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EFFECT OF HUMIC ACID ON THE ADSORPTION OF ZINC AND BORON IN CALCAREOUS SOIL AND GROWTH AND YIELD OF SUNFLOWER.

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ABSTRACT

The study aimed to investigate the effect of adding humic acid on the adsorption of zinc and boron and on sunflower growth and yield. Field experiment was conducted at one of the research fields of the College of Agricultural Engineering Sciences, University of Baghdad, during the spring season of 2022, using sunflower (*Helianthus annuus* L.), cultivar Shamoos planted in Clay loam soil. The experiment involved three factors using a randomized complete block design (RCBD) with three replicates: humic acid (0 and 50 kg ha^{1})and them symbols H_0,H_1, zinc sulfate (0, 15, and 30 kg ha^{-1}) them symbols Zn_0,Zn_1,Zn_2, and boron (0, 6, and 12 kg ha^{-1}) and its symbols B_0,B_1,B_2. Results showed that adding humic acid increased zinc and boron adsorption capacity in the soil. Moreover, humic acid, zinc and boron significantly improved plant height, leaf area, seed yield and water-use efficiency, with the highest water-use efficiency observed in the Zn_2 treatment at 1.6642 kg m^{-3}.

Keywords: leaf area, the organic acids , the plant height, water-use efficiency

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INTRODUCTION

Humic acid is one of the primary components of humus. Its molecular structure includes aromatic and aliphatic groups, as well as active functional groups such as carboxyl, phenol, ketone, and amine. The bioactivity of these compounds is attributed to their aromatic structure, which contains numerous functional groups on each ring Ali and Shaker (2018). Indicated that organic fertilizers improve the soil's organic matter content, positively affecting optimal plant growth and crop quality. Boron is an essential element for plants, playing a crucial role in regulating nutrient concentrations within the plant to achieve optimal growth. It is involved in the transport of sugars within the plant and contributes to cell division and the development and strengthening of cell walls, along with (Al-Tameemi and Al-Juboori, 2021), stated that most rocks in the Earth's crust contain varying concentrations of boron, depending on their nature. Boron is crucial for producing high-quality crops, enhancing physiological, chemical, and biological processes, and regulating hormones within plants. Zinc, on the other hand, is an essential micronutrient for the growth and completion of the life cycle in all plants. It is involved in the formation and function of many key enzymes responsible for anabolic and catabolic processes, redox reactions, and the synthesis of essential hormones and amino acids in plants Cakmak (2017). The adsorption process of micronutrients is one of the most important chemical processes that determine the amount of plant nutrients, chemicals and organic materials retained in the soil. It is a fundamental process that affects nutrient availability in the soil. Therefore, studying the adsorption mechanism is crucial to evaluate the availability and toxicity of micronutrients and heavy metals for plants. Boron faces adsorption challenges in saline-calcareous soils, with a significant increase in adsorbed boron as the added boron concentration increases. Adsorption is a key factor in controlling the fixation and release of boron,

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thus determining its efficiency in plant use . Most agricultural soils, particularly calcareous soils, suffer from zinc deficiency due to chemical reactions such as retention (adsorption and precipitation) and the formation of complexes Patel and Savalia (2008). Sunflower (*Helianthus annuus* L.) is a widely grown strategic oil crop due to its economic importance and diverse uses. It is drought-resistant and has various applications, including oil extraction from oil-producing cultivars Al-Badri (2016). The research aims to investigate the effect of adding humic acid on the adsorption of zinc and boron, as well as the growth and yield of sunflower.

MATERIALS AND METHODS

A field experiment was conducted during the spring season of 2022 in fields of the College of Agricultural Engineering Sciences, University of Baghdad, for cultivating sunflower (*Helianthus annuus* L., Shamoos cultivar). The soil texture of the field was classified as clay-Loam. All necessary field operations, including plowing, soil smoothing, and leveling, were carried out. The seeds were planted in rows, with a spacing of 0.75 m between the rows and 0.25m between the holes. Soil samples were randomly taken from the top layer (0–0.3 m) from several locations in the field and thoroughly mixed to obtain a composite sample representing the entire field. The soil was dried, crushed with a wooden hammer, and sieved through a 2mm sieve. All necessary physical and chemical analyses were performed on the soil as shown in Table (1), following the methods outlined in (Page *et al*,1982 and Black 1965 and Salem and Ali 2017). The recommended fertilizers for the crop were applied at a rate of 120 kg N ha^{-1}, 60 kg P ha^{-1}, and 100 kg K ha^{-1},as per the fertilization recommendation Al-Hamdani and Suleiman (2014). Sunflower seeds (Shamoos cultivar) were sown, and irrigation was performed using a drip irrigation system. The soil moisture content was measured using the gravimetric method todetermine irrigation timing and depth, and irrigation was applied after 50% of the available water was depleted. Digital meters were used to ensure equal water distribution among the experimental units.

