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The Effects of Poultry Manure and Micronutrients on the Growth, Fruit Productivity and Chemical Constituents of *Coriandrum sativum* L.

Youssry Abdel-Hamid Mohamed[1]*, Elsayed Hammad Ammer[1], Ahmed El-Gohary Ibrahim[2], Ahmed Ali Mahmoud[1]

1 Horticulture Department, Faculty of Agriculture, Al-Azhar University, Cairo, Egypt
2 National Research Center, Dokki, Giza, Egypt

*Corresponding author's email: ahmedahmed.4919@azhar.edu.eg

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ABSTRACT

The current research evaluated the influence of organic amendments, specifically PM (poultry manure), and micronutrients, namely manganese ($MnSO_4$) and zinc ($ZnSO_4$), on the growth, yield, and chemical composition of coriander (*Coriandrum sativum* L.). The study employed a split-plot design with three replicates to evaluate the effects of poultry manure as the main factor. Poultry manure was applied at four rates: 0, 7, 14, and 21 m3 ha^{-1}. The secondary factor comprised five foliar treatments: tap water (control), $MnSO_4$ at 50 and 100 ppm, and ZnSO4 at 50 and 100 ppm. The results demonstrated that poultry manure at 21 m^3 ha^{-1} significantly enhanced plant growth parameters, yield, essential oil production, and chemical properties compared to lower application rates and the control. Similarly, foliar applications of $MnSO_4$ at 100 ppm improved plant development, thereby increasing plant height, branch count, herb dry weight, and fruit yield, along with essential oil content and chemical constituents. The most pronounced effects occurred from the combined treatment of poultry manure at 21 m^3 ha^{-1} and $MnSO_4$ at 100 ppm, which, during two consecutive growing seasons, increased plant height by 25.8 and 29.7%, branch count by 77.6 and 65.3%, herb dry weight by 134.8 and 116.3%, fruit yield per ha by 128.6 and 100.2%, and essential oil percentage by 50.0 and 50.2%, respectively, compared to the control. These findings revealed the efficacy of integrating organic manure with targeted micronutrient applications as a sustainable strategy to restore soil fertility and optimize coriander production.

Introduction

Coriandrum sativum is an annual herb of the Apiaceae family, primarily cultivated for its various applications of fresh leaves and dried seeds that have biochemical and medicinal properties (Serri et al., 2021). It possesses a taproot system and an erect stem that reaches 20–120 cm, beginning to flower 45–60 d after sowing, and features green lanceolate leaves along with small, asymmetrical umbels of white or light pink flowers. Its seeds are ovate, globular schizocarps divided into two mericarps (Gupta and Das, 1997; Yeung and Bowra, 2011; Bhuiyan et al., 2009). Known for its use over more than 3,000 years in both culinary and medicinal contexts, as evidenced by ancient texts like the Ebers Papyrus and biblical narratives, it is native to the Mediterranean and Middle East and occurs wild in regions such as Egypt and Sudan. Today, it is globally cultivated, with India emerging as the largest producer (Laribi et al., 2015; Adams et al., 2012; Meena et al., 2014; Sahib et al., 2013; Yadav, 2010; Kant et al., 2017). Both its seeds and leaves are valued for their aroma and color, while its essential oil, whose yield and composition change during ontogenesis, is a key bioactive component in food,

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medicinal, and cosmetic applications (Kubo et al., 2004; Verma et al., 2011; Neffati and Marzouk, 2008).

Sustainable agriculture seeks to achieve high crop productivity while minimizing environmental impacts, particularly in challenging semi-arid regions where low soil organic matter contributes to diminished soil health and reduced agricultural output (Al-Sayed et al., 2024). In Egypt's Northwestern Coastal region, where calcareous soils with high pH and calcium carbonate content constitute approximately 8% of the total land area, crops often require elevated fertilizer inputs to overcome nutrient deficiencies and achieve optimal yields (Rasha, 2005; Ali et al., 2020). Poultry manure is a readily available fertilizer that can serve as a viable alternative to chemical fertilizers. Its application has been documented to result in a significant increase in soil nitrogen levels, with studies reporting a 53% rise from 0.09% to 0.14%, as well as an enhancement in exchangeable cations (Boateng et al., 2006). In agricultural practices, the primary motivations for utilizing poultry manure include its role as an organic soil amendment and its capacity to supply essential nutrients to crops (Warnen et al., 2006). Poultry manure is recognized as an exceptional organic fertilizer due to its high content of nitrogen (N), phosphorus (P), potassium (K), and other vital nutrients (Farhad et al., 2009). Furthermore, it has reportedly provided a greater supply of plant-available phosphorus compared to other organic sources (Garg and Bahl, 2008; Uwah et al., 2012).

