Effect of Foliar and Soil Application of Chelated Zinc, Humic Acid, and Tryptophan Amino Acid Spray on the Growth and Yield of Maize (*Zea mays* L.) under Salt-Stressed Soil Conditions

MUNTAHA MAHMOUD JAWAD Hussein Aziz Mohammed [2]

Muntahamahmoud@uodiyala.edu.iq husseinaziz@uodiyala.edu.iq

[1,2]Department of Soil Science and Water Recourses College of Agriculture, University of Diyala, Diyala, Iraq

Abstract

A field experiment was conducted at the Research Station of the Department of Soil Sciences and Water Resources, College of Agriculture, University of Diyala, during the autumn season of 2025. The study aimed to evaluate the effects of chelating zinc application, humic acid, and foliar spraying of the amino acid tryptophan on the growth and yield of yellow corn (*Zea mays* L., cv. Drachma) grown in salt-affected soil. The study was laid out in a Randomized Complete Block Design (RCBD) using a factorial arrangement with three replications, comprising 36 experimental units. The experiment involved three factors: chelating zinc applied at three levels (0, 5, and 10 g plant^{-1}), humic acid at two levels (0 and 5 g plant^{-1}), and foliar application of tryptophan at two concentrations (0 and 100 mg L^{-1}). The recorded data were statistically analyzed using the SAS software, and the Least Significant Difference (LSD) test was adopted to compare treatment means at a probability level of 0.05%. The results are summarized as follows:

The addition of zinc at the third level (10 g plant^{-1}) decreased electrical conductivity (EC) values, increased soil organic matter percentage, increased available zinc concentration in the soil and in plant grains, and increased total grain yield, with statistically significant percentage increases/changes of (62.67%, 25.74%, 75.67%, 86.43%, and 21.31%, respectively).

Meanwhile, the application of humic acid at the second level (5 g plant^{-1}) led to a reduction in electrical conductivity values and an increase in soil organic matter percentage, available zinc concentration in the soil, grain zinc concentration, and total grain yield, with statistically significant increases of (19.72%, 29.41%, 91.17%, 29.23%, and 12.60%, respectively).

Furthermore, foliar spraying of amino acid at the second level (100 mg L^{-1}) significantly increased grain zinc content and total grain yield, with significant increases of (7.67% and 17.21%, respectively).

Scientific Keywords: Electrical Conductivity (EC), Soil Organic Matter (SOM), Available Zinc in Soil, Total Yield.

Introduction

Salinity stress represents a major constraint impacting crop productivity, necessitating the investigation of sustainable strategies to enhance plant tolerance (35). Saline environments exert negative effects on 20% of the world's arable land due to anthropogenic activities and climate change (8). High salinity causes osmotic stress, ionic imbalance, and toxicity through the excessive influx of sodium ions (Na^+), thereby impairing crucial physiological processes and vital functions in plants. Furthermore, salt

ISSN 2072-3857

stress inflicts cellular and membrane damage, disrupts photosynthetic activity, and elevates oxidative stress via the accumulation of reactive oxygen species (ROS), ultimately limiting overall crop yield (37).

Understanding the concept of stress tolerance in plants regarding its physiological mechanisms serves as a crucial objective (6). A comprehensive grasp of the physiological, biochemical, and genetic mechanisms underlying plant responses to saline conditions is indispensable and forms the focal point of botanical research, particularly under salt stress (14). Additionally, plants subjected to salinity often undergo various oxidative alterations, such as the generation of reactive oxygen species (ROS), lipid peroxidation, and the degradation of the plasma membrane (15). Consequently, unraveling the physiological and biochemical patterns of salinity tolerance can provide reliable selection criteria to enhance plant adaptability in saline environments (17).

Zinc (Zn) is considered an essential micronutrient for plant growth and the completion of its life cycle. However, it has not received sufficient attention in terms of fertilizer application, leading to crop yields containing low concentrations of this critical element. Consequently, this yields negative outcomes, manifested as reduced yield or the appearance of nutrient deficiency symptoms on the plant (25). Zinc is a vital nutrient playing a distinct role in plant growth; it contributes to mitigating the adverse effects of salinity stress. Zinc application enhances seed germination, increases water uptake efficiency, improves plant water relations, and optimizes nutrient uptake and homeostasis, thereby bolstering plant performance under saline conditions. Furthermore, zinc supplementation helps protect the photosynthetic apparatus from salinity-induced oxidative stress, promotes stomatal movement, chlorophyll biosynthesis, and carbon fixation. It also increases hormone levels and stimulates antioxidant enzyme activities to counteract the toxic effects of salt stress (18). Humic acid mitigates abiotic stresses by increasing chlorophyll content, enhancing photosynthesis, and boosting antioxidant enzyme activities, as reported by (26). Additionally, it regulates osmotic balance, promotes osmotic adjustments, and improves salinity tolerance (42). Humic acid increases proline accumulation in salt-stressed plants, reduces osmotic stress, and its application is associated with a decrease in glycine betaine (GB) content in plants subjected to salt stress, indicating an improvement in water status and balance, and thus mitigating the damage of salt accumulation (5). In recent years, diverse studies have revealed the potential role of humic acid in enhancing plant salt tolerance. As a biostimulant, humic acid plays a major role in maintaining physiological activities during salt stress exposure by upregulating antioxidant production through the regulation of genes conferring salinity tolerance (26). Organic humic acids, including humic acid, play an essential role in promoting plant growth by increasing nutrient availability and helping prevent nutrient leaching from the soil (38).