Table 1. Some chemical and physical properties of the soil before planting

Parameter		Value	Unit
Soil reaction 1:1 (pH)		7.65	---
Electrical conductivity 1:1		2.82	dS m^{-1}
Cation exchange capacity		24.53	cmol$_+$ kg^{-1}
Organic matter		6.10	g kg^{-1}
Carbonates minerals		225.80	
Dissolved ion	Ca^{+2}	6.57	mmol L^{-1}
	Mg^{+2}	4.80	
	Na^{+1}	5.08	
	K^{+1}	0.73	
	Cl^{-1}	20.92	
	HCO_3^{-1}	1.63	
	CO_3^{-2}	Nill	
	SO_4^{-2}	2.82	
Available nitrogen		21.14	mg kg^{-1} soil
Available phosphorus		5.45	
Available potassium		68.25	
Available boron		0.42	
Total boron		6.43	
Available zinc		0.88	
Total zinc		13.75	
Bulk density		1.37	Mg m^{-3}
Available water		0.14	cm^3 cm^{-3}
Sand		425	g kg^{-1}
Silt		275	
Clay		300	
Soil texture		Clay Loam	

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A field experiment was conducted to investigate the effects of three factors using a randomized complete block design with three replicates. The first factor was the addition of solid humic acid to the soil at planting, with two levels: no humic acid (0 kg ha^{-1}, H_0) as a control and 50 kg ha^{-1} (H_1). The second factor involved the addition of zinc in the form of zinc sulfate ($ZN.SO_4.7H_2O$, 23% zinc) at three levels: no addition (0 kg ha-^{1}, Zn_0), 15 kg Zn ha^{-1} (Zn_1), and 30 kg Zn ha^{-1} (Zn_2). The third factor was the addition of boron to the soil at planting in the form of boric acid (containing 17% boron) at three levels: no addition (0 kg ha^{-1}, B_0), 6 kg B ha^{-1} (B_1), and 12 kg B ha^{-1} (B_2). To determine the effect of adding humic acid on zinc adsorption, 5 grams of soil treated with 50 kg ha^{-1} of Humic acid in solution form were taken after 60 days of planting (when the floral disks appeared in the field). A control soil sample without humic acid addition was also taken for comparison. The samples were placed in 50 ml plastic centrifuge tubes, and the volume was adjusted to 50 ml using a zinc solution dissolved in $CaCl_2$ (prepared from chelated zinc EDTA-Zn) at concentrations of 10, 20, 40, 60, 80, 100, and 120 mg Zn L^{-1}, with three replicates for each. To inhibit the activity of soil microorganisms, 0.5 ml of toluene was added. The tubes were sealed and shaken for 120 minutes using a shaker at 175 rpm at a constant temperature of 298 K (25°C). The samples were then left for 24 hours to reach equilibrium and were shaken again for 15 minutes. The samples were centrifuged at 4000 rpm for 5 minutes, after which they were filtered using Whatman No. 42 filter paper to obtain the equilibrium solution from the soil. The zinc concentration in the solution was determined using atomic absorption spectrophotometry, and the adsorbed zinc was calculated using the following equation:

$$\text{Adsorbed amount} = \frac{\text{(Conc.of added element-Conc. of remaining element in equilibrium solution)}}{\text{Weight of soil}} \text{ x volume of solution}$$

Where: Adsorbed amount is in micrograms per gram (µg g^{-1}).
Concentration of added element is in milligrams per liter (mg L^{-1}).
Concentration of remaining element is in milligrams per liter (mg L^{-1}).
Weight of soil is in grams (g).
Volume of solution is in milliliters (ml).
To study boron adsorption in the soil, following the method described, 5 grams of incubated soil were weighed and placed in a 50 ml centrifuge tube. The volume was then adjusted to 50 ml using a boron solution in the form of boric acid (H_3BO_3) at concentrations of 3, 6, 9, 12, 15, 18, and 21 mg B kg^{-1} soil, with three replicates. As mentioned above, boron in the supernatant was measured using the colorimetric method with carmine dye, and the absorbance was measured with a spectrophotometer at a wavelength of 585 nm. The amount of boron adsorbed was calculated in the same way as the adsorbed zinc. The Langmuir single-surface equation was applied to describe the adsorption reactions of zinc and boron. The Langmuir equation constants were calculated after plotting the linear relationship between C/X on the y-axis and C on the x-axis, resulting in a straight line. The slope of this line represents the value of 1/X max, and the intercept represents the value of 1/kX were max. From these, the constants X max and k derived, and the product of these constants was used to find the Maximum Buffering Capacity (MBC).
The general form of the equation is:

$$\frac{c}{X} = \frac{1}{Kxm} + \frac{c}{Xm}$$

Where:
X: Amount of adsorbed zinc or boron per unit weight of soil (mg Zn or B kg^{-1} soil).
C: Concentration of zinc or boron in the equilibrium solution (mg Zn or B L^{-1}).
Xm: Constant representing the maximum adsorption capacity (mg Zn or B kg^{-1} soil).
K: Constant representing the binding energy (ml µg^{-1} Zn or B).
Some Studied Traits Ten plants were taken from the middle row of each experimental unit, and the following measurements were recorded:
Plant height: The height of the plant was measured from the soil surface to the base of the flower disk (cm), according to Elsahookie and Mahmoud.

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Leaf Area (m^2): At full flowering, the maximum leaf width was measured using the following formula, as mentioned in Elsahookie and Eldabas (1982).