Medicinal plants, including coriander (*Coriandrum sativum* L.), frequently experience micronutrient deficiencies, particularly manganese (Mn) and zinc (Zn), in alkaline soils, where high pH and calcium carbonate content limit nutrient bioavailability. These deficiencies often manifest from flowering to maturity, adversely affecting plant growth and yield in regions where coriander is cultivated annually. To address this challenge, a study was conducted to investigate the effects of foliar micronutrient sprays, specifically $MnSO_4$ and $ZnSO_4$, on coriander growth parameters and yield in alkaline soil conditions. Manganese (Mn) ranks among the principal micronutrients, playing a crucial role in plant physiology as an integral component of enzymes that underpin photosynthesis and various metabolic pathways. It is a key constituent of the superoxide dismutase antioxidant enzyme, which safeguards plant cells by neutralizing free radicals that could otherwise cause tissue degradation. Mn is indispensable in photosynthesis, forming a structural element of the photosystem II water-splitting complex, where it facilitates electron storage and transfer to chlorophyll reaction centers (Diedrick, 2010; Millaleo et al., 2010). As an essential element across nearly all living organisms, Mn fulfills dual functions: serving as an enzyme cofactor or acting as a catalytically active metal within biological clusters (Andresen et al., 2018). Furthermore, Mn participates in redox reactions associated with the photosynthetic electron transport system. A deficiency in Mn can profoundly affect chloroplast functionality, resulting in interveinal chlorosis and inhibited growth. Additionally, manganese contributes to preventing lodging and enhancing disease resistance in plants (Weisany et al., 2013). Zinc (Zn) is an essential micronutrient for regulating fruit set, fruit growth and quality indices (Souri and Hatamian, 2019). It serves as a component of carbonic anhydrase enzymes found in all photosynthetic tissues, playing a vital role in chlorophyll biosynthesis (Azadi and Gharaghani, 2016). Additionally, zinc contributes to the production of tryptophan, a precursor in the biosynthesis of auxin, a key plant hormone. In zinc-deficient plants, shoots and buds exhibit significantly reduced auxin levels, leading to dwarfism and diminished growth rates. Furthermore, zinc deficiency results in stunted plant development and prolonged growth periods (Azadi and Gharaghani, 2016). Zinc is crucial for chlorophyll formation, cell division, meristematic activity, tissue expansion, and the structural development of cell walls (Souri et al., 2017; Souri and Hatamian, 2019). A significant portion of soils in Egypt are alkaline (calcareous), leading to deficiencies in macronutrients as well as micronutrients such as manganese and zinc. To address these challenges, organic fertilizers and micronutrient foliar sprays have been explored to mitigate the effects of alkaline soil. It is hypothesized that such soil types influence medicinal plant yield and essential oil composition. Therefore, this study was conducted to evaluate the effects of poultry manure applied at different rates and foliar sprays of manganese ($MnSO_4$) and zinc ($ZnSO_4$) on various quantitative and qualitative parameters of coriander under Egyptian alkaline soil conditions.

Materials and Methods

Plant materials

Seeds of coriander (*Coriandrum sativum* L.), a variety traditionally cultivated in Egypt, were obtained from the Medicinal and Aromatic Plants Research Department, Horticulture Research Institute, Agricultural Research Center, Giza, Egypt. This cultivar is widely grown throughout the country due to its superior growth performance, high productivity, and adaptability to the soil properties and climatic conditions characteristic of the central and southern regions of Egypt.

Treatments and experimental design

A field experiment was conducted over two successive growing seasons, 2023/2024 and

2024/2025, at the agricultural farm of the Faculty of Agriculture, Al-Azhar University, Assiut Branch, Egypt. Analysis of the soil's physical and chemical properties indicated a clay texture composition (19.4% sand, 27.2% silt, and 53.4% clay), with a pH of 8.71 (measured in a 1:2.5 soil-to-distilled water suspension), an electrical conductivity (EC) of 1.03 dS m^{-1} (in a 1:5 soil solution), 1.97% total $CaCO_3$, 0.97% organic matter, 0.70% total nitrogen, 0.21% total phosphorus, and 41% total potassium. Soluble ions in the soil paste (meq L^{-1}) included Cl^- (3.32), HCO_3^- (4.49), SO_4^{2-} (3.05), Ca^{2+} (5.25), Mg^{2+} (0.52), Na^+ (1.30), and K^+ (3.79). The experimental setup utilized a split-plot design, implemented across three replicates.

The following factors were analyzed in the experiment:

I- Poultry manure, incorporated during soil preparation at application rates of 0, 7, 14, and 21 m^3 ha^{-1} (denoted as control, PM1, PM2, and PM3, respectively), was sourced from the poultry farm of the Faculty of Agriculture, Al-Azhar University, Assiut, Egypt. It was randomly assigned to the main plots and subjected to analytical evaluation to determine its nutrient composition, following the method outlined by Jackson (1973), with results presented in Table 1.

Table 1. The average nutrient composition and physical properties of poultry manure utilized across the two experimental seasons (2023/2024 and 2024/2025).

Organic matter%	**pH**	**EC mm cm^{-1}**	**Total N %**	**mg kg^{-1}**					
				Available P (Olsen P; Olsen et al., 1954)	**Exchangeable K (Ammonium acetate K)**	**Available**			
						Zn	**Mn**	**Cu**	**Fe**
71.20	6.46	3.91	3.25	34	714	155	116	21	1954

II- Foliar spray treatments of micronutrients were administered, consisting of a control (no spray), $MnSO_4$ (28% manganese with the molecular formula MnO_4S, molecular weight 151.00 g mol^{-1}) at concentrations of 50 and 100 ppm, and $ZnSO_4$ (35% zinc with the molecular formula $SO_4(Zn)$ and molecular weight 161.47 g mol^{-1}) at 50 and 100 ppm, applied to the subplots. These micronutrients were sourced from Al-Gomhoria Chemical Company.

Thus, the experiment comprised 20 distinct treatment combinations, with each treatment replicated three times. Each experimental unit (plot) consisted of three rows, measuring 2.1 x 1.8 meters. All treatments maintained a uniform row spacing of 0.30 meters. Seeds were sown on November 10th of each growing season, and thinning was performed after 40 d, retaining two plants per hill, resulting in a total of 42 plants per experimental unit. Foliar spray applications of micronutrients commenced 15 d post-thinning. To minimize leaching effects, $MnSO_4$ and $ZnSO_4$ treatments were applied with a 1 d interval between them and was done early in the morning [average high temperature (20-23 °C) and low (6-10 °C)]. Each experimental unit received a total volume of 3000 mL of the respective treatment solution. All spray solutions included Tween 20 at 0.1% (1 mL L^{-1}) as a wetting agent, while control plots were treated with distilled water only. These foliar applications were repeated twice more at 21 d intervals. Standard agricultural practices, including irrigation, weeding, and fertilization, were adhered to throughout the study. The fertilization regimen involved the application of superphosphate at 200 kg per feddan during soil preparation. Nitrogen was supplied as $(NH_4)_2SO_4$ at 200 kg per feddan, administered in two equal doses of 100 kg per feddan: the first dose was applied immediately after thinning, and the second dose 30 d later. Potassium was provided as K_2SO_4 at a rate of 50 kg per feddan, coinciding with the first and second nitrogen doses.

Data collection and yield assessment

Plant growth measurements

At the end of the growing season, coinciding with the flowering stage 120 d after sowing, vegetative growth parameters of coriander were measured and recorded. These included measurements of plant height, number of branches, and herb dry weight. The herb dry weight was determined by oven-drying samples at 70 °C until a constant weight was achieved.