Amino acids are considered biostimulants that not only enhance protein synthesis but also regulate cellular energy, redox balance, and cellular immune functions (20). Tryptophan is a unique amino acid containing an indole ring. Upon entering plant cells, tryptophan is converted into numerous secondary products such as serotonin, niacin, and auxins (30). Tryptophan promotes plant growth and productivity through the continuous release of auxins. Moreover, foliar- or soil-applied tryptophan exhibits positive effects on auxin biosynthesis and its cross-talk with plant hormones, not only under optimal conditions but also under environmental stress conditions (27).

Maize (*Zea mays* L.) is a major economically important cereal crop due to its nutritional value in human and animal diets. Maize is fast-growing and yields abundantly within a period not exceeding three months, with the

ISSN 2072-3857

capacity to produce green forage exceeding 70 t/h (3). Maize ranks as the second most widely cultivated crop globally, contributing approximately 1,137 million metric tons to global production, significantly supporting global food security, and driving gross domestic product (GDP) growth across countries, with the United States being the leading producer (32). Osmotic and ionic stresses are primarily responsible for reducing cereal growth; salinity negatively affects maize growth and yield throughout the plant's life cycle depending on the duration and severity of the stress (11).

This study aims to:

1.Evaluate the effects of zinc application, humic acid, tryptophan foliar spraying, and their interactions on various soil properties under salt stress conditions.

2.Determine the effects of zinc application, humic acid, tryptophan foliar spraying, and their interactions on the growth and yield of maize (*Zea mays* L.) under salt stress conditions.

3. Assess the physiological and productive responses of maize, as well as soil characteristics, to the different treatments (chelated zinc, humic acid, and the amino acid tryptophan). Note that economic feasibility was beyond the scope of the present study.

Materials and Methods

A field experiment was conducted at the College of Agriculture, University of Diyala (Postgraduate Research Project Site), during the autumn season of 2025–2026. The objective was to evaluate the effect of chelated zinc soil application, humic acid soil application, and tryptophan foliar spraying on the growth and yield of yellow corn (*Zea mays* L.) grown in saline-affected soil. The trial was carried out over a single growing season at a single site to ensure precise control over environmental variables and experimental factors, as well as to guarantee study completion within the approved academic timeframe. Some chemical and physical properties of the experimental soil, measured according to standard methods reported in (34), are presented in Table 1.

The study was laid out in a Randomized Complete Block Design (RCBD) using (2×2×3) a factorial arrangement. Accordingly, the experiment comprised 12 treatment combinations, replicated three times, yielding a total of 36 experimental units. Data were subjected to statistical analysis using SAS software, and treatment means were compared using the Least Significant Difference (LSD) test at the probability level 0.05%.

The study included three experimental factors:

Chelated Zinc (Zn): Applied to the soil at three levels (0, 5, and 10 g plant^{-1}).

Humic Acid: Applied to the soil at two levels (0 and 5 g plant^{-1}).

Tryptophan: Applied as a foliar spray at two concentrations (0 and 100 mg L^{-1}). Spray solutions were prepared by dissolving the specified amounts in distilled water, with a surfactant added to reduce surface tension. Foliar spraying was performed twice during the growing season: the first at the 6–8 leaf stage (25–35 days after sowing), and the second 7–10 days prior to tasseling (45–55 days after sowing). Applications were conducted during early morning hours to maximize absorption efficiency and minimize evaporative loss.

The experimental land was divided into three blocks, each containing 12 experimental units, separated by 1.5 m buffer alleys between adjacent blocks. Yellow corn seeds (cv. *Drachma*) were sown on July 20, 2025, at a seeding rate of 4 seeds per hill. A strip irrigation system was utilized to meet crop water requirements. Organic manure (sheep

ISSN 2072-3857

manure) was incorporated into the soil at a rate of 50 kg per experimental unit. Each experimental unit measured 7 m in length and 1 m in width.

Empirical measurements

Soil Electrical Conductivity (EC): Electrical conductivity was measured using a 1:1 (w/v) soil-to-water ratio according to the method described by (34).

Soil Organic Matter (OM): Soil organic matter was determined by the potassium dichromate oxidation method (Walkley-Black Method) as outlined in (19).

Available Soil Zinc Concentration (mg kg^{-1} soil): Available zinc (Zn) in the soil was estimated following the method of (22) using DTPA extracting solution (0.005 M DTPA + 0.1 M Triethanolamine + 0.01 M $CaCl_2$ عند pH=7.3). Ten grams of soil were shaken with (20ml) of the extracting solution for two hours, after which the solution was filtered, and the zinc concentration was measured using an Atomic Absorption Spectrophotometer.

Grain Zinc Concentration (%): Zinc (Zn) content in maize grains was determined following sample digestion. Briefly, (0.5gm) of finely ground, dry seed sample was digested using a concentrated acid mixture of nitric acid (HNO_3) and perchloric acid ($HClO_4$) until a clear solution was obtained. The solution was then filtered and brought to volume with distilled water. Subsequently, the zinc concentration was measured using an Atomic Absorption Spectrophotometer (AAS), according to the standard method described in the *Official Methods of Analysis* of the Association of Official Analytical Chemists (AOAC) (1).

