Rhoades, 1996). Soil organic matter was calculated using the Walkley–Black wet oxidation method (Nelson and Sommers, 1996) and soil total N by the micro-Kjeldahl digestion method (Bremner, 1996). Olsen extractable phosphorus (Olsen *et al.,* 1954) was extracted by 0.5 M $NaHCO_3$ at pH 8.5. Available K (AK) was extracted with 1.0 M NH_4OAc at pH 7.0 and measured by flame photometry (Helmke and Sparks, 1996).

The available soil zinc (Zn) was extracted using the DTPA method (0.005 M DTPA + 0.01 M $CaCl_2$ + 0.1 M TEA, pH 7.3) described by Lindsay and Norvell (1978) and measured by Atomic Absorption Spectrophotometry (AAS, AA-7000, Shimadzu, Japan). The initial DTPA-extractable soil Zn concentration was 0.60 mg kg^{-1}, which is below the commonly accepted critical range of 0.80–1.00 mg kg^{-1} for horticultural crops, indicating low zinc availability in the experimental soil (Lindsay and Norvell,

Table 1. Selected physical and chemical properties of the plastic-house soil

Soil Property	Value
Texture	Sandy loam
pH	7.8
ECe (dS m^{-1})	2.9
Organic matter (%)	1.08
Nitrogen (N, mg kg^{-1})	19.6
Phosphorus (P, mg kg^{-1})	8.1
Potassium (K, mg kg^{-1})	158.9
Available Zinc (mg kg^{-1})	0.6
Sand (%)	59.5
Silt (%)	25.0
Clay (%)	15.5

1978; Alloway, 2008).

The field was ploughed and levelled, the beds were made, and the soil was split into 36 experimental units, each 0.8 m wide and 5.0 m long. Seeds were sown in the nursery on 2 January 2025. On 16 January, seedlings were transplanted to the plastic house. Seedlings were planted on soil beds at a spacing of 0.8 m between row centers and 0.5 m between plants within the row, establishing an experimental plot density of 2.5 plants m^{-2} (equivalent to 25,000 plants ha^{-1}). This actual experimental planting density matches standard local commercial practices and served as the direct basis for scaling individual plant yield data to unit area (t ha^{-1}) for statistical and economic evaluations. Each plot contained 10 plants and represented one experimental unit. To avoid biases from continuous harvesting, each unit was divided equally: five plants were dedicated to destructive sampling for vegetative growth parameters (plant height, leaf count, leaf area, and shoot dry weight), while the remaining five intact plants were reserved exclusively for non-destructive fruit yield data collection throughout the season. Plant measurements were averaged within each experimental unit prior to statistical analysis. Foliar spraying started on 27 February at the flowering stage. Before planting, a basal compound NPK fertilizer (15-15-15) was applied at 150 kg ha^{-1}. Drip fertigation was used to provide supplemental fertilization twice per week with a water-soluble NPK (20-20-20 + TE) at a rate of 2.5 kg ha^{-1} per fertigation over a 19-week period (38 fertigation applications, totaling 95 kg ha^{-1} of 20-20-20). Across the entire growing season, total macronutrient applications amounted to 41.5 kg N ha^{-1}, 41.5 kg P_2O_5 ha^{-1} (18.1 kg P ha^{-1}), and 41.5 kg K_2O ha^{-1} (34.4 kg K ha^{-1}), ensuring an adequate and uniform macronutrient supply across all experimental plots. Drip irrigation was scheduled to meet 100% of crop evapotranspiration (ETc) calculated via the FAO-56 Penman-Monteith methodology. Irrigation water quality remained suitable and uniform throughout the trial (EC 1.10–1.25 dS m^{-1}, pH 7.10–7.30). To control potential pests and diseases, all experimental plots received uniform applications of imidacloprid (0.5 mL L^{-1}) for aphid control (applied on 10 February and 20 March 2025) and copper oxychloride (2.5 g L^{-1}) for downy mildew prevention (applied on 18 February and 5 April 2025). To eliminate potential chemical interactions, pH alterations, or nutrient competition between copper (Cu^{2+}) and zinc (Zn^{2+}), all plant protection applications were strictly scheduled at least 5 to 7 days apart from any nano-zinc foliar spraying events. Harvesting took place from 5 March 2025 to 30 May 2025.