Yield characteristics

Following harvest at the fruit maturity stage, the fruit yield was quantified as fruit weight in g per plant and kg ha^{-1}. After air-drying the fruits under shaded conditions for one week, their average weight per plant was determined in grams. Using the experimental plant spacing of 42 plants per 3.78 m^2, the yield was extrapolated to kg ha^{-1}.

Chemical constituents

Essential oil extraction and yield calculation

Air-dried fruits underwent essential oil extraction via hydrodistillation by employing a Clevenger-type apparatus, as outlined by Koşar et al. (2007). Fruit samples, each weighing 100 g and representing the three replicates per treatment, were ground prior to distillation. The pulverized fruits were immersed in distilled water and subjected to hydrodistillation for a duration of 3 h using the Clevenger-type apparatus. The percentage of distilled essential oils was duly recorded, and the oil yield per plant was calculated per ha.

GC-MS analysis of essential oil

The essential oil extracted from coriander fruits was analyzed using gas chromatography-mass spectrometry (GC-MS) to determine its chemical composition across five treatment groups: a control group and the four most effective treatments. These treatments were defined as follows: T1 (control; no poultry manure or micronutrient spray); T2 (poultry manure at 7 m^3 ha^{-1} (PM1) + $MnSO_4$ foliar spray at 100 ppm); T3 (poultry manure at 14 m^3 ha^{-1} (PM2) + $MnSO_4$ foliar spray at 100 ppm); T4 (poultry manure at 21 m^3 ha^{-1} (PM3) + $MnSO_4$ foliar spray at 100 ppm). The analysis was conducted using a DS Chrom 6200 gas chromatograph equipped with a flame ionization detector (FID). Component separation was achieved through gas-liquid chromatography (GLC), and the relative percentages of essential oil constituents were determined by comparing their retention times (RT) with those of authentic reference samples, as described by Guenther and Joseph (1978).

Analysis of N, P, and K elements

Chemical analyses of dry herb samples, which were collected at the flowering stage, included the determination of total nitrogen, assessed using a modified micro-Kjeldahl method (AOAC, 1990). Phosphorus was measured by a colorimeter at 882 nm according to the procedure described by Murphy and Riley (1962). Potassium was quantified via flame photometry following the method outlined by Cottenie et al. (1982).

Statistical analysis

The data were subjected to statistical analysis using analysis of variance (ANOVA) tailored for a split-plot design, with poultry manure and $MnSO_4$, $ZnSO_4$, and their combinations serving as the evaluated factors. The least significant difference (LSD) test at a significance level of $P = 0.05$ was employed to identify significant differences among treatment means (Gomez and Gomez, 1984). Statistical analyses were performed using Statistic version 9 software (Analytical Software, 2008).

Results

Growth parameters

Impact of poultry manure (PM) on coriander growth parameters

PM application can significantly increase all growth parameters (i.e., plant height, the number of branches per plant, and herb dry weight g per plant) of coriander across both experimental seasons (Table 2). Evidently, the application of PM at all tested rates resulted in a notable enhancement of all measured growth parameters compared to the control in both seasons. Particularly, the application of PM at a rate of 21 m^3 ha^{-1} markedly increased plant height by 16.5 and 20.7%, the number of branches per plant by 57.3 and 45.9%, and herb dry weight by 92.4 and 70.8% compared to the control during the two seasons, respectively.

Impact of foliar spray application of micronutrients on coriander growth

Table 2 indicates significant variations in plant height, number of branches, and herb dry weight (g per plant) of coriander plants attributable to the foliar spray application of the evaluated micronutrients across both the first and second experimental seasons. The application of all tested micronutrients at various concentrations via foliar spraying markedly improved all aforementioned growth parameters in both seasons compared to the control. The most substantial enhancements were noted in plants treated with $MnSO_4$ at the higher concentration (100 ppm), which yielded increases of 6.6 and 9.7% in plant height, 15.6 and 11.6% in branch count, and 22.7 and 25.4% in herb dry weight, compared to the control during the first and second seasons, respectively.

Interaction effects of study factors on coriander growth parameters

During the two experimental seasons, a statistically significant interaction between the two study factors was observed for the aforementioned attributes of coriander, with certain exceptions. These exceptions include the control group of poultry manure (PM) treatment combined with $MnSO_4$ at 50 ppm and $ZnSO_4$ at 50 ppm for plant height across both seasons. The control group of PM with $MnSO_4$ at 50 ppm and $ZnSO_4$ at 50 ppm, as well as PM at 7 m^3 ha^{-1} with the control group of the micronutrients treatment in the first season, and the control group of PM with $ZnSO_4$ at 50 ppm in the second season for the number of branches per plant. The exception also included the control group of PM with $MnSO_4$ at 50 ppm and $ZnSO_4$ at 50 ppm across both seasons, and the control group of PM with $ZnSO_4$ at 100 ppm in the second season. Also, PM at 3 m^3 fed^{-1} with the control group of micronutrients treatment in the second season for herb dry weight (g) per plant

(Table 2). Based on the collected data, the combination of PM at 21 m^3 ha^{-1} with foliar application of $MnSO_4$ at the higher concentration (100 ppm) emerged as the most effective treatment for enhancing these growth parameters across both experimental seasons.

Table 2. Effect of poultry manure and micronutrients on plant height, branch count, and herb dry weigh (g per plant) of coriander plants during the two growing seasons.