Total Grain Yield (t/h): Total grain yield was determined by harvesting three plants selected randomly from the center of each experimental unit. The average weight per plant was obtained using a sensitive analytical balance. Total grain yield was then converted and expressed in metric tons per hectare (t/h) by dividing the yield in grams by 1,000,000, according to equation (29).

$$\text{Total grain yield (t ha}^{-1}) = \frac{\text{Grain yield per plant (g)} \times \text{Plant density}}{1000000}$$

Table (1) Some chemical and physical properties of the soil sample used prior to planting.

الوحدة	القيمة	الصِفة	
dsm^{-1}	36.2	EC (1:1)	
	8.26	pH (1:1)	
gm kg^{-1} soil	1.16	Organic Matter	
	286.0	$CaCo_3$	
mg kg^{-1} soil	7.0	Available Nitrogen	Available Nutrients
	6.38	Available Phosphorus	
	131.0	Available Potassium	
	0.60	Available Zinc	
gm cm^3	1.6	Bulk Density	
%	48.31	) Clay(	Soil texture
	28.70	) Silt(	
	22.99	) Sand(	
	) Silty clay(		

ISSN 2072-3857

RESULTS AND DISCUSSION

Soil Electrical Conductivity (EC) (ds m□¹)

The results presented in Table (2) indicate that the control level without zinc application (Zn□) significantly exceeded the third level (Zn□□) and the second level (Zn□) in this trait, recording a mean of 17.00 ds m□¹ compared to 10.45 ds m□¹ and 13.01 ds m□¹, respectively.

Regarding humic acid, the control treatment without application (H□) significantly surpassed the second level (H□), achieving a mean of 14.69 ds m□¹ compared to 12.27 ds m□¹, with an increase percentage of 19.72%.

Similarly, the non-foliar application level of the amino acid tryptophan (T□) significantly exceeded the foliar spray treatment (T□□□), obtaining a mean of 14.07 ds m□¹ compared to 12.89 ds m□¹, representing an increase percentage of 9.15%.

The dual interaction between zinc and humic acid (Zn × H) led to a reduction in soil EC values; the highest mean (18.68 ds m□¹) was observed under the treatment combination (Zn□ g plant□¹ + H□ g plant□¹), whereas the lowest mean (9.55 ds m□¹) was recorded under (Zn□□ g plant□¹ + H□ g plant□¹), with a percentage difference of 95.60%.

Significant differences were also observed for the interaction between zinc levels and tryptophan foliar application levels (Zn × T). The highest mean for this trait reached 18.19 ds m□¹ under the (Zn□ g plant□¹ + T□ mg L□¹) treatment combination, while the lowest mean was 10.06 ds m□¹ under (Zn□□ g plant□¹ + T□□□ mg L□¹), with a percentage difference of 43.24%.

Furthermore, the interaction between humic acid levels and tryptophan application levels (H × T) was statistically significant. The (H□ g plant□¹ + T□ mg L□¹) treatment yielded the highest mean value of 15.49 ds m□¹, whereas the (H□ g plant□¹ + T□□□ mg L□¹) treatment recorded the lowest value at 11.88 ds m□¹, with a percentage difference of 30.38%.

As for the three-way interaction among zinc, humic acid, and tryptophan foliar application (Zn × H × T), the highest mean for this trait (19.53 ds m□¹) was observed under the combination (Zn□ g plant□¹ + H□ g plant□¹ + T□ mg L□¹), whereas the lowest mean (9.08 ds m□¹) was recorded under (Zn□□ g plant□¹ + H□ g plant□¹ + T□□□ mg L□¹), reflecting a percentage difference of 115.08%.

Table (2): Effect of Zinc Addition, Humic Acid, and Tryptophan Foliar Application on Soil Electrical Conductivity (EC) in Saline-Affected Soil.

Zn*H	Foliar application of the amino acid tryptophan (mg L□¹)		Application of humic acid (g plant□¹)	Chelated Zinc Application (g plant□¹) Zn
	100	0		
18.68	17.83	19.53	**0**	**0**
15.32	13.78	16.86	**5**	
14.05	12.82	15.28	**0**	**5**
11.96	12.80	11.12	**5**	
11.35	11.04	11.66	**0**	**10**

ISSN 2072-3857

9.55	9.08	10.02	**5**	
0.85	1.25		**LSD 0.05**	
Average Zn				
17.00	15.81	18.19	**0**	**Zn*T**
13.01	12.81	13.20	**5**	
10.45	10.06	10.84	**10**	
0.59	0.85		**LSD 0.05**	
Average H				
14.69	13.89	15.49	**0**	**H*T**
12.27	11.88	12.66	**5**	
0.35	0.66		**LSD 0.05**	
	12.89	14.07	**Average T**	
	0.35		**LSD 0.05**	

The symbols refer to: Zn_0 = no zinc addition, Zn_5 = zinc addition at (5 gm plant^{-1}), Zn_{10} = zinc addition at (10 gm plant^{-1}), H_0 = no humic acid addition, H_5= humic acid addition at (5gm plant^{-1}), T_0 = no foliar application of tryptophan amino acid, T_{100} = foliar application of tryptophan amino acid at (100 mg L^{-1}).