Foliar spray volume calibration: Canopy size at each application stage was used to determine the volume to be sprayed on the leaves to achieve complete wetting until run-off, without drip losses. Application rates were around 300 liters per hectare for the first spray (early flowering stage), 450 liters per hectare for the second spray (2 weeks later), and 600 liters per hectare for the third spray (full canopy stage). Deionized water containing 0.05% (v/v) Tween-20 was sprayed on control plots at identical volumes.

Yield data collection and chronology: Harvest was carried out continuously from 5 March to 30 May 2025 through several pickings. Total yield per plant represented the total yield of all successive harvests of the 12-week harvest period. The three-spray treatment aimed to maintain nutrient and metabolic activity throughout the long harvesting period to support early establishment and sustained fruit set and expansion. The three-spray treatment aimed to maintain nutrient and metabolic activity throughout the long harvesting period to support early establishment and sustained fruit set and expansion.

Yield data collection and chronology: Harvesting began on 5 March 2025 and was carried out continuously until 30 May 2025 through several pickings; the second and third sprays were applied on 13 and 27 March 2025, respectively. Total yield per plant represented the total yield of all successive harvests of the 12-week harvest period. The three-spray treatment aimed to maintain nutrient and metabolic activity throughout the long harvesting period to support early establishment and sustained fruit set and expansion.

Measured traits

Plant height (cm): Plant height was measured from the soil surface to the apical meristem at the end of the growing season using a standard measuring tape on the five designated plants per experimental unit, and the mean height was recorded.

Number of leaves (leaves $plant^{-1}$): Total active, fully expanded leaves (> 3 cm in length) were counted directly on intact plants prior to destructive plant removal at the end of the season for the same five designated plants, and expressed as mean leaves per plant.

Leaf area (cm^2 $plant^{-1}$): Leaf area was determined using the leaf-disc dry-weight method described by Květ *et al.* (1971). From the five destructively sampled plants per plot, a composite sample of 10 mature, fully expanded leaves (two leaves per plant) was randomly selected from the middle canopy position (between the 8th and 12th nodes). Leaf discs of 1.0 cm diameter (3 discs per leaf, totaling 30 discs) were precisely punched, avoiding primary veins, using a cork borer.

The area of one disc was calculated as
$\pi r^2 = \pi \times (0.5\ cm)^2 = 0.7854\ cm^2$.
Therefore, the total area of the 30 discs was 23.562 cm^2.

The sampled leaves and the excised discs were oven-dried separately at 68–70 °C for 72 h until constant weight was achieved. Total leaf area of the 10 sampled leaves was calculated using the following equation:

LA_{10} (cm^2) = [Dry weight of 10 sampled leaves (g) × 23.562 cm^2] ÷ [Dry weight of 30 discs (g)]

LA_{10} = Total leaf area of the 10 sampled leaves (cm^2)

W_l = Dry weight of the 10 sampled leaves (g)

Wd = Dry weight of the 30 leaf discs (g)

The average leaf area (cm^2 $leaf^{-1}$) was obtained by dividing LA_{10} by 10. The total leaf area per plant (cm^2 $plant^{-1}$) was then

calculated as the average leaf area multiplied by the mean number of leaves per plant. This method provides a reasonably accurate estimate of total plant leaf area because it relies on the proportionality of leaf dry weight to leaf surface area (Watson and Watson, 1953).

Shoot dry weight (g): Following height and leaf measurements, the above-ground vegetative biomass of the same five plants was harvested by severing the stems at the soil line (roots were completely removed). Stems and leaves were thoroughly rinsed with distilled water, oven-dried at 70 °C for 72 h until constant weight, and weighed on a precision balance. The remaining 5 plants per experimental unit were left intact for total fruit yield determination.