Micronutrients (M)	**Poultry manure levels (m^3 ha^{-1}) (A)**									
	First season					**Second season**				
	Control	**PM1**	**PM2**	**PM3**	**Mean (M)**	**Control**	**PM1**	**PM2**	**PM3**	**Mean (M)**
Plant height (cm)										
Control	82.5	87.9	90.9	95.5	89.2	85.6	92.2	97.5	101.2	94.1
$MnSO_4$ (50 ppm)	85.0	89.9	93.5	99.2	91.9	89.0	96.2	100.9	107.5	98.4
$MnSO_4$ (100 ppm)	88.7	92.1	95.9	103.8	95.1	91.5	104.2	106.1	111.0	103.2
$ZnSO_4$ (50 ppm)	83.6	89.0	93.0	98.3	91.0	88.1	95.4	99.5	105.9	97.2
$ZnSO_4$ (100 ppm)	88.6	91.9	95.2	102.3	94.5	89.4	101.4	107.0	109.8	101.9
Mean (P)	85.7	90.2	93.7	99.8		88.7	97.9	102.2	107.1	
LSD 0.05	PM: 1.9		M: 1.4	PMxM: 2.9		PM: 3.5		M: 1.9	PMxM: 3.8	
Branch count per plant										
Control	5.44	6.04	6.89	8.84	6.80	6.05	7.28	7.64	9.77	7.68
$MnSO_4$ (50 ppm)	5.88	6.71	7.33	9.41	7.33	6.79	7.79	8.28	9.88	8.18
$MnSO_4$ (100 ppm)	6.25	7.19	8.33	9.66	7.86	7.27	8.23	8.77	10.00	8.57
$ZnSO_4$ (50 ppm)	5.87	6.63	7.22	9.21	7.23	6.62	7.63	8.22	9.87	8.08
$ZnSO_4$ (100 ppm)	6.13	7.11	8.22	9.44	7.73	7.16	7.89	8.51	9.95	8.38
Mean (P)	5.92	6.73	7.60	9.31		6.78	7.76	8.29	9.89	
LSD 0.05	PM: 0.41		M: 0.33	PMxM: 0.65		PM: 0.60		M: 0.34	PMxM: 0.68	
Herb dry weight (g) per plant										
Control	20.7	24.1	31.2	40.3	29.1	24.6	28.6	35.5	42.1	32.7
$MnSO_4$ (50 ppm)	23.9	29.6	34.0	46.7	33.6	28.5	33.1	40.4	48.1	37.5
$MnSO_4$ (100 ppm)	25.9	31.5	36.8	48.6	35.7	30.8	36.5	43.6	53.2	41.0
$ZnSO_4$ (50 ppm)	23.2	29.1	33.2	44.2	32.4	27.7	32.8	39.0	46.8	36.6
$ZnSO_4$ (100 ppm)	24.4	30.2	35.8	47.3	34.4	28.8	35.2	43.1	49.5	39.1
Mean (P)	23.6	28.9	34.2	45.4		28.1	33.2	40.3	48.0	
LSD 0.05	PM: 2.3		M: 1.7	PMxM: 3.4		PM: 3.3		M: 2.2	PMxM: 4.4	

PM1= 7 m^3 ha^{-1}; PM2= 14 m^3 ha^{-1}; PM3= 21 m^3 ha^{-1}.

Fruit yield

Impact of poultry manure on coriander fruit yield

As presented in Table 3, the application of diverse PM treatments to coriander plants across the two agricultural seasons significantly enhanced fruit yield compared to the untreated control. Notably, the application of PM at 21 m^3 ha^{-1} yielded the highest fruit production during both the first and second seasons. This treatment markedly elevated fruit yield by 83.3 and 78.1% compared to the control across the two growing periods, respectively. The absolute yields under this treatment were recorded at 3173.8 kg ha^{-1} and 3457.5 kg ha^{-1}, compared to control yields of 1731.7 kg ha^{-1} and 1941.4 kg ha^{-1}.

Impact of $MnSO_4$ and $ZnSO_4$ foliar applications on coriander fruit yield

The results indicated that foliar applications of MnSO4 and ZnSO4 across the two growing seasons significantly influenced coriander fruit yield per plant and per feddan. The data reveal that all tested concentrations of these micronutrients led to a notable increase in fruit yield compared to untreated plants. Notably, foliar spraying with $MnSO_4$ at a concentration of 100 ppm proved to be the most effective in enhancing this trait across both seasons, compared to other treatments and the control group. Quantitatively, this optimal treatment augmented fruit yield by 27.1% and 32.8%, compared to the control group, during the two consecutive seasons, respectively. Specifically, it produced yields of 2736.7 and 2981.7 kg ha^{-1}, compared to control yields of 2154.1 and 2245.9 kg ha^{-1} across the two seasons, respectively (Table 3).

Table 3. Effect of poultry manure and micronutrients on fruit yield (g) per plant and fruit yield (kg fed^{-1}) of coriander plants during the two growing seasons.

Micronutrients (M)	Poultry manure levels (m^3 ha^{-1}) (A)									
	First season					Second season				
	Control	PM1	PM2	PM3	Mean (M)	Control	PM1	PM2	PM3	Mean (M)
Fruit yield (g) per plant										
Control	14.2	18.6	21.3	26.7	20.2	15.7	19.0	21.0	28.5	21.1
$MnSO_4$ (50 ppm)	15.9	22.4	24.7	29.1	23.0	17.5	24.6	26.4	32.1	25.2
$MnSO_4$ (100 ppm)	19.2	24.7	26.2	32.4	25.7	21.4	25.7	29.5	35.2	28.0
$ZnSO_4$ (50 ppm)	14.7	20.6	23.5	28.9	21.9	16.3	22.6	26.4	31.4	24.2
$ZnSO_4$ (100 ppm)	17.2	24.6	25.8	31.7	24.8	20.2	25.2	28.6	34.9	27.2
Mean (P)	16.2	22.2	24.3	29.8		18.2	23.4	26.4	32.4	
LSD 0.05	PM: 1.3		M: 1.5	PMxM: 2.9		PM: 1.7		M: 1.6	PMxM: 3.3	
Fruit yield (kg) ha^{-1}										
Control	1513.1	1984.6	2273.1	2845.5	2154.1	1671.2	2031.6	2241.6	3039.4	2245.9
$MnSO_4$ (50 ppm)	1694.5	2387.4	2638.8	3105.7	2456.6	1867.4	2621.3	2816.6	3427.5	2683.2
$MnSO_4$ (100 ppm)	2049.7	2637.8	2799.9	3459.5	2736.7	2281.6	2741.3	3147.9	3756.1	2981.7
$ZnSO_4$ (50 ppm)	1570.7	2196.2	2510.2	3078.7	2339.0	1733.5	2412.8	2812.4	3346.1	2576.2
$ZnSO_4$ (100 ppm)	1830.3	2622.8	2754.7	3379.6	2646.8	2153.2	2688.0	3048.9	3718.4	2902.1
Mean (P)	1731.7	2365.8	2595.3	3173.8		1941.4	2499.0	2813.5	3457.5	
LSD 0.05	PM: 173.6		M: 156.5	PMxM: 312.9		PM: 183.5		M: 173.8	PMxM: 347.6	

PM1= 7 m^3 ha^{-1}; PM2= 14 m^3 ha^{-1}; PM3= 21 m^3 ha^{-1}.