Soil Organic Matter Percentage (%)

The results presented in Table 3 demonstrated that the third zinc application level (Zn_{10}) significantly surpassed the control level (Zn_0) in increasing the soil organic matter percentage, recording an average of 1.27% compared to 1.01% for the control, representing an increase of 25.74%.

Similarly, the second humic acid application level (H_5) significantly outperformed the non-treated control (H_0), achieving an average of 1.32% against 1.02% for the control, with an increase rate of 29.41%.

The results in the same table also highlight a significant interaction effect between zinc and humic acid applications on boosting soil organic matter percentage. The highest average (1.48%) was recorded under the combination of (Zn_{10} gm plant^{-1} + H_5 gm plant^{-1}), whereas the lowest average (0.84%) was observed in the absence of both treatments, yielding a significant increase of 76.19%.

Regarding the interaction between zinc levels and tryptophan foliar application, significant differences were observed. The highest average soil organic matter percentage reached 1.33% under the treatment combination (Zn_{10} gm plant^{-1} + T_{100} mg L^{-1}), whereas the lowest value (0.92%) was recorded under (Zn_0 gm plant^{-1} + T_0 mg L^{-1}), marking an increase of 44.56%.

For the interaction between humic acid and tryptophan levels, a statistically significant effect was also evident. The treatment (H_5 gm plant^{-1} + T_{100} mg L^{-1}) recorded the highest mean value of 1.38%, while the control combination (H_0 gm plant^{-1}+ T_0 gm plant^{-1})

ISSN 2072-3857

yielded the lowest mean value of 0.94%, with an increase rate of 46.81%.

The three-way interaction among zinc, humic acid, and tryptophan foliar spraying had a statistically significant positive effect on enhancing soil organic matter content. The highest percentage (1.55%) was achieved with the combined application level (Zn_{10} gm plant^{-1} + H_5 gm plant^{-1} + T_{100} mg L^{-1}), whereas the lowest mean (0.77%) was recorded in the control treatment lacking all three compounds, reflecting an overall increase of 101.29%.

Table (3) Effect of Zinc and Humic Acid Soil Addition and Tryptophan Foliar Application on Soil Organic Matter Percentage (%) in Saline-Affected Soil.

Zn*H	Foliar application of the amino acid tryptophan (mg L□¹)		Application of humic acid (g plant□¹)	Chelated Zinc Application (g plant□¹) Zn
	100	0		
0.84	0.91	0.77	0	0
1.18	1.29	1.07	5	
1.17	1.32	1.03	0	5
1.31	1.32	1.29	5	
1.07	1.11	1.03	0	10
1.48	1.55	1.42	5	
0.35	0.42		LSD 0.05	
Average Zn				
1.01	1.10	0.92	0	Zn*T
1.24	1.32	1.16	5	
1.27	1.33	1.22	10	
0.12	0.35		LSD 0.05	
Average H				
1.02	1.11	0.94	0	H*T
1.32	1.38	1.26	5	
0.19	0.20		LSD 0.05	
	1.25	1.10	Average T	
	N.S		LSD 0.05	

The symbols refer to: Zn_0 = no zinc addition, Zn_5 = zinc addition at (5 gm plant^{-1}), Zn_{10} = zinc addition at (10 gm plant^{-1}), H_0 = no humic acid addition, H_5= humic acid addition at (5gm plant^{-1}), T_0 = no foliar application of tryptophan amino acid, T_{100} = foliar application of tryptophan amino acid at (100 mg L^{-1}).

ISSN 2072-3857

The results showed that the addition of zinc to the soil at a rate of 10 g plant^{-1} resulted in a decrease in electrical conductivity (EC) values compared to the non-addition control, while increasing the soil organic matter content, as presented in Tables (2 and 3). The addition of mineral fertilizers such as zinc sulfate ($ZnSO_4$) dissociates in the soil solution into zinc ions (Zn^{+2}) and sulfate ions (SO_4^{+2}); this increase in soluble ion concentration typically elevates the soil's electrical conductivity (EC). Conversely, adding zinc in a chelated form such as Zn-EDTA or as insoluble compounds like zinc oxide (ZnO) exerts a significantly lower effect on increasing EC compared to highly soluble mineral salts. Regarding soil organic matter, the addition of zinc as a micronutrient does not directly add substantial organic matter to the soil; however, it stimulates plant growth and root biomass. The resulting increase in root tissue and root exudates subsequently leads to the long-term enrichment of soil organic matter. Numerous factors influence the availability of zinc to plants, including soil texture, organic matter content, soil electrical conductivity (EC), soil pH, calcium carbonate content, macronutrients such as phosphorus, as well as soil temperature and moisture (40).