$LA = 0.65\ \Sigma\ (L)^2$

Where:

LA = Leaf Area

0.65 = Constant

$\Sigma(L)^2$ = Sum of the squares of the leaf widths.

Total Seed Yield (tons ha^{-1}) was calculated using the following formula:

Total Seed Yield (tons ha^{-1}) = Mean Seed Yield ($plant^{-1}$) x plant density (ha^{-1})=

Water Use Efficiency was calculated using the following formula

$$\text{Water Use Efficiency} = \frac{\text{Total Seed Yield (kg ha}^{-1})}{\text{Amount of water used (m}^3\text{ ha}^{-1})}$$

RESULTS AND DISCUSSION

Effect of Humic acid on zinc adsorption in soil: The adsorbed zinc in the soil represents the difference between the amount of zinc added and the residual amount in the equilibrium solution. The Langmuir equation (single-surface model) was used to describe the adsorption of zinc in soil treated with humic acid. This approach allowed for assessing the impact of humic acid addition on the adsorption process by calculating the equation parameters, which represent the maximum amount of adsorbed zinc (Xm) and the zinc binding energy to the soil (k).

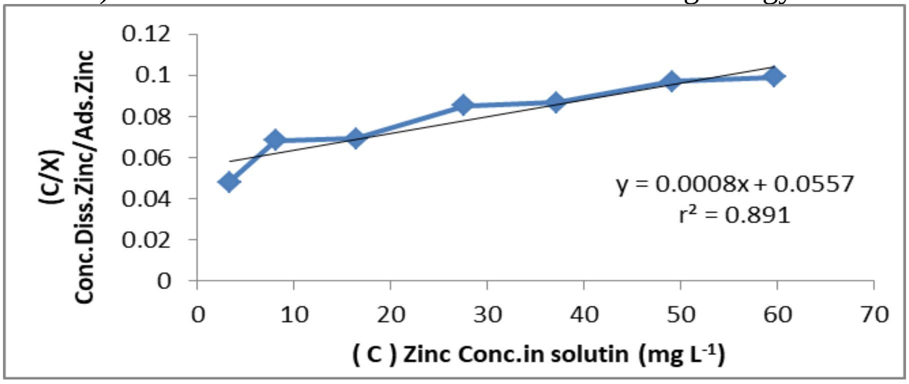

Figure 1. Adsorption of zinc with addition of Humic acid according to Langmuir equation

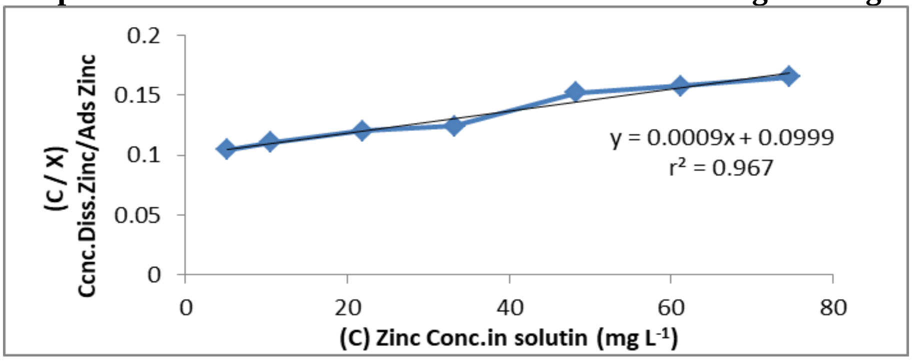

Figure 2. Adsorption of zinc with not addition of Humic acid according to Langmuir equation

Table 2. The effect of humic acid on the maximum adsorption values (Xm) of zinc and the binding energy (k).

No.	Treatment	Maximum Adsorption (Xm) mg Zn kg^{-1} soil	Binding Energy (k) ml mg^{-1} soil
1	Soil treated with 50 kg humic acid ha^{-1}	1250.00	0.0718
2	Soil not treated with humic acid	1111.11	0.0090

The results from Figures (1 and 2) as well as Table (2) indicate that the addition of humic acid to the soil led to an increase in the amount of adsorbed zinc. The maximum adsorption capacity with the addition of humic acid reached 1250.00 mg Zn kg^{-1} soil, while it decreased to 1111.11 mg Zn kg^{-1} soil in the absence of humic acid. The increase in adsorbed zinc due to humic acid addition can be attributed to the fact that organic acids

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enhance the soil's cation exchange capacity and retain ions in the soil solution Jameel (2020). This is due to the presence of active groups in humic acids, which form natural chelating compounds that are seven times more effective than the mineral clay colloids Sánchez-Sánchez *et al*. (2002) . These findings are consistent with those of (Ali *et al*.,2014), who indicated that the addition of humic acids to the soil increases the cation exchange capacity, thus enhancing the adsorption of ions from the soil solution. The negative charge carried by these acids helps in binding ions, especially divalent ones. The addition of humic acid led to an increase in the binding energy between the zinc ion and the active groups of the acid, reaching 0.0718 ml mg^{-1} soil in the case of humic acid addition, compared to 0.009 ml mg^{-1} soil without the acid. This increase can be attributed to the negative charges possessed by the active groups of the acid, which enhance the binding energy of the positively charged zinc ions.