Interaction effects on coriander fruit yield

Table 3 clearly demonstrates that the interaction of applied treatments significantly influenced coriander fruit yield per plant and per feddan across both seasons. Notably, the combined treatments consistently surpassed the control group in fruit yield during both years. Specifically, the combination of poultry manure (PM) at 21 m^3 ha^{-1} combined with $MnSO_4$ at 100 ppm emerged as the most effective treatment in both agricultural seasons when compared to all other treatment combinations. These treatments yielded the highest outputs, recording 3459.5 and 3756.1 kg ha^{-1}, markedly surpassing the control yields of 1513.1 and 1671.2 kg ha^{-1}.

Essential oil production parameters (% per plant and L ha^{-1})

Impact of poultry manure on essential oil production

Table 4 suggests that organic matter, specifically poultry manure (PM), exerted a positive influence on the essential oil percentage and yield per feddan in coriander fruits across both agricultural seasons. Notably, all PM application rates during both seasons led to a significant increase in these parameters compared to the control treatment. At the highest PM rate of 21 m^3 ha^{-1}, the essential oil percentage attained values of 0.309 and 0.317%, while the oil yield reached its maximum of 9.83 and 10.98 L ha^{-1} in the first and second seasons, respectively.

Impact of micronutrient treatments ($MnSO_4$ and $ZnSO_4$) on essential oil production

The data indicated that micronutrient treatments, specifically $MnSO_4$ and $ZnSO_4$, significantly influenced the essential oil percentage and yield per feddan of coriander fruits across both seasons. Notable differences among these treatments were consistently observed in both growing seasons. Foliar application of $MnSO_4$ at 100 ppm proved to be the most effective in enhancing these parameters compared to the control and other treatments across the two seasons. At this concentration, the essential oil percentages reached 0.281 and 0.287%, with corresponding yields of 7.84 and 8.73 L fed^{-1} in the first and second seasons, respectively (Table 4).

Table 4. Effect of poultry manure and micronutrients on essential oil percentage and essential oil yield (L) fed^{-1} of coriander plants during the two growing seasons.

Micronutrients (M)	**Poultry manure levels (m^3 ha^{-1}) (A)**									
	First season					**Second season**				
	Control	**PM1**	**PM2**	**PM3**	**Mean (M)**	**Control**	**PM1**	**PM2**	**PM3**	**Mean (M)**
Essential oil %										
Control	0.212	0.230	0.251	0.298	0.248	0.217	0.234	0.268	0.309	0.257
$MnSO_4$ (50 ppm)	0.218	0.255	0.292	0.311	0.269	0.229	0.264	0.298	0.317	0.277
$MnSO_4$ (100 ppm)	0.234	0.276	0.295	0.318	0.281	0.237	0.284	0.302	0.326	0.287
$ZnSO_4$ (50 ppm)	0.215	0.251	0.290	0.303	0.264	0.218	0.265	0.297	0.310	0.273
$ZnSO_4$ (100 ppm)	0.228	0.270	0.293	0.316	0.277	0.232	0.279	0.300	0.323	0.284
Mean (P)	0.221	0.257	0.284	0.309		0.227	0.265	0.293	0.317	
LSD 0.05	PM: 0.006 M: 0.005 PMxM: 0.011					PM: 0.011 M: 0.006 PMxM: 0.013				
Essential oil (L) fed^{-1}										
Control	3.21	4.57	5.70	8.48	5.49	3.62	4.76	6.02	9.40	5.95
$MnSO_4$ (50 ppm)	3.70	6.10	7.71	9.66	6.79	4.28	6.92	8.41	10.87	7.62
$MnSO_4$ (100 ppm)	4.79	7.28	8.26	11.02	7.84	5.40	7.78	9.53	12.23	8.73
$ZnSO_4$ (50 ppm)	3.37	5.51	7.27	9.32	6.37	3.78	6.38	8.36	10.38	7.22
$ZnSO_4$ (100 ppm)	4.17	7.08	8.06	10.67	7.50	5.00	7.51	9.16	12.00	8.42
Mean (P)	3.85	6.11	7.40	9.83		4.42	6.67	8.30	10.98	
LSD 0.05	PM: 0.40 M: 0.47 PMxM: 0.93					PM: 0.68 M: 0.59 PMxM: 1.17				

PM1 = 7 m^3 ha^{-1}; PM2 = 14 m^3 ha^{-1}; PM3 = 21 m^3 ha^{-1}.

Interaction effects of investigated factors on essential oil production

Table 4 indicates a statistically significant influence of the interaction between the two studied factors on the essential oil percentage and yield of coriander fruits across both experimental seasons, with the exception of the control of poultry manure (PM) combined with $MnSO_4$ at 50 ppm and $ZnSO_4$ at 50 ppm in both seasons. Evidently, these parameters exhibited substantial increases in both seasons when subjected to the majority of combined treatments compared to the untreated controls. Notably, the application of PM 21 m^3 ha^{-1} combined with $MnSO_4$ at 100 ppm achieved the highest values for these attributes during both growing seasons compared to all other combined treatments.