The observed reduction in electrical conductivity and the increase in organic matter may be attributed to the vital role of humic acid addition in improving the plant environment. Humic acid is characterized by a high cation exchange capacity (CEC), enabling it to adsorb and bind toxic sodium (Na^+) and chloride (Cl^{-1}) ions on its surfaces, thereby reducing the concentration of free salts in the soil solution adjacent to the roots. Humic acid enhances soil permeability and structure, which facilitates the leaching of harmful salts beyond the root zone during irrigation. Furthermore, it mitigates the adverse effects of high electrical conductivity by lowering osmotic pressure on the plant and improving water and nutrient uptake. The application of humic acid directly increases the amount of soil organic matter, as it represents the primary and chemically most active component of stable organic matter (humus); its addition directly elevates the active organic matter fraction in the soil. Additionally, humic acid stimulates microbial activity and soil microorganisms, fostering the mineralization and decomposition of plant residues into stable humus. Humic acid also binds to clay particles to form stable aggregates, thereby reducing the loss or rapid leaching of organic matter and maintaining its stability (16).

Available Zinc Concentration in Soil (mg Zn kg^{-1} soil)

The results in Table (4) indicated that zinc application at the third level (Zn10) achieved the highest soil zinc concentration, with a mean of 0.65 mg kg^{-1} soil. This was significantly superior to the first level (Zn0), which recorded 0.37 mg kg^{-1} soil, and the second level (Zn5), which reached 0.48 mg kg^{-1} soil, representing percentage increases of 75.67% and 35.41%, respectively.

The second level of humic acid application (H5) significantly surpassed the first level (H0), achieving a mean of 0.65 mg kg^{-1} soil compared to 0.34 mg kg^{-1} soil for H0, with an increase percentage of 91.17%.

The second level of foliar-applied tryptophan (T100) recorded the highest mean for this trait at 0.51 mg kg^{-1} soil, significantly outperforming the first level (T0), which achieved a mean of 0.49 mg kg^{-1} soil, representing a significant increase of 4.08%.

The interaction between zinc and humic acid (Zn × H) significantly increased soil zinc concentration. The highest mean was recorded at 0.79 mg kg^{-1} soil under the treatment

ISSN 2072-3857

(Zn10 g plant□¹ + H5 g plant□¹), whereas the lowest mean was 0.26 mg kg□¹ soil under the treatment (Zn0 g plant□¹ + H0 g plant□¹), representing an increase of 203.84%.

Regarding the interaction between zinc levels and tryptophan foliar spray levels (Zn × T), significant differences were observed. The highest mean soil zinc concentration reached 0.65 mg kg□¹ soil under the treatment (Zn10 g plant□¹ + T100 mg L□¹), while the lowest mean was 0.35 mg kg□¹ soil under the treatment (Zn0 g plant□¹ + T0 mg L□¹), with an increase percentage of 85.71%.

The interaction between humic acid levels and tryptophan foliar application levels was also statistically significant. The treatment (H5 g plant□¹ + T100 mg L□¹) yielded the highest mean for this trait at 0.66 mg kg□¹ soil, whereas the treatment (H0 g plant□¹ + T0 mg L□¹) produced the lowest value at 0.34 mg kg□¹ soil, with an increase percentage of 94.11%.

Furthermore, the three-way interaction among zinc application, humic acid, and tryptophan foliar spray achieved the highest mean for this trait at 0.80 mg kg□¹ soil under the treatment (Zn10 g plant□¹ + H5 g plant□¹ + T100 mg L□¹), while the lowest mean was 0.24 mg kg□¹ soil under the treatment (Zn0 g plant□¹ + H0 g plant□¹ + T0 mg L□¹), representing an increase of 233.33%.

Table (4): Effect of Zinc Addition, Humic Acid, and Tryptophan Foliar Application on Available Soil Zinc Concentration (mg kg□¹ Soil) in Salt-Affected Soil.

Zn*H	**Foliar application of the amino acid tryptophan (mg L□¹)**		**Application of humic acid (g plant□¹)**	**Chelated Zinc Application (g plant□¹) Zn**
	100	**0**		
0.26	0.29	0.24	**0**	**0**
0.47	0.49	0.46	**5**	
0.27	0.28	0.27	**0**	**5**
0.27	0.70	0.68	**5**	
0.50	0.50	0.51	**0**	**10**
0.79	0.80	0.79	**5**	
0.35	0.37		**LSD 0.05**	
Average Zn				
0.37	0.39	0.35	**0**	**Zn*T**
0.48	0.49	0.47	**5**	
0.65	0.65	0.65	**10**	
0.15	0.35		**LSD 0.05**	
Average H				
0.34	0.35	0.34	**0**	**H*T**
0.65	0.66	0.64	**5**	

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0.10	0.25		**LSD 0.05**
	0.51	0.49	**Average T**
	N.S		**LSD 0.05**

The symbols refer to: Zn_0 = no zinc addition, Zn_5 = zinc addition at (5 gm plant^{-1}), Zn_{10} = zinc addition at (10 gm plant^{-1}), H_0 = no humic acid addition, H_5= humic acid addition at (5gm plant^{-1}), T_0 = no foliar application of tryptophan amino acid, T_{100} = foliar application of tryptophan amino acid at (100 mg L^{-1}).

Zinc Concentration in Grains (mg kg□¹ Dry Matter)

Results in Table (5) indicated that the third level of zinc application (Zn10) achieved the highest zinc concentration in grains, with a mean of 37.94 mg kg□¹ dry matter. It significantly surpassed the first level (Zn0), which recorded a mean of 20.35 mg kg□¹ dry matter, and the second level (Zn5), which reached 27.81 mg kg□¹ dry matter, representing increase percentages of 86.43% and 36.42% for the different application levels, respectively.