Yield traits: Yield parameters were evaluated based exclusively on marketable fruit production (defined as healthy, unblemished, and well-formed fruits meeting standard commercial criteria; damaged, diseased, or severely misshapen fruits were counted, weighed, and excluded from final yield calculations). Fruit length (cm) was measured on a representative sample of 10 marketable fruits per plot per picking using a digital caliper. The number of fruits (fruits plant^{-1}) was determined by counting all harvested marketable fruits from the five intact plants throughout the 12-week harvest period and dividing by the number of intact plants (5). Cumulative marketable yield per plant (kg plant^{-1}) was obtained by summing the total weight of marketable harvests from intact plants and dividing by the plant count. Average fruit weight (g) was subsequently calculated by dividing the total cumulative marketable fruit yield per experimental unit by the total number of harvested marketable fruits.

Statistical analysis: Data were subjected to a two-factor analysis of variance (ANOVA) for a factorial experiment arranged in a Randomized Complete Block Design (RCBD) with three replications using GenStat statistical software (VSN International). Each experimental plot served as the experimental unit, while plants sampled within each plot were the observation units. Prior to ANOVA, the statistical assumptions of residual normality and homogeneity of variances were verified using the Shapiro–Wilk test on model residuals and Levene's test, respectively. The linear statistical model accounted for the main effects of cultivars (Factor A), nano-zinc concentrations (Factor B), their two-way interactions (Cultivar × nano-Zn), and block effects. Treatment means were compared using Fisher's Protected Least Significant Difference (LSD) test at a significance level of $P \leq 0.05$ (Al-Sahouki and Wahib, 1990), applied strictly following a significant ANOVA F-test.

Results and discussion

Overall statistical evaluation and variance analysis: The ANOVA results showed that both hybrid and ZnO NPs concentration had a highly significant effect ($P < 0.001$) on all the measured parameters (Table 2). Similarly, the interaction between hybrid and ZnO NPs treatment (A × B) exerted a statistically significant influence on all evaluated traits, ranging from $P < 0.05$ for fruit length to $P < 0.001$ for vegetative growth and total yield.

Vegetative traits: Compared with the control treatments, the vegetative growth of all three cucumber hybrids was significantly higher when ZnO NPs were applied to the leaf surfaces (Table 3). The maximum plant height, number of leaves, leaf area, and shoot dry weight were recorded in Grow Imp. F1, followed by Wazir F1, while Princestar RZ F1 recorded the lowest values across all vegetative parameters.

Leaf area increased by 26.25% for foliar application at 6 mg L^{-1}; leaf number increased by 26.40% at the same rate of foliar application; plant height increased by 23.64% at the same foliar application rate, and shoot dry weight showed the greatest increase of 84.99% for the foliar application at 6 mg L^{-1}.

The highest interaction values were recorded for plant height (303.87 cm) and shoot dry weight (47.33 g) in Grow Imp. F1 supplied with 6 mg L^{-1} of ZnO NPs. These represent increases of 29.3% in plant height and 79.8% in shoot dry weight when compared directly to the untreated control of the same hybrid (Grow Imp. F1 at 0 mg L^{-1} of ZnO NPs). This differential response highlights that genetic background and zinc nutritional status act synergistically to govern overall vegetative growth performance.

It should be noted that all experimental plots received adequate and uniform basal and fertigation NPK applications (41.5 kg ha^{-1} each of N, P_2O_5, and K_2O). The observed growth and yield responses occurred under uniform basal and fertigation NPK applications.

While physiological parameters were not directly measured in this study, the observed morphological improvements may be explained by previously reported Zn-mediated physiological processes, including enhanced photosynthetic efficiency, chlorophyll retention, and biomass accumulation (Alloway, 2008). Previous literature indicates that foliar application of ZnO nanoparticles facilitates efficient cuticular and stomatal penetration, thereby supplying metabolic Zn during critical growth stages to support these structural and physiological processes (Prasad *et al.,* 2012). These results agree with Hussein and Atallah (2017) for cucumber, Al-Musawi, (2023) for sweet pepper, and Ahmed *et al.* (2023a) for tomato.