Essential oil components

The GC/MS chromatography analysis of coriander essential oil, conducted as part of the study, identified 15 distinct compounds. Table 5 presents the five primary chemical constituents of the essential oil extracted from dried coriander fruits under the experimental conditions. Comparative analysis of the oil's chemical composition highlights the prominence of linalool, γ-terpinene, α-pinene, p-cymene, and geranyl acetate, which exhibited the highest concentrations among the identified compounds (Table 5). The highest average concentration of linalool (65.01%) was observed in treatment T4, which involved the application of poultry manure at a rate of 21 m^3 ha^{-1} combined with a foliar spray of $MnSO_4$ at 100 ppm. The peak of p-cymene (4.67%) was recorded in treatment T2, consisting of poultry manure at a rate of 7 m^3 ha^{-1} combined with $MnSO_4$ at 100 ppm. The highest concentration of γ-terpinene (10.26%) was noted in treatment T4 (poultry manure at a rate of 21 m^3 ha^{-1} + $MnSO_4$ at 100 ppm). The maximum proportion of α-pinene (6.24%) was observed in treatment T4 (PM3 + $MnSO_4$ at 100 ppm). The highest level of geranyl acetate (6.61%) was recorded in treatment

T3, which applied poultry manure at a rate of 14 m^3 ha^{-1} combined with $MnSO_4$ at 100 ppm. These results demonstrate a significant influence of the treatments on enhancing the concentrations of key essential oil components in coriander. The variations in compound proportions across treatments underscore the impact of nutrient management strategies, particularly the combination of poultry manure and manganese foliar sprays. These findings align with previous research by Mahfouz and Sharaf Eldin (2007) and Msaada et al. (2007), which reported increased oil yield and altered constituent ratios due to optimized fertilization practices that ensure adequate nutrient availability for plant growth and metabolism.

Table 5. Interaction effect of poultry manure and micronutrient sprays on essential oil components of coriander plants (2024/2025 season).

No.	Compound	RT	Treatments			
			T1	T2	T3	T4
1	α-Pinene	6.14	4.19	5.55	6.22	6.24
2	β-Pinene	6.88	0.43	0.64	0.68	0.73
3	p-Cymene	7.49	3.24	4.67	4.42	4.05
4	D-Limonene	8.17	-	2.29	1.57	1.17
5	γ-Terpinene	9.24	8.24	9.34	10.18	10.26
6	Linalool	10.29	53.57	57.22	62.81	65.01
7	(+)-2-Bornanone	12.37	1.31	1.09	1.3	1.18
8	Terpinen-4-ol	12.97	0.64	0.71	0.75	0.61
9	Decanal	13.24	2.67	2.05	0.73	-
10	trans-Dihydrocarvone	13.69	0.51	-	0.24	-
11	(-)-Carvone	14.28	11.05	4.59	0.61	0.6
12	Geraniol	14.95	0.82	0.8	0.88	0.75
13	Piperitone	15.24	2.97	-	0.76	1.05
14	Geranyl acetate	17.68	5.28	6.07	6.61	5.11
15	Apiol	23.48	5.07	4.98	2.22	3.24
	Number of identified compounds		14	13	15	13
	Total % of identified compounds		99.99	100	99.98	100

T1= control; T2 = PM1 (7 m^3 ha^{-1}) + $MnSO_4$ (100 ppm); T3 = PM2 (14 m^3 ha^{-1}) + $MnSO_4$ (100 ppm); T4 = PM3 (21 m^3 ha^{-1}) + $MnSO_4$ (100 ppm).

Nutrient composition analysis

Impact of poultry manure on nutrient percentages

Table 6 reveals that the application of poultry manure as an organic amendment significantly elevated the percentages of nitrogen (N), phosphorus (P), and potassium (K) in the dried herb of coriander plants compared to the control. The findings indicate that plants treated with poultry manure (PM) at a rate of 21 m^3 ha^{-1} exhibited the highest levels of these three key nutrients. Specifically, these optimal treatments enhanced N% by 34.2 and 32.0%, P% by 17.4 and 17.6%, and K% by 32.7 and 33.3%, compared to untreated plants across the two seasons, respectively.

Impact of micronutrient application on nutrient percentages

Table 6 demonstrates that the application of the evaluated micronutrients at all concentrations significantly enhanced the percentages of nitrogen (N), phosphorus (P), and potassium (K) in the dried herb of coriander plants compared to the control treatment across both seasons. Notably, foliar application of $MnSO_4$ at 100 ppm caused the highest concentrations of these nutrients during the first and second seasons. Statistically, this optimal treatment increased N, P, and K percentages above the control by 14.2 and 12.0%, 7.6 and 7.4%, and 11.8 and 12.1% across the two consecutive seasons, respectively.

Table 6. Effect of poultry manure and micronutrients on N, P, and K percentages of coriander dried herb during the two growing seasons.

Micronutrients (M)	Poultry manure levels (m^3 ha^{-1}) (A)									
	First season					Second season				
	Control	PM1	PM2	PM3	Mean (M)	Control	PM1	PM2	PM3	Mean (M)
					N%					
Control	1.79	1.95	2.23	2.51	2.12	1.88	2.12	2.34	2.64	2.25
$MnSO_4$ (50 ppm)	1.95	2.27	2.54	2.58	2.34	2.07	2.39	2.61	2.68	2.44
$MnSO_4$ (100 ppm)	2.01	2.39	2.61	2.67	2.42	2.12	2.50	2.69	2.75	2.52
$ZnSO_4$ (50 ppm)	1.89	2.24	2.50	2.55	2.29	1.98	2.35	2.53	2.63	2.38
$ZnSO_4$ (100 ppm)	2.00	2.36	2.55	2.62	2.38	2.10	2.48	2.63	2.70	2.48
Mean (P)	1.93	2.24	2.49	2.59		2.03	2.37	2.56	2.68	
LSD 0.05	PM: 0.10		M: 0.06	PMxM: 0.13		PM: 0.11		M: 0.06	PMxM: 0.13	
					P%					
Control	0.314	0.336	0.345	0.375	0.342	0.334	0.356	0.366	0.394	0.363
$MnSO_4$ (50 ppm)	0.326	0.347	0.378	0.384	0.359	0.345	0.368	0.396	0.408	0.379
$MnSO_4$ (100 ppm)	0.337	0.358	0.383	0.393	0.368	0.357	0.380	0.405	0.419	0.390
$ZnSO_4$ (50 ppm)	0.324	0.340	0.374	0.381	0.355	0.344	0.360	0.392	0.404	0.375
$ZnSO_4$ (100 ppm)	0.334	0.357	0.380	0.387	0.364	0.354	0.377	0.399	0.414	0.386
Mean (P)	0.327	0.347	0.372	0.384		0.347	0.368	0.392	0.408	
LSD 0.05	PM: 0.013		M: 0.011	PMxM: 0.023		PM: 0.010		M: 0.014	PMxM: 0.027	
					K%					
Control	0.93	1.03	1.14	1.29	1.10	1.00	1.05	1.20	1.37	1.16
$MnSO_4$ (50 ppm)	0.99	1.15	1.23	1.27	1.16	1.05	1.19	1.30	1.39	1.23
$MnSO_4$ (100 ppm)	1.03	1.21	1.29	1.39	1.23	1.09	1.28	1.35	1.47	1.30
$ZnSO_4$ (50 ppm)	0.96	1.12	1.20	1.25	1.13	1.02	1.18	1.26	1.34	1.20
$ZnSO_4$ (100 ppm)	1.02	1.18	1.26	1.31	1.19	1.08	1.25	1.32	1.44	1.27
Mean (P)	0.98	1.14	1.22	1.30		1.05	1.19	1.28	1.40	
LSD 0.05	PM: 0.05		M: 0.05	PMxM: 0.10		PM: 0.08		M: 0.06	PMxM: 0.12	