The second level of humic acid application (H5) was significantly superior, recording a mean of 32.40 mg kg□¹ dry matter compared to the first level (H0), which yielded 25.07 mg kg□¹ dry matter, representing an increase percentage of 29.24%.

The second level of tryptophan amino acid foliar application (T100) achieved a mean of 29.76 mg kg□¹ dry matter, outperforming the first level (T0), which recorded 27.64 mg kg□¹ dry matter, with an increase percentage of 7.67%.

The two-way interaction between zinc and humic acid (Zn × H) significantly affected the increase of zinc content in grains. The highest mean was recorded under the treatment combination (Zn10 g plant□¹ + H5 g plant□¹) at 43.56 mg kg□¹ dry matter, while the lowest mean was recorded under the treatment combination (Zn0 g plant□¹ + H0 g plant□¹) at 18.04 mg kg□¹ dry matter, achieving an increase percentage of 141.46%.

Regarding the interaction between zinc application levels and tryptophan foliar application levels (Zn × T), significant differences were observed. The highest mean (39.70 mg kg□¹ dry matter) was recorded under the treatment combination (Zn10 g plant□¹ + T100 mg L□¹), whereas the lowest mean for this trait (19.93 mg kg□¹ dry matter) was recorded under the treatment combination (Zn0 g plant□¹ + T0 mg L□¹), showing an increase percentage of 99.19%.

Concerning the interaction between humic acid levels and tryptophan foliar application levels (H × T), it proved to be statistically significant. The treatment combination (H5 g plant□¹ + T100 mg L□¹) yielded the highest mean for this trait (33.13 mg kg□¹ dry matter), while the treatment combination (H0 g plant□¹ + T0 mg L□¹) gave the lowest value (23.62 mg kg□¹ dry matter), representing an increase percentage of 40.26%.

The three-way interaction among zinc, humic acid, and tryptophan foliar application achieved the highest mean for this trait at 44.50 mg kg□¹ dry matter under the treatment combination (Zn10 g plant□¹ + H5 g plant□¹ + T100 mg L□¹), whereas the lowest mean (17.83 mg kg□¹ dry matter) was recorded under the control treatment combination (Zn0 g plant□¹ + H0 g plant□¹ + T0 mg L□¹), with an overall increase percentage of 149.57%.

ISSN 2072-3857

Table (5): Effect of Zinc Addition, Humic Acid, and Tryptophan Foliar Application to Salt-Affected Soil on Grain Zinc Concentration (mg kg^{-1} Dry Matter).

Zn*H	Foliar application of the amino acid tryptophan (mg L□¹)		Application of humic acid (g plant□¹)	Chelated Zinc Application (g plant□¹) Zn
	100	0		
18.04	18.26	17.83	**0**	**0**
22.66	23.30	22.03	**5**	
24.65	26.00	23.30	**0**	**5**
30.96	31.60	30.33	**5**	
32.31	34.90	29.73	**0**	**10**
43.56	44.50	42.63	**5**	
10.22	12.00		**LSD 0.05**	
Average Zn				
20.35	20.78	19.93	**0**	**Zn*T**
27.81	28.8	26.81	**5**	
37.94	39.7	36.18	**10**	
8.15	10.22		**LSD 0.05**	
Average H				
25.07	26.51	23.62	**0**	**H*T**
32.40	33.13	31.66	**5**	
1.70	7.16		**LSD 0.05**	
	29.76	27.64	**Average T**	
	1.70		**LSD 0.05**	

The symbols refer to: Zn_0 = no zinc addition, Zn_5 = zinc addition at (5 gm $plant^{-1}$), Zn_{10} = zinc addition at (10 gm $plant^{-1}$), H_0 = no humic acid addition, H_5= humic acid addition at (5gm $plant^{-1}$), T_0 = no foliar application of tryptophan amino acid, T_{100} = foliar application of tryptophan amino acid at (100 mg L^{-1}).

The results revealed that applying zinc to the soil at a level of (10 g plant□¹) led to a significant increase in soil nutrient availability and in the grain zinc (Zn) concentration of yellow corn (maize), as shown in Tables (4 and 5). This is attributed to zinc being an essential element involved in fundamental plant metabolic processes, enhancing growth, productivity, and the quality of available soil nutrients. Estimates indicate that more than

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half of the soils used for food crop cultivation suffer from zinc deficiency. Furthermore, micronutrient fertilization has been proven to exert a profound effect on a wide range of crops (39).