Effect of Humic Acid on Boron Adsorption in Soil: Understanding the distribution of boron between the liquid and solid phases of the soil is crucial for determining its availability and interactions in the soil. The amount of adsorbed boron increases with the amount of boron added and depends on the type of adsorption surface Abood and Sherif (2022); Al-Falahi, (2000). The use of adsorption isotherms, which establish a relationship between the adsorbed material and the adsorption surface at equilibrium under constant temperature, is essential for understanding the nature of adsorption. This can be mathematically described by the Langmuir single-surface equation, using the equation's constants to characterize the soil's adsorption properties Gupta and Solanki (2013). It also mathematically describes the thermodynamic equilibrium between boron in the liquid and solid phases of the soil and determines the soil's adsorption parameters. Figures (3 and 4) along with Table (3) show the effect of humic acid addition on boron adsorption. The Langmuir equation constants indicate an increase in the amount of boron adsorbed in the soil treated with humic acid. The maximum boron adsorption capacity in the humic acid-treated soil reached 625.00 mg B kg^{-1} soil, while it decreased to 175.43 mg B kg^{-1} soil in the untreated soil. This increase can be attributed to the high chemical affinity of boron with humic acid Waraich *et al*. (2011). Organic matter in the soil acts to chelate boron and plays a key role in the adsorption dynamics and the availability of boron in the soil.

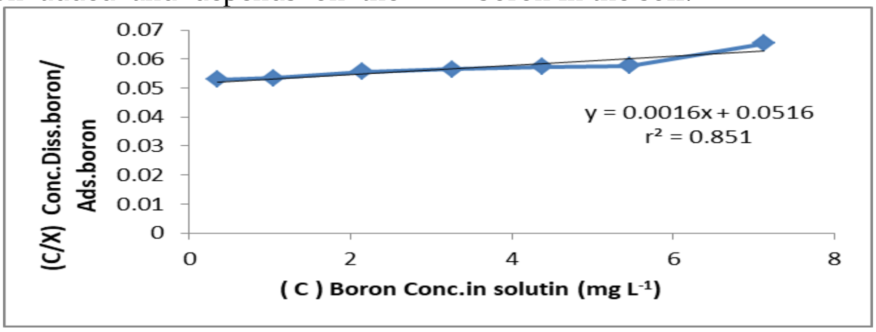

Figure 3. Boron Adsorption with addition of Humic acid according to Langmuir equation

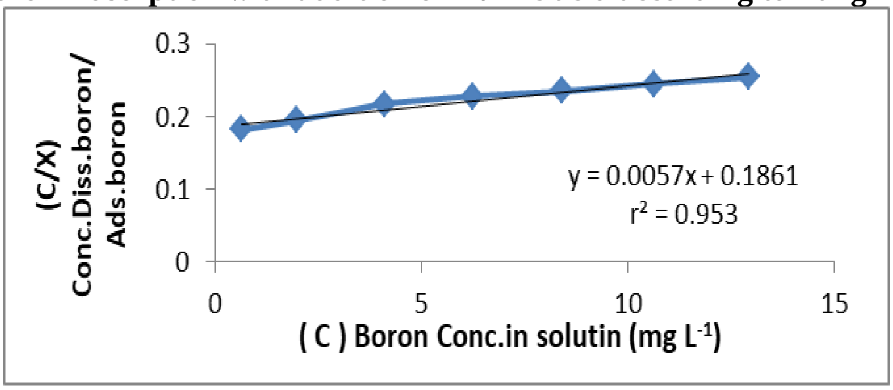

Figure 4. Boron Adsorption with not addition of Humic acid according to Langmuir equation

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Table 3. The effect of humic acid on the maximum adsorption values (Xm) of boron and the binding energy (k).

No.	Treatment	Maximum Adsorption (Xm) mg B kg⁻¹ soil	Binding Energy (k) ml mg⁻¹ soil
1	Soil treated with 50 kg humic acid ha⁻¹	625.00	0.0310
2	Soil not treated with humic acid	175.43	0.0306

Effect of Humic acid and levels of zinc and boron on growth indicators and yield of Sunflower