PM1 = 7 m^3 ha^{-1}; PM2 = 14 m^3 ha^{-1}; PM3 = 21 m^3 ha^{-1}.

Combined effects of organic matter and micronutrients on nutrient percentages

The data in Table 6 highlight a significant influence of the combined application of organic matter and the evaluated micronutrients on the percentages of nitrogen (N), phosphorus (P), and potassium (K) across both experimental seasons, with certain exceptions. These exceptions include N% for the treatment of control PM with $ZnSO_4$ at 50 ppm in both seasons; P% for control PM with $MnSO_4$ at 50 ppm, control PM with $ZnSO_4$ at 50 ppm, control PM with $ZnSO_4$ at 100 ppm, and control PM with $MnSO_4$ at 100 ppm in the second season, as well as PM at 7 m^3 ha^{-1} with control micronutrients in both seasons; and K% for control PM with $MnSO_4$ at 50 ppm, control PM with $ZnSO_4$ at 50 ppm, control PM with $ZnSO_4$ at 100 ppm, and control PM with $MnSO_4$ at 100 ppm in the second season, along with PM at 7 m^3 ha^{-1} with control micronutrients in the second season. Nevertheless, the combined treatment of PM (21 m^3 ha^{-1}) with $MnSO_4$ at 100 ppm consistently demonstrated the most effective increases in N, P, and K percentages compared to all other interaction treatments across both seasons.

Discussion

This research demonstrated that integrating poultry manure with micronutrients, notably manganese and zinc, markedly enhances coriander growth parameters, yield attributes, essential oil production, and chemical constituents. Optimal results were obtained with a poultry manure application rate of 21 m^3 ha^{-1} combined with a 100 ppm $MnSO_4$ foliar spray, as evidenced by Tables 2–6. These improvements address the pervasive challenges of alkaline soils in arid regions such as Egypt, where elevated pH restricts the solubility of key nutrients including N, P, K, Zn, Mn, Fe, and Cu, thereby impeding medicinal plant cultivation.

Organic manures, particularly poultry manure, significantly improve soil fertility by lowering pH through rhizosphere acidification, driven by the release of hydrogen ions (H^+) and organic acids during organic matter decomposition (Hannachi et al., 2015; Angelova et al., 2013). They also increase total organic carbon, N, P, and other essential nutrients (Jones et al., 2012). This fosters enhanced nutrient solubility, improved soil chemical properties, greater organic matter content, higher cation exchange capacity (CEC), water-holding capacity, porosity, and microbial activity. Collectively, these improvements alleviate salinity and alkalinity stresses and optimize plant growth conditions (Elsakhawy et al., 2022; Elsonbaty et al., 2025; Paredes et al., 2016; Eid and El-Ghawwas, 2002; Abo Elazm, 2008; Ahmed et al., 2011; Kalbani et al., 2016; Jalali and Ranjbar, 2009; Tejada et al., 2006; Wang et al., 2014).

The nutrient profile of poultry manure, rich in N for cell division, P for metabolism, and K for structural integrity, further amplifies these effects. It promotes the mineralization of organic N and P into bioavailable forms during decomposition, thereby enhancing nutrient cycling, phytohormone synthesis, and root vigor (Mohamed, 2010; Agbede et al., 2008; Rezaei, 2013; Goswami et al., 2017). Empirical data reveal substantial increases in coriander-specific traits, including plant height, branching, herb dry weight, and fruit yield, particularly at higher application rates (Tables 2 and 3). These findings are consistent with broader research on medicinal plants such as chamomile, thyme, basil, cumin, and coriander, where organic manures similarly improved dry matter yield and plant height (Fallahi et al., 2008; Azizi et al., 2008; Safaei et al., 2014; Makizadeh et al., 2011; Ahmadian et al., 2009; Yogesh et al., 2016; Rania et al., 2022).

Beyond vegetative growth, poultry manure significantly increases essential oil percentage and yield (Table 4) through synergistic improvements in soil health, water retention, gradual nutrient uptake, rhizosphere microbial activity, nitrogen fixation, phytohormone release, nutrient retention, and reduced nitrogen loss (Shakir et al., 2019; Rahmanian et al., 2017; Edris et al., 2003; Lee et al., 2004; Taiwo et al., 2002; Omar et al., 2016). Higher application rates correlate with enhanced oil biosynthesis via improved nutrient absorption and enzyme activity, consistent with findings in caraway, coriander, dill, white lupin, *Thymus vulgaris*, *Mentha piperita* var. citrata, and basil (Omer et al., 2020; Hamza et al., 2021; Rasouli et al., 2022; Khalid and Shafei, 2005; Darzi et al., 2012; Santiago et al., 2008; Noroozisharaf and Kavian, 2018; Hendawy et al., 2015; Mahmoud et al., 2025).