Fruit traits*:* ZnO NPs application significantly enhanced all fruit characteristics and total yield parameters across all cucumber hybrids (Table 4). Wazir F1 produced the highest overall fruit yield, followed by Grow Imp. F1, while Princestar RZ F1

Table 2. Summary of Analysis of Variance (ANOVA Mean Squares) for vegetative growth, fruit characteristics, and yield traits of cucumber

Source of Variation (SOV)	df	Plant height (cm)	Number of leaves plant^{-1}	Leaf area (cm^2 plant^{-1})	Shoot dry weight (g)	Fruit length (cm)	Number of fruits plant^{-1})	Average fruit weight (g)	Yield per plant (kg)
Replications (Blocks)	2	207.99083	11.60583	29800.58333	11.60583	0.00063	0.00146	0.00188	0.00006
Cultivar (A)	2	1728.21383	351.85668	5507852.25000	305.52173	7.41228	288.59598	70.70453	4.11718
Nano-Zn (B)	3	4893.46997	257.79103	5445075.66700	611.12187	13.41649	199.04063	97.12996	3.12748
Interaction (A × B)	6	109.77919	9.12578	55633.91667	4.84799	0.18484	4.91558	5.38666	0.08894
Residual Error	22	0.48629	0.40583	152.58333	0.40583	0.07063	0.17919	0.20142	0.00406
CV (%)		0.279	1.184	0.161	2.106	1.788	1.406	0.426	2.000

df: degrees of freedom; ns: non-significant ($P > 0.05$); * statistically significant at $P < 0.05$; *** statistically significant at $P < 0.001$; CV: Coefficient of Variation.

Table 3. Effect of cucumber cultivar, foliar ZnO NPs application, and their interactions on vegetative growth traits

Cultivar	ZnO NPs concentration (mg L^{-1})	Plant height (cm)	Number of leaves (leaves $plant^{-1}$)	Leaf area (cm^2 $plant^{-1}$)	Shoot dry weight (g)
Grow Imp. F1	0 (Control)	234.97 i	53.19 de	7486 g	26.33 f
	2	250.30 e	56.91 c	7976 d	30.67 e
	4	262.30 d	59.30 b	8733 b	37.33 c
	6	303.87 a	69.42 a	9414 a	47.33 a
Princestar RZ F1	0 (Control)	223.93 k	43.46 i	6407 k	18.67 h
	2	226.97 j	47.81 h	6612 j	21.00 g
	4	237.30 h	50.77 g	7328 h	25.33 f
	6	267.97 c	53.96 d	7942 e	36.33 c
Wazir F1	0 (Control)	227.63 j	48.26 h	6632 j	21.67 g
	2	243.30 g	51.45 fg	7267 i	26.00 f
	4	245.63 f	52.24 ef	7600 f	32.67 d
	6	276.97 b	59.78 b	8553 c	39.67 b
L.S.D 0.05 (A×B)		1.18	1.08	20.92	1.08
Mean by Cultivar	Grow Imp. F1	262.86 a	59.71 a	8402 a	35.42 a
	Princestar RZ F1	239.04 c	49.00 c	7072 c	25.33 c
	Wazir F1	248.38 b	52.93 b	7513 b	30.00 b
LSD 0.05 (A)		0.59	0.54	10.46	0.54
Mean by ZnO NPs concentration	0	228.84 d	48.30 d	6841 d	22.22 d
	2	240.19 c	52.06 c	7285 c	25.89 c
	4	248.41 b	54.10 b	7887 b	31.78 b
	6	282.93 a	61.06 a	8637 a	41.11 a
LSD 0.05 (B)		0.68	0.62	12.08	0.62

Different letters within the same column indicate significant differences according to the LSD test at the 0.05 probability level.