The findings demonstrated a significant increase in available soil zinc upon zinc application. The primary nutrient status of the soil at maize harvest was markedly affected by applying different forms and methods of zinc, with the highest concentrations recorded for nitrogen, phosphorus, potassium, and zinc. This superior accumulation of nitrogen, phosphorus, potassium, and zinc can be explained by the formation of stable complexes between zinc and functional groups—such as phenolic, hydroxyl, carboxyl, and amine groups—present in the soil, which assist in retaining zinc in a mobile and plant-available pool (41). According to (43), humic substances are recognized for exhibiting auxin-like effects resulting from the stimulation of plasma membrane ATPase activity, an underlying mechanism involving ATPase participation. This enzyme amplifies the electrochemical gradient and accelerates nutrient uptake, as evidenced by the upregulated expression of transporter genes (33). This occurs through altering gene expression and the biosynthesis of chemical compounds within plant cells, such as those involved in the Krebs cycle, nitrate reduction, phosphorus metabolism, glycolysis, and photosynthesis, alongside the influence of humic acids on secondary metabolism (36). Moreover, humic acid is considered particularly crucial for boosting soil microbial activity, accelerating seed germination, and facilitating the uptake of nutrients, including nitrogen, phosphorus, potassium, and zinc (9). Numerous studies have shown that humic acid application not only promotes plant growth and improves crop quality across various cultivated species, but also enhances the chemical and physical properties of the soil. (23) observed that soils treated with humic acid contained significantly higher zinc levels compared to untreated soils, likely due to the presence of hydrophilic and hydrophobic domains that enhance surface activity. Humic chemical substances function as nutrient carriers and bind to cell membrane components (12).

Furthermore, the results showed that adding zinc to the soil at a rate of (10 g plant^{-1}) significantly increased grain zinc concentration, as detailed in Table (5). The positive response to varying zinc application concentrations can be interpreted by its initial low availability in the field soil (Table 5)—a level insufficient to satisfy the requirements of yellow corn, especially given that the optimal critical threshold for soil zinc content is (1.5 mg kg^{-1} soil). The experimental field soil is saline, characterized by high carbonate mineral content (286.0 g kg^{-1} soil), an alkaline reaction (pH 8.26), and low organic matter content (1.16 g kg^{-1} soil), resulting in poor nutrient availability. Consequently, applying zinc at (10 g plant^{-1}) raised the concentrations of available nutrients in the soil—specifically nitrogen, phosphorus, potassium, and zinc—thereby enhancing their accumulation in the crop yield (2).

The elevated concentrations of nitrogen, phosphorus, potassium, and zinc in the grains upon humic acid application may be attributed to its effective role in facilitating soil nutrient uptake. (13) pointed out that humic acid helps mitigate the negative impacts of salinity stress, thereby increasing the availability of both macro- and micronutrients (including N, P, K, and Zn), enhancing cell membrane permeability, and elevating tissue nutrient concentrations within the plant. Additionally, the increase in grain N, P, K, and Zn concentrations following the foliar application of the amino acid tryptophan may stem from its key role in enhancing plant absorption efficiency. As noted by (24), tryptophan spraying produced a significant increase in the plant content of nitrogen, phosphorus, potassium, and zinc, thereby enhancing the plant's physiological response to supplementary nutrients.

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Total Grain Yield (t ha□¹)

The results presented in Table (6) indicate that the third level of zinc application (Zn10) significantly surpassed the first level (Zn0) and the second level (Zn5) in total grain yield, recording a mean of 15.31 t ha□¹. This represents significant increases of 21.31% and 15.02% over the Zn0 level (12.62 t ha□¹) and Zn5 level (13.31 t ha□¹), respectively. Regarding humic acid application, the second level (H5) significantly surpassed the first level (H0), recording a mean of 14.56 t ha□¹ compared to 12.93 t ha□¹ for H0, with an increase percentage of 12.61%. Similarly, the results showed that the second level of tryptophan amino acid foliar spraying (T100) was significantly superior to the first level (T0), yielding a mean of 14.84 t ha□¹ compared to 12.66 t ha□¹ for T0, representing an increase of 17.21%.

The two-way interaction between zinc and humic acid (Zn × H) resulted in an increase in total grain yield. The highest mean yield reached 16.15 t ha□¹ under the treatment combination (Zn10 g plant□¹ + H5 g plant□¹), whereas the lowest mean was 12.02 t ha□¹ observed in the control treatment (Zn0 g plant□¹ + H0 g plant□¹), achieving an increase of 34.35%. Furthermore, the interaction between zinc levels and tryptophan foliar spraying levels (Zn × T) showed significant differences. The highest mean total grain yield was 16.51 t ha□¹ recorded under the treatment combination (Zn10 g plant□¹ + T100 mg L□¹), while the lowest mean was 11.84 t ha□¹ under the control treatment (Zn0 g plant□¹ + T0 mg L□¹), with an increase percentage of 39.44%.

The interaction between humic acid levels and tryptophan spraying levels also exhibited significant differences. The treatment combination (H5 g plant□¹ + T100 mg L□¹) produced the highest mean for this trait (15.74 t ha□¹), whereas the treatment combination (H0 g plant□¹ + T0 mg L□¹) recorded the lowest value (11.93 t ha□¹), with an increase of 31.93%.

Finally, the three-way interaction among zinc, humic acid, and tryptophan amino acid foliar application achieved the highest mean total grain yield of 17.52 t ha□¹ under the treatment combination (Zn10 g plant□¹ + H5 g plant□¹ + T100 mg L□¹), while the lowest mean of 11.16 t ha□¹ was obtained in the control treatment (Zn0 g plant□¹ + H0 g plant□¹ + T0 mg L□¹), representing an overall increase of 56.98%.

Table (6) Effect of zinc and humic acid application and tryptophan amino acid foliar spray on total grain yield (Mg ha□¹) in a salt-affected soil.