In addition, poultry manure enhances plant tissue N, P, and K content (Table 6) by decomposing organic matter and releasing micronutrients (Fe, Zn, Mn) into soluble forms, thereby facilitating macronutrient uptake that promotes vegetative growth and dry weight accumulation (Adholeya and Prakash, 2004). These results are supported by Ayeni (2008), who reported increased plant uptake of N, P, and K with poultry manure, and by Ewulo et al. (2008) and Akanni and Ojeniyi (2008), who observed improved soil nutrient content and enhanced absorption of N, P, K, Ca, and Mg in tomato plants and Amaranthus. Collectively, these mechanisms underscore the transformative potential of poultry manure in sustainable agriculture, overcoming alkaline soil barriers to optimize medicinal plant productivity and quality.

Zinc and manganese are pivotal for plant growth, yield, and secondary metabolite production due to their critical roles in enzymatic activity, photosynthesis, and diverse metabolic processes (Das, 2014; Shebl et al., 2020). Zinc functions as a cofactor in numerous enzymatic reactions, regulating chlorophyll synthesis, pollen function, and fertilization, while also promoting cell division and elongation. These processes collectively enhance plant morphology, including plant height, branching, and shoot development (Kaya and Higgs, 2002; Cakmak, 2008; Pandey et al., 2006; Rosramifard et al., 2012). In this study, Zn supplementation significantly improved coriander's growth parameters, in agreement with Reda et al. (2014), who reported similar enhancements in faba bean, and with studies on medicinal plants such as *Ocimum basilicum*, *Pelargonium graveolens*, and *Salvia farinacea* (Said Al-Ahl and Mahmoud, 2010; Ayad et al., 2010; Nahed and Balbaa, 2007).

Manganese, equally essential, supports photosynthesis by acting as a cofactor in the oxygen-evolving complex of photosystem II, facilitating water splitting and electron transfer, which together enhance photosynthetic efficiency and biomass accumulation (Nickelsen and Rengstl, 2013; Chen et al., 2017; Ciurli et al., 2021). However, careful management of Mn application is crucial, as excessive levels can disrupt chloroplast structure and impair electron transport, ultimately leading to toxicity (Chen et al., 2017). Nazarovna et al. (2020) reported a 9.6% increase in plant height with low to medium Mn levels, but a 7.4% reduction at high levels, underscoring the need for precise dosing. In this study, the 100 ppm $MnSO_4$ application optimized growth without inducing toxicity, indicating an effective and safe concentration.

Photosynthesis, encompassing light absorption, electron transfer, energy fixation, and photoassimilate biosynthesis, is fundamental to plant growth and yield (Blankenship, 2014). Adequate Zn and Mn nutrition optimizes these processes by enhancing phosphorus and nitrogen utilization, auxin synthesis, and nucleic acid and protein production, all of which contribute to robust vegetative growth and seed development (Singh et al., 2002; Sharma et al., 1999; Guo et al., 2019; Bloom and Lancaster, 2018).

The synergistic effects of Zn and Mn in this study likely improved photosynthetic efficiency, as evidenced by increased herb dry weight and fruit yield (Tables 2 and 3). Mn deficiency, which typically causes chlorosis, necrosis, and reduced nutrient reutilization, was alleviated by $MnSO_4$ application, consistent with Mousavi et al. (2007), who reported positive impacts of micronutrient supplementation on crop yield. The combined application of Zn and Mn also significantly enhanced coriander fruit quality by catalyzing the breakdown of complex compounds into simpler forms, such as glucose, amino acids, and fatty acids, which improve germination and seedling development (Santosh, 2012). Zinc's role in auxin regulation and protein synthesis further supports seed production and quality, as reflected in higher germination rates and greater root and shoot elongation, consistent with Pariari et al. (2009) on fenugreek.

The essential oil yield likewise increased significantly with Zn and Mn treatments (Table 4), driven by higher fruit yield, enhanced enzyme activity, and improved metabolic efficiency. These results are in agreement with Khalid (2015) and Mehrab (2017), who reported increased essential oil yields in coriander and lemon balm with Zn and Mn supplementation, and with Akhtar et al. (2009), El-Tohamy et al. (2009), Soliman et al. (2015), and Andresen et al. (2018), who noted improved oil yields in various crops following micronutrient application.

GC-MS analysis identified 15 volatile compounds, with linalool (65.01% in T4), γ-terpinene (10.26% in T4), α-pinene (6.24% in T4), p-cymene (4.67% in T2), and geranyl acetate (6.61% in T3) as predominant constituents. Variations across treatments (T2: PM1 + $MnSO_4$; T3: PM2 + $MnSO_4$; T4: PM3 + $MnSO_4$) highlight the influence of micronutrient availability on terpenoid biosynthesis, mediated by Zn's role in enzyme activation and Mn contribution to metabolic efficiency.

The integrated use of poultry manure and Zn/Mn foliar sprays presents a sustainable approach to overcoming micronutrient deficiencies in alkaline soils, enhancing coriander growth, yield, and essential oil production. By addressing nutrient limitations and optimizing photosynthetic and metabolic processes, this strategy reduces dependence on synthetic fertilizers, aligning with sustainable agricultural practices in arid regions such as Egypt.

Conclusion

The current study illustrated that combining a high poultry manure application rate of 21 m^3 ha^{-1} with 100 ppm $MnSO_4$ foliar spray produces synergistic effects that significantly enhance vegetative growth, fruit yield, and essential oil output in coriander plants. This dual approach harnesses the nutrient-rich properties of poultry manure together with the growth-promoting effects of manganese sulfate to optimize plant performance. Specifically, the results demonstrate notable improvements in vegetative growth (greater plant height, branch number, and biomass), fruit yield (increased quantity and quality of coriander fruits), and essential oil production (enhanced yield of essential oil). This integrated strategy provides a promising, eco-friendly framework for improving both the quantity and quality of aromatic crop yields under practical field conditions, offering a sustainable option for farmers seeking to maximize productivity while minimizing environmental impact.

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Author Contributions

All authors contributed equally to the research and manuscript preparation. Their roles included writing the original draft, editing and refining the content and finalizing the manuscript for submission. All authors read and agreed to submit the manuscript to the journal, ensuring consensus on its content and conclusions. All authors have read and agreed to the published version of the manuscript.

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Conflict of Interest

The authors indicate no conflict of interest in this work.

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