Table 4. Effect of cucumber cultivar, foliar ZnO NPs application, and their interactions on fruit traits

Cultivar	ZnO NPs concentration (mg L^{-1})	Fruit length (cm)	Number of fruits (fruits $plant^{-1}$)	Fruit weight (g)	Yield per plant (kg)
Grow Imp. F1	0 (Control)	13.00 h	22.10 h	99.71 h	2.21 h
	2	14.67 ef	28.70 e	106.76 d	3.06 e
	4	15.00 de	32.57 c	108.51 bc	3.53 c
	6	15.67 c	35.67 b	108.90 b	3.89 b
Princestar RZ F1	0 (Control)	12.67 h	20.83 i	98.77 i	2.06 i
	2	14.33 fg	24.27 g	102.05 g	2.48 g
	4	14.67 ef	26.20 f	103.70 f	2.72 f
	6	15.33 cd	30.07 d	105.72 e	3.18 d
Wazir F1	0 (Control)	14.00 g	30.30 d	104.20 f	3.16 de
	2	15.33 cd	33.27 c	105.85 e	3.52 c
	4	16.33 b	36.00 b	107.78 c	3.88 b
	6	17.33 a	40.97 a	111.20 a	4.56 a
L.S.D 0.05 (A×B)		0.45	0.72	0.76	0.11
Mean by Cultivar	Grow Imp. F1	14.59 b	29.76 b	105.97 b	3.17 b
	Princestar RZ F1	14.25 c	25.34 c	102.56 c	2.61 c
	Wazir F1	15.75 a	35.14 a	107.26 a	3.78 a
LSD 0.05 (A)		0.23	0.36	0.38	0.05
Mean by ZnO NPs concentration	0	13.22 d	24.41 d	100.89 d	2.47 d
	2	14.78 c	28.74 c	104.89 c	3.02 c
	4	15.33 b	31.59 b	106.66 b	3.38 b
	6	16.11 a	35.57 a	108.61 a	3.87 a
LSD 0.05 (B)		0.26	0.41	0.44	0.06

registered the lowest values. Under 6 mg L^{-1} ZnO NPs, fruit length increased by 21.83%, average fruit weight by 7.65%, fruit number per plant by 45.72%, and total yield per plant by 56.53% relative to the untreated control. The hybrid × ZnO NPs interaction was highly significant ($P < 0.001$): Wazir F1 with 6 mg L^{-1} ZnO NPs yielded 4.556 kg $plant^{-1}$, representing a 44.00% increase over the untreated control of the same hybrid (Wazir F1 at 0 mg L^{-1} ZnO NPs). These yield improvements may be associated with enhanced sink strength and previously reported Zn-mediated physiological processes governing assimilate partitioning during reproductive development (Broadley *et al.,* 2012; Marschner, 2012). Differing hybrid responses reflect genetic priorities in assimilate partitioning, with Wazir F1 directing greater resources toward reproductive output and Grow Imp. F1 maintaining stronger vegetative growth. These results align with previous work on cucumber (Javadimoghadam *et al*., 2015; Hussein and Khalaf, 2022), sweet pepper (Al-Musawi, 2023), and tomato (Ahmed *et al*., 2023a).

Food safety, environmental considerations, and study limitations: ZnO NPs foliar application showed promising agronomic advantages and economic returns under greenhouse conditions. Further studies should evaluate Zn accumulation in fruits and long-term environmental effects before commercial application (Kah *et al*., 2021; Kang *et al*., 2024).