Plant Height: The results in Table (4) indicate significant differences in plant height at full maturity. The treatment Zn_2 (with zinc addition) resulted in the highest plant height of 220.15 cm, compared to no zinc addition, where the treatment Zn_0 recorded a height of 156.09 cm. This can be attributed to the importance of zinc in physiological and chemical processes, as well as growth regulation, since it acts as a cofactor in regulating a wide range of proteins, enzymes, and the fertilization process, ultimately promoting plant growth. (Hafeez and Saleem, 2013). also highlighted zinc's crucial role in protein synthesis, photosynthesis, the plant's antioxidant defense system, and various physiological processes. Zinc also plays a key role in biochemical processes, regulating growth, enzymes, proteins, and many biochemical pathways. As for the effect of humic acid addition, it significantly increased plant height, with the H_1 treatment resulting in the highest plant height of 191.02 cm, while the control treatment H_0 recorded the lowest height of 176.37 cm. This is attributed to the role of humic acid, which is considered a good organic amendment that improves the physical, chemical and fertility properties of the soil, as well as increasing nutrient availability and absorption and promoting root growth and spread, leading to an increase in plant height. This finding aligns with Al-Araji and Al-Tamimi (2020), who noted that the addition of 50 kg ha⁻¹ of humic acid as a soil amendment enhanced sunflower plant height by improving the soil's physical and chemical properties and increasing nutrient availability for absorption, which positively affected root spread and plant growth, ultimately leading to increased plant height. The results also indicated significant differences in plant height with the addition of boron. The B_2 treatment recorded the highest plant height of 198.55 cm, while the control treatment B_0 had the lowest height of 167.73 cm. This increase is attributed to the vital role of boron in various biological processes within the plant, such as cell wall elongation, which leads to increased plant height. This finding aligns with Khan *et al.*(2016), who reported that boron influences many biological processes in plants, such as cell wall synthesis, DNA synthesis, and cell wall elongation. The results of the two-way interaction between humic acid and zinc showed a significant effect, with the H_1Zn_2 treatment recording the highest plant height of 229.10 cm compared to the control treatment H_0Zn_0, which recorded a height of 149.78 cm. This increase can be attributed to the role of humic acid in improving the soil's chemical and physical properties, thereby enhancing the availability of micronutrients, especially zinc, in addition to providing essential nutrients for the plant. The added zinc also plays a role in promoting plant growth by participating in the synthesis of hormones, nucleic acids, and cell division, leading to increased plant growth and height Al-Khafaji (2015). Furthermore, the results of the interaction between humic acid and boron showed no significant differences in plant height. However, the H_1B_2 treatment recorded the highest value of 205.56 cm, while the H_0B_0 treatment had the lowest value of 160.64 cm. As for the two-way interaction between zinc and boron, a significant effect was observed in increasing plant height. The highest height was recorded in the Zn_2B_2 treatment, reaching 234.03 cm, while the Zn_0B_0 treatment resulted in the lowest plant height at 139.75 cm. This increase can be attributed to the role of zinc and boron in promoting plant growth through their active involvement in crop growth and production, as they are essential micronutrients for plants, participating in various biological processes

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within the plant Al-Doori (2019). The results of the three-way interaction between humic acid, zinc, and boron showed significant differences in plant height. The highest value was recorded in the $H_1Zn_2B_2$ treatment, reaching 242.57 cm, compared to the control treatment $H_0Zn_0B_0$, which recorded 135.87 cm. This increase can be attributed to the active roles of humic acid, zinc, and boron in promoting cell growth, elongation, and division, thereby increasing plant height. They stimulate root growth, enhance cell membrane permeability, regulate biological processes, and encourage plant growth by influencing plant hormones and regulating the activity of enzymes and proteins. They also affect various biochemical pathways such as carbohydrate metabolism, carbon fixation, protein metabolism, fertilization, and the production of viable, highly fertile pollen grains Saleem *et al*. (2022).

Table 4. Effect of Humic acid, levels of zinc and boron on plant height at full maturity(cm)

H	Zn	B B_0	B_1	B_2	Zn x H
	Zn_0	135.87	147.67	165.80	149.78
H_0	Zn_1	148.57	172.57	183.31	168.15
	Zn_2	197.50	210.61	225.50	211.20
	Zn_0	143.63	164.00	179.60	162.41
H_1	Zn_1	167.57	182.57	194.53	181.55
	Zn_2	213.27	231.47	242.57	229.10
H		B x H			Mean H
H_0		160.64	176.95	191.53	176.37
H_1		174.82	192.68	205.56	191.02
Zn		B x Zn			Mean Zn
Zn_0		139.75	155.83	172.70	156.09
Zn_1		158.07	177.57	188.92	174.85
Zn_2		205.38	221.04	234.03	220.15
Mean B		167.73	184.81	198.55	
$LSD_{0.05}$		H	B	Zn	Zn x H
		0.77	0.95	0.95	1.34
$LSD_{0.05}$		B x H	B x Zn	B x H x Zn	
		N.S	1.64	2.32	

Leaf Area (m^2)

The results in Table (5) shows that the addition of humic acid, along with different levels of zinc and boron, significantly increased leaf area values at full maturity. The Zn_2 treatment recorded the highest value of 0.635 m^2 with the highest zinc level, compared to the Zn_0 treatment, which recorded 0.415 m^2. This increase is attributed to the role of zinc in enhancing cell elongation, energy compound formation, and amino acid production, which positively influences the leaf area of the plant. This finding aligns with Al-Hamdani and Suleiman (2014), who reported significant differences in leaf area as a result of fertilization treatments, with all zinc-fertilized treatments outperforming the control. The results of adding humic acid showed a significant difference in leaf area, with the H_1 treatment recording the highest value of 0.572 m^2, while the H_0 treatment recorded the lowest leaf area of 0.500 m^2. These results can be attributed to the role of humic acid, which is considered a good organic amendment that improves the physical, chemical and fertility properties of the soil, enhances the availability and absorption of nutrients and promotes root growth and spread. Its nutrient content also contributed to improving root and leaf growth, which, in turn, increased the leaf area. This finding is consistent with (Hatami, 2017 and Mindari *et al*, 2014), who explained that the application of humic acid, either as a soil amendment or foliar spray, increased the leaf area of sunflower plants by improving the physical, chemical and fertility properties of the soil. Furthermore, humic acid plays a role in enhancing photosynthesis, respiration, and the production of energy needed for cell division, increasing cell number and size,

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which leads to increased plant growth and, consequently, greater root spread and plant development. The results showed the effect of added boron on leaf area, with the B_2 treatment recording the highest value of 0.5873 m², while the B_0 treatment recorded the lowest leaf area of 0.4715 m². This increase is attributed to boron being an essential micronutrient within the plant, helping to promote plant growth and enhance photosynthesis rates, which in turn increases leaf area. This finding is consistent with the (Ganie *et al*, (2013) and Al-Wakeel *et al*, (2013).