Zn*H	Foliar application of the amino acid tryptophan (mg L□¹)		Application of humic acid (g plant□¹)	Chelated Zinc Application (g plant□¹) Zn
	100	0		
12.02	12.88	11.16	**0**	**0**
13.22	13.93	12.52	**5**	
12.31	13.43	11.17	**0**	**5**
14.32	15.76	12.88	**5**	

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14.48	15.49	13.47	**0**	**10**
16.15	17.52	14.77	**5**	
2.00	2.14		**LSD 0.05**	
Average Zn				
12.62	13.41	11.84	**0**	**Zn*T**
13.31	14.59	12.03	**5**	
15.31	16.51	14.12	**10**	
1.35	2.00		**LSD 0.05**	
Average H				
12.93	13.94	11.93	**0**	**H*T**
14.56	15.74	13.39	**5**	
1.10	1.60		**LSD 0.05**	
	14.84	12.66	**Average T**	
	1.10		**LSD 0.05**	

The symbols refer to: Zn_0 = no zinc addition, Zn_5 = zinc addition at (5 gm plant^{-1}), Zn_{10} = zinc addition at (10 gm plant^{-1}), H_0 = no humic acid addition, H_5= humic acid addition at (5gm plant^{-1}), T_0 = no foliar application of tryptophan amino acid, T_{100} = foliar application of tryptophan amino acid at (100 mg L^{-1}).

The results show that adding zinc to the soil (10 g plant□¹) achieved a significant increase in total grain yield, as shown in Table (6). This is attributed to its vital role in phosphorylation processes, glucose synthesis, and its entry into numerous enzyme systems regulating metabolic reactions, as well as its important role in pollen formation, fertilization, flowering, fruit production, and mature seed formation (28). This aligns with (2), who noted the importance of zinc in phosphorylation processes, glucose formation, lipid and glycerol synthesis, and starch formation in seeds. Furthermore, zinc participates in more than 500 plant proteins and acts against free radicals that react with cellular molecules, thereby protecting cells against various oxidative stresses.

The increase in total grain yield may also be attributed to the vital role of humic acid application in improving the plant growth environment. (21) indicated that adding humic acid to the soil contributes to improving its physical properties, reducing bulk density, and increasing total porosity. This provides better aeration and promotes the spread and deep establishment of the root system, which positively reflects on water and nutrient uptake efficiency (26). In addition, humic acid encourages the growth and proliferation of microorganisms, plays a key role in biotic and abiotic reactions within the rhizosphere, and increases the availability and uptake of soil nutrients. Consequently, this enhances dry matter accumulation, leading to higher biological yield, individual plant yield, and overall productivity (42).

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The significant superiority in total grain yield under tryptophan foliar application may be attributed to the role of this amino acid as an essential building block in protein synthesis. Tryptophan itself serves as an important source of nitrogen and carbon, plays a major role in reducing flower drop, promotes fruit ripening, improves crop quality and quantity, and aids in response mechanisms against biotic and abiotic stresses (7).

The application levels for chelated zinc, humic acid, and tryptophan foliar spray were selected based on previous studies demonstrating the efficacy of these concentrations in improving soil properties and mitigating salinity stress. The control treatment (0 g plant□¹) was included to evaluate baseline plant performance without additives, whereas the two levels (5 and 10 g plant□¹) were selected to test the dose-response effect and determine significant differences and maximum growth and productivity responses compared to the control.

As clarified by (31), the amino acid tryptophan was selected at two spraying levels (0 and 100 ppm). Similarly, (10) reported the use of three levels of chelated zinc fertilizer (0, 5, and 10 kg ha□¹). The application levels for humic acid (0 and 5 g plant□¹) were selected to determine the effects of both levels and evaluate the differences between them in terms of soil chemical and physical properties, vegetative traits, and available nutrients in both soil and plant.

Recommendations

1. Zinc Application: It is recommended to apply zinc as an essential and standalone element, owing to its crucial role in enhancing vegetative growth parameters and crop yield, as well as improving the characteristics of salt-affected soils.

2. Humic Acid Application: The use of humic acid is recommended to improve the properties of salt-affected soils.

3. Foliar Spraying of Tryptophan: Foliar application of the amino acid tryptophan is recommended to mitigate salinity stress and enhance plant tolerance.

4. Optimal Combination Treatment: It is recommended to adopt the combined application of the highest levels of the three studied factors: applying zinc at 10 gm plant$^{-1,}$ Humic acid at 5 gm plant$^{-1,}$ a and foliar spraying of tryptophan at a concentration of 100 mg L^{-1}.

(pH). The binary interaction between zinc and tryptophan is recommended to enhance total grain yield.

Conclusions and Recommendations

Conclusions:

1.The application of zinc and humic acid led to a significant and noticeable reduction in soil electrical conductivity (EC).

2.The application of zinc and humic acid resulted in a direct increase in soil organic matter content with increasing application levels.

3.The individual and interactive applications of zinc, humic acid, and tryptophan foliar spray led to an increase in total grain yield.

4.The application of zinc, humic acid, and tryptophan foliar spray increased both available soil zinc and zinc concentration in the grains.

5.Maize (*Zea mays* L., cv. Drachma) exhibited a positive response to the environmental conditions of Diyala Governorate.

5. Dual Interactions: the binary interaction between zinc and humic acid is recommended to increase soil organic matter content, reduce electrical conductivity (EC) and lower soil

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ISSN 2072-3857

ISSN 2072-3857