Economic consideration: A partial budget analysis was performed to evaluate the economic viability of foliar application of ZnO NPs under commercial greenhouse production conditions. All key input parameters, labor assumptions, operational expenditures, and output market values were standardized based on localized 2025 market assessments (Table 5 & Table 6). To ensure methodological rigor, the partial budget was evaluated relative to the actual experimental sprayed control (which received three foliar applications of deionized water containing 0.05% v/v Tween-20). Under this primary comparator, common operational costs—specifically foliar application labor ($150.00 USD ha^{-1} for three spraying events at $50.00 USD ha^{-1} per application) and basic surfactant inputs—were shared identically across all experimental treatments and excluded from incremental expenditure calculations. (Note: if evaluated relative to an unsprayed commercial baseline, this application labor represents an additional fixed operating expense of $150.00 USD ha^{-1}). Overall treatment mean yields from Table 4 were calculated directly from cumulative per-plant yields using the actual experimental planting density of 25,000 plants ha^{-1} (derived from the 0.8 m × 0.5 m spacing; 2.5 plants m^{-2}). Total yield increased from 61.85 t ha^{-1} in the sprayed control treatment to 75.53, 84.45, and 96.83 t ha^{-1} at 2, 4, and 6 mg L^{-1} ZnO NPs, respectively. Based on an average seasonal farm-gate cucumber price of 0.50 USD kg^{-1} (Central Statistical Organization, 2025), additional gross revenues reached $6,840.00, $11,300.00, and $17,490.00 USD ha^{-1} for 2, 4, and 6 mg L^{-1} treatments, respectively. Total seasonal foliar spray volume reached 1,350 L ha^{-1} (300, 450, and 600 L ha^{-1} for the first, second, and third sprays, respectively), requiring active ZnO NP masses of 2.7, 5.4, and 8.1 g ha^{-1} for 2, 4, and 6 mg L^{-1} treatments, respectively (corresponding to raw active chemical material costs of $0.49, $0.97, and $1.46 USD ha^{-1} at $180 kg^{-1}). Specialized fertilizer formulation overheads were standardized at 50.00, 100.00, and 150.00 USD ha^{-1} for 2, 4, and 6 mg L^{-1} treatments, respectively (incorporating nanomaterial processing, ultrasonic probe sonication energy, specialized technical labor for suspension stabilization, commercial packaging, and minimum processing fees; Table 5). Incremental harvest and transportation costs scaled with additional yield at 30.00 USD ton^{-1} ($410.40, $678.00, and $1,049.40 USD ha^{-1} for 2, 4, and 6 mg L^{-1}; Table 5 & Table 6). When evaluated against the actual sprayed control, total additional operating expenses for 2, 4, and 6 mg L^{-1} were $460.40, $778.00, and $1,199.40 USD ha^{-1}, respectively ($610.40, $928.00, and $1,349.40 USD ha^{-1} if including application labor against an unsprayed baseline). Consequently, foliar application of

Table 5. Summary of economic input parameters, unit costs, and data sources used in the partial budget analysis

Parameter / Cost Item	Baseline | Unit	Unit Cost (USD)	Source / Reference Basis
Cucumber Farm-gate Price	USD kg^{-1}	$0.50	Central Statistical Organization (CSO), Ministry of Planning, Iraq (2025)
ZnO Nanoparticle Powder	USD kg^{-1}	$180.00	Commercial chemical quote (Sigma-Aldrich / Iraqi local agent, 2025)
Application Labor Rate	USD person-day^{-1}	$15.00	Local agricultural labor market rate (Babylon Governorate, central Iraq)
Foliar Application Labor	USD ha^{-1} $application^{-1}$	$50.00	Based on 3.33 person-days ha^{-1} per foliar spraying event (3 sprays total)
Incremental Harvest & Transport	USD t^{-1}	$30.00	Local commercial transport and yield-handling labor rate
Commercial Plant Density	plants ha^{-1}	25,000	Standard greenhouse commercial spacing (0.8 m × 0.5 m)

Note: Nano-Zn fertilizer formulation costs ($50.00, $100.00, and $150.00 USD ha^{-1} for 2, 4, and 6 mg L^{-1}, respectively) represent standardized commercial formulation expenditures. While raw active ZnO NP powder costs account for $0.49, $0.97, and $1.46 USD ha^{-1} (2.7, 5.4, and 8.1 g ha^{-1} at $180 USD kg^{-1} based on 1,350 L ha^{-1} total volume), the formulation cost incorporates 0.05% v/v Tween-20 surfactant (≈ $13.50 USD ha^{-1}), ultrasonic probe sonication energy, technical laboratory labor for dispersion and stabilization, commercial packaging, and minimum commercial order fees.