Table 5. Effect of Humic acid, levels of zinc and boron on leaf area (m²) at full maturity

H	Zn	B B_0	B_1	B_2	Zn x H
	Zn_0	0.299	0.388	0.443	0.377
H_0	Zn_1	0.487	0.510	0.557	0.518
	Zn_2	0.564	0.611	0.648	0.607
	Zn_0	0.305	0.515	0.543	0.454
H_1	Zn_1	0.570	0.605	0.622	0.599
	Zn_2	0.604	0.678	0.711	0.664
H		B x H			Mean H
H_0		0.450	0.503	0.549	0.501
H_1		0.493	0.599	0.625	0.573
Zn		B x Zn			Mean Zn
Zn_0		0.302	0.451	0.493	0.415
Zn_1		0.528	0.557	0.589	0.558
Zn_2		0.584	0.644	0.679	0.636
Mean B		0.471	0.551	0.587	
$LSD_{0.05}$		H 0.0007	B 0.0009	Zn 0.0009	Zn x H 0.0013
$LSD_{0.05}$		B x H 0.0013	B x Zn 0.0016	B x H x Zn 0.0022	

The results of the two-way interaction between humic acid and zinc showed a significant difference, with the H_1Zn_2 treatment recording the highest value of 0.6643 m², compared to the control treatment H_0Zn_0, which recorded the lowest value of 0.3767 m². This can be attributed to the important role of humic acid in enhancing the availability of nutrients in the soil, providing essential nutrients, and improving soil properties. Additionally, the added zinc contributed to the growth of the plant's vegetative system, thereby increasing leaf area Al-Doori (2019).The results of the interaction between humic acid and boron showed significant differences in leaf area. The H_1B_2 treatment recorded the highest value of 0.6253 m², while the H_0B_0 treatment, which represents the control, recorded the lowest value of 0.4499 m². This increase can be attributed to the important role of humic acid in enhancing nutrient availability in the soil and providing essential nutrients. Boron also plays a key role in transporting photosynthetic products, sugar translocation within the plant, cell division, and the movement of certain growth hormones. These factors contributed to the significant increase in leaf area values Muscolo *et al*, (2007) and Van Eynde *et al*, (2020). The results of the interaction between zinc and boron showed a significant effect on leaf area, with the Zn_2B_2 treatment recording the highest average value of 0.679 m², while the Zn_0B_0 treatment recorded the lowest average of 0.302 m². The addition of zinc and boron led to increased plant growth, and consequently, an increase in leaf area, as these are essential nutrients for plant growth. This finding is consistent with (Ravikumar *et al*,2021), who reported in their studies that the proper management of micronutrient application, such as zinc and boron, resulted in increased growth indicators, including leaf area, for sunflower crops. The results of the three-way interaction between humic acid, zinc, and boron showed a significant difference in average leaf area. The highest value was recorded in the $H_1Zn_2B_2$ treatment, reaching 0.711m², compared to the control

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treatment $H_0Zn_0B_0$, which recorded 0.299 m². This increase can be attributed to the important roles of humic acid, zinc and boron in promoting plant growth by encouraging root development, improving nutrient availability, enhancing soil structure boron are crucial micronutrients involved in various physiological and biological processes within the plant, leading to increased leaf area Poudineh *et al*, 2015 and Saleem *et al*, 2022).

Total Seed Yield (Mg ha⁻¹)

The results from Table (6) indicate that the addition of humic acid, along with different levels of zinc and boron, significantly increased total seed yield at post-harvest. The Zn_2 treatment recorded the highest yield, reaching 5.469 Mg ha⁻¹, while the Zn_0 treatment recorded 4.557 Mg ha⁻¹. This increase can be attributed to the essential role of zinc in physiological and chemical processes, as well as in regulating plant growth. This aligns with what (Keerio *et al.*, 2020) indicated, highlighting the potential use of zinc to improve the growth, yield, and quality of sunflower plants, especially in areas with zinc deficiency. Such methods can contribute to enhancing current fertilization strategies and help improve total seed yield. The results of humic acid addition also showed significant differences in increasing total seed yield. The H_1 treatment recorded the highest yield with an increase of 5.384 Mg ha⁻¹, while the control treatment H_0 recorded the lowest yield of 4.663 Mg ha⁻¹. This increase is attributed to the role of humic acid, which is a good organic material that improves the physical, chemical, and fertility properties of the soil. It also enhances the availability and absorption of nutrients, thereby increasing the total seed yield. This finding is consistent with (Al-Araji A and Al-Tamimi 2020), who noted that the addition of 50 kg ha⁻¹ of humic acid as a soil amendment significantly increased the total seed yield, with the highest yield recorded at 7.40 Mg ha⁻¹, representing a 22.92% increase compared to the control treatment. Regarding the impact of boron addition.

Table 6. Effect of humic acid, levels of zinc and boron on total seed yield (Mg ha⁻¹) at full maturity

H	Zn	B B_0	B_1	B_2	Zn x H
	Zn_0	3.804	4.240	4.668	4.237
H_0	Zn_1	4.105	4.711	5.145	4.654
	Zn_2	4.716	5.204	5.412	5.111
	Zn_0	4.389	4.878	5.364	4.877
H_1	Zn_1	4.994	5.403	5.940	5.446
	Zn_2	5.468	5.890	6.128	5.829
H		B x H			Mean H
H_0		4.208	4.718	5.075	4.667
H_1		4.950	5.390	5.811	5.384
Zn		B x Zn			Mean Zn
Zn_0		4.097	4.559	5.016	4.557
Zn_1		4.550	5.057	5.543	5.050
Zn_2		5.092	5.547	5.770	5.470
Mean B		4.579	5.054	5.443	
$LSD_{0.05}$		H	B	Zn	Zn x H
		0.052	0.064	0.064	N.S
$LSD_{0.05}$		B x H	B x Zn	B x H x Zn	
		N.S	0.111	N.S	

The B_2 treatment achieved the highest total seed yield of 5.443 Mg ha⁻¹, whereas the control treatment B_0 produced the lowest yield at 4.579 Mg ha⁻¹.This increase can be attributed to the important role of boron in improving the growth and yield of sunflower. Several studies have indicated that sunflower crops require significant amounts of boron to achieve optimal growth and total seed yield da Silva *et al*. (2016). The results of the two-way

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interaction between humic acid and zinc showed no significant difference, with the H_1Zn_2 treatment recording the highest value of 5.829 Mg ha⁻¹, compared to the control treatment, which recorded the lowest value of 4.237 Mg ha⁻¹. Similarly, the interaction between humic acid and boron revealed no significant difference in total seed yield values. The results of the interaction between different levels of zinc and boron showed a significant effect on total seed yield, with the Zn_2B_2 treatment recording the highest yield at 5.770 Mg ha⁻¹, while the Zn_0B_0 treatment, representing the control, recorded the lowest yield at 4.096 Mg ha⁻¹. This increase can be attributed to the roles of boron and zinc in various physiological and biological processes within the plant, leading to enhanced growth and production of the sunflower crop. This finding is consistent with the observations (Faisal *et al*., 2023 and Kaleri *et al*., 2024), who reported that the addition of boron and zinc significantly improved the growth and seed yield of sunflower plants. The results of the three-way interaction between humic acid, zinc, and boron showed no significant difference in total seed yield. However, the highest value was recorded in the $H_1Zn_2B_2$ treatment at 6.1280 Mg ha⁻¹, compared to the control treatment $H_0Zn_0B_0$, which recorded 3.8040 Mg ha⁻¹. This increase can be attributed to the roles of boron and zinc in various biological processes within the plant, which contribute to enhanced growth and production of the sunflower crop. This aligns with the findings of (Amin *et al*.,2023), who reported that the addition of boron and zinc significantly influenced all growth indicators of sunflower, including increased growth and total seed yield. Humic acid also enhances cell membrane permeability, stimulates enzymatic reactions, improves cell division and elongation, increases the production of plant enzymes, and stimulates vitamins within the cells. Additionally, it improves nutrient availability, enhances soil properties, and boosts vegetative growth, leading to an increase in carbohydrate production and, consequently, higher total yield. These findings are consistent with Pettit (2016) and Poudineh *et al.* (2015).

Water Use Efficiency (kg m⁻³)

The results in Table (7) show a significant difference in water use efficiency after harvest with the addition of zinc. The Zn_2 treatment recorded the highest value at 1.664 kg m⁻³, while the Zn_0 treatment recorded the lowest value at 1.385 kg m⁻³. This can be attributed to the important role of zinc in protecting plants under environmental stress conditions. Zinc plays a key role in regulating stomata, maintaining plasma membrane integrity, and preserving plant water relations. Zinc deficiency reduces the plant's ability to adapt, which subsequently affects water use efficiency . The results of humic acid addition showed significant differences in water use efficiency, with the H_1 treatment recording the highest value of 1.637 kg m⁻³, while the control treatment H_0 recorded the lowest value at 1.419 kg m⁻³. This can be attributed to the role of humic acid, which is an excellent organic material that improves the physical properties of the soil and enhances its water retention capacity. This promotes root growth, leading to increased water and nutrient absorption, positively affecting yield and maintaining the plant's water content. As a result, water use efficiency increased. This finding is consistent with (Al-Abaied and Salih, 2020 ; Al-Araji and Al-Tamimi, 2020), who reported that the addition of organic materials to the soil significantly improved water use efficiency due to better soil chemical and physical properties, increased water retention, and higher seed yield.=