Table 6. Partial budget analysis of foliar nano-zinc application on cucumber production (hypothetical commercial extrapolation on a per hectare basis, USD)

Parameter / Metric	0 mg L^{-1} (Control)	2 mg L^{-1}	4 mg L^{-1}	6 mg L^{-1}
Overall Mean Yield per Plant (kg $plant^{-1}$)	2.474	3.021	3.378	3.873
Total Yield per Hectare (t ha^{-1}) [a]	61.85	75.53	84.45	96.83
Yield Increase over Control (t ha^{-1})	—	+13.68	+22.60	+34.98
Gross Revenue (USD ha^{-1}) [b]	$30,925.00	$37,765.00	$42,225.00	$48,415.00
Additional Gross Revenue (USD ha^{-1})	—	$6,840.00	$11,300.00	$17,490.00
Nano-Zn Fertilizer Cost (USD ha^{-1}) [c]	$0.00	$50.00	$100.00	$150.00
Application and Labor Costs (USD ha^{-1})[d]	$0.00	$150.00	$150.00	$150.00
Incremental Harvest and Transport Costs (USD ha^{-1}) [e]	$0.00	$410.40	$678.00	$1,049.40
Total Additional Costs (USD ha^{-1})	$0.00	$610.40	$928.00	$1,349.40
Net Additional Return (USD ha^{-1})	—	$6,229.60	$10,372.00	$16,140.60

Note: †ZnO NP formulation cost: Based on a total seasonal spray volume of 1,350 L ha^{-1} (300, 450, and 600 L ha^{-1} for sprays 1, 2, and 3), active ZnO NP mass requirements are 2.7, 5.4, and 8.1 g ha^{-1} for 2, 4, and 6 mg L^{-1} treatments, respectively (corresponding to raw active material costs of $0.49, $0.97, and $1.46 ha^{-1} at $180 kg^{-1}). The reported fertilizer formulation costs ($50.00, $100.00, and $150.00 ha^{-1}) cover active nano-materials, 0.05% v/v Tween-20 surfactant (≈ $13.50 ha^{-1}), ultrasonic probe sonication energy overheads, technical labor for suspension stabilization, and commercial packaging.

6 mg L^{-1} ZnO NPs generated the highest Net Additional Return (NAR) of $16,290.60 USD ha^{-1} relative to the sprayed control ($16,140.60 USD ha^{-1} relative to an unsprayed commercial baseline; Table 6).

Foliar application of ZnO NPs significantly improved vegetative growth parameters, yield components, and productivity of cucumber hybrids grown in soil with low zinc levels (DTPA-Zn = 0.60 mg kg^{-1}). The yield performance of the evaluated hybrids differed, and the hybrids were grouped into different agronomic performance profiles: Fruit number per plant, average fruit weight, fruit length, and total yield per plant were the highest with Wazir F1, while Grow Imp. F1 had the highest vegetative biomass (plant height, leaf number, leaf area, and shoot dry weight). However, the lowest overall values were observed for growth and yield traits of Princestar RZ F1. For all three hybrids, the foliar spraying of ZnO NPs at 6 mg L^{-1} resulted in the greatest improvement in vegetative and reproductive characteristics (highest net additional return, according to the partial budget model).

These conclusions are only valid for the agronomic and economic parameters that were measured in a specific experimental design, however. Because internal fruit quality parameters (such as TSS, firmness, and vitamin C) and safety assessments (including fruit zinc bioaccumulation, cellular nanoparticle residues, worker exposure, and long-term soil/water environmental fate) were not evaluated, direct commercial recommendations cannot be made at this stage. Multi-season field trials incorporating comprehensive fruit residue profiling, dietary safety assessments, and ecotoxicological monitoring are essential before recommending ZnO NPs formulations for commercial agricultural practices.

Acknowledgments

The authors sincerely thank the staff of the Plant Production Techniques Department and the Soil and Water Techniques Department, Al-Musayyab Technical College, Al-Furat Al-Awsat Technical University, for their continuous guidance and support throughout the study.

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Received: March, 2026; Revised: April, 2026; Accepted: May, 2026