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Table 7. Effect of humic acid, levels of zinc and boron on water use efficiency (kg m⁻³) at full maturity

H	Zn	B			Zn x H
		B_0	B_1	B_2	
H_0	Zn_0	1.156	1.289	1.419	1.288
	Zn_1	1.248	1.432	1.564	1.414
	Zn_2	1.434	1.582	1.645	1.553
H_1	Zn_0	1.334	1.483	1.630	1.482
	Zn_1	1.518	1.642	1.805	1.655
	Zn_2	1.662	1.790	1.873	1.775
H			B x H		Mean H
H_0		1.279	1.434	1.542	1.419
H_1		1.505	1.638	1.769	1.637
Zn			B x Zn		Mean Zn
Zn_0		1.245	1.386	1.525	1.385
Zn_1		1.383	1.537	1.685	1.535
Zn_2		1.548	1.686	1.759	1.664
Mean B		1.392	1.536	1.656	
LSD 0.05		H	B	Zn	Zn x H
		0.0157	0.0193	0.0193	N.S
LSD 0.05		B x H	B x Zn	B x H x Zn	
		N.S	0.0333	N.S	

The results indicated a significant effect of boron addition on water use efficiency, with the B_2 treatment recording the highest value of 1.656 kg m^{-3}, while the control treatment B_0 recorded the lowest value at 1.392 kg m^{-3}. This improvement can be attributed to the crucial role of boron in enhancing the growth and yield of sunflower, as it participates in various physiological processes within the plant, contributing to increased total seed yield. This finding aligns with (Halder *et al*.,2022), who reported that boron addition positively mitigated the effects of drought stress on sunflower plants, and that boron provided the best results for growth and seed yield under optimal irrigation conditions. The results of the two-way interaction between humic acid and zinc showed no significant difference, with the H_1Zn_2 treatment recording the highest value of 1.775 kg m^{-3}, compared to the control treatment, which recorded the lowest value of 1.288 kg m^{-3}. The results of the interaction between humic acid and boron also showed no significant difference in water use efficiency values. The H_1B_2 treatment recorded the highest value at 1.769 kg m^{-3}, while the H_0B_0 treatment, representing the control, recorded the lowest value at 1.279 kg m^{-3}. The results of the interaction between different levels of zinc and boron showed a significant effect on water use efficiency values. The highest value was recorded in the Zn_2B_2 treatment at 1.759 kg m^{-3}, while the lowest value was recorded in the Zn_0B_0 treatment, representing the control, at 1.245 kg m^{-3}. Zinc and boron play a crucial role in regulating stomata, maintaining membrane and cell wall integrity, and promoting root and vegetative growth. They also influence the plant's water relations. The deficiency of these elements reduces the plant's ability to adapt to drought conditions, thereby negatively affecting water use efficiency

CONCLUSION

This study concluded that the combined addition of humic acid, zinc, and boron significantly improved sunflower growth, yield, and water use efficiency. The $H_1Zn_2B_2$ treatment recorded the highest values for plant height, leaf area, total seed yield), and water use efficiency. Humic acid enhanced soil properties, increasing nutrient availability and root development, while zinc and boron played critical roles in regulating stomatal function, maintaining cell membrane integrity, and promoting cell division and sugar transport.

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These improvements contributed to better adaptability to stress conditions and optimized water utilization. The study underscores the importance of integrating these nutrients into fertilization strategies to maximize sunflower productivity, especially in nutrient-poor soils or water-limited environments.

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تأثير حامض الهيومك في امتزاز الزنك والبورون في تربة كلسية ونمو وحاصل زهرة الشمس

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المستخلص

نُفذت تجربة حقلية في أحد الحقول البحثية التابعة لكلية علوم الهندسة الزراعية، جامعة بغداد، خلال الموسم الربيعي لعام 2022، بزراعة نبات زهرة الشمس (*Helianthus annuus* L.)، الصنف شموس في تربة مزيجه طينية. هدفت الدراسة إلى معرفة تأثير إضافة حامض الهيومك على امتزاز الزنك والبورون وعلى نمو وحاصل زهرة الشمس. تضمنت التجربة ثلاثة عوامل باستخدام تصميم القطاعات الكاملة المعشاة (RCBD) بثلاث مكررات: حامض الهيومك (0 و 50 كغم هكتار$^{-1}$) ورمز له H_0 وH_1، كبريتات الزنك (0، 15، و 30 كغم هكتار$^{-1}$) ورمز لهم Zn_0 وZn_1 وZn_2، وحامض البوريك (0، 6، و 12 كغم هكتار$^{-1}$) ورمز لهم B_0 وB_1 وB_2. أظهرت النتائج أن إضافة حامض الهيومك زادت من سعة الامتزاز للزنك والبورون في التربة. كما أثرت إضافة حامض الهيومك والزنك والبورون بشكل معنوي في ارتفاع النبات، وزيادة المساحة الورقية، وحاصل البذور الكلي، وزادت كفاءة استخدام المياه، حيث حققت المعاملة Zn2 أعلى قيمة بلغت 1.6642 كغم م$^{-3}$.

الكلمات المفتاحية: المساحة الورقية، الحوامض العضوية, ارتفاع النبات, كفاءة استعمال المياه.