Synergistic Effects of Biofertilizer and Humic Acid on Soil Fertility Nutrient Uptake and Productivity of Zea mays Under Salinity Stress

Waleed F. Hassan[1]

waleed.almayahi@uokufa.edu.iq

University of Kufa

Mohammad H. Dawood

University of Telafer

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Abstract

The essential soil salinity condition of arid and semi-arid territories functions as a fundamental abiotic factor which creates obstacles for plants to receive nutrients while decreasing agricultural yield. The study investigated how biofertilizer from *Klebsiella oxytoca* combined with humic acid (HA) affected soil characteristics through its two separate actions and its combined impact during saline stress conditions when maize (*Zea mays* L.) developed its grains. In this experiment, a randomized complete block design (RCBD) was utilized to test four treatments over three replications while employing three different irrigation salinity levels: S_0 (1.6 dS m^{-1}), S_1 (3.0 dS m^{-1}), and S_2 (6.0 dS m^{-1}). The combination of biofertilizer and HA treatment raised soil organic matter by 18.7% and chlorophyll content (SPAD) by 26.8% and nitrogen uptake by 25.7% and grain yield by 25.4% beyond the control group. The study results show that microbial inoculants can effectively reduce salinity-related yield losses in combination with humic substances which improve soil health for maize production systems that provide sustainable solutions to manage saline soils.

1. Introduction

Soil salinity has become a major global agricultural threat that especially impacts arid and semi-arid regions, which suffer from salinity problems on about 20 percent of their irrigated farmland [1]. Salinity produces physiological effects that create osmotic stress and ionic toxicity and oxidative damage and nutritional balance disruption, which together block plant growth and chlorophyll production and photosynthesis efficiency [2]. Maize (*Zea mays* L.) serves as an essential worldwide cereal crop which provides food and animal feed and bioenergy, but it demonstrates high sensitivity to salt stress which hampers its ability to absorb and distribute vital nutrients such as nitrogen (N) and phosphorus (P) and potassium (K), thus reducing its crop output and food security according to Ocwa, Harsanyi [3].

The traditional methods for fixing saline soils through chemical fertilizer overuse have reached a point of environmental unsustainability which results in environmental damage and groundwater pollution and decreased nutrient efficiency [4]. The need for environmentally friendly techniques which strengthen soil health and crop salinity resistance has become urgent because ecological integrity needs to remain intact. The most promising biostimulants include biofertilizers which contain plant growth-promoting microorganisms (PGPM) and humic acid (HA) which serves as an essential soil organic matter component [5].

Biofertilizers using *Klebsiella oxytoca* improve soil fertility by fixing nitrogen, making phosphate more soluble, moving potassium, and making phytohormones, which help roots grow and make plants more resistant to stress [6, 7]. The soil physicochemical properties of humic acid (HA) improve through its ability to increase cation exchange capacity (CEC) and enhance water retention and its micronutrient chelation capacity and its activation of plasma membrane H^+-ATPase which supports root development and nutrient absorption in saline environments [5, 8].

The complete advantages of biofertilizers and HA have been explained yet scientists have not studied their combined effects on maize systems that grow in salt-affected areas. Recent research shows that using integrated bio-organic amendments will improve microbial diversity and enzyme activity and nutrient cycling better than using separate applications [9, 10]. Researchers have not conducted enough research to evaluate how different salinity levels affect soil organic matter dynamics and nutrient absorption efficiency and photosynthetic efficiency and crop yield stability. Consequently, the objectives of this experiment were to 1. evaluate the individual and combined effects of *Klebsiella oxytoca* biofertilizer and HA on maize growth, physiology, and grain yield under three salinity levels. 2. Assess changes in soil fertility indicators and plant nutrient uptake. And 3 to explain the physiological mechanisms underlying salinity mitigation. In this experiment we expected that using both biofertilizer and HA together would boost soil health and nutrient use efficiency and maize productivity in saline conditions at a greater degree than using the amendments separately.

2. Materials and methods

2.1. Experimental site and soil characteristics

The field experiment was conducted during the 2024 growing season at the Agricultural Research Station, College of Agriculture, University of Kufa, Al-Najaf Governorate, Iraq (32°00' N, 44°19' E; 33 m a.s.l.). The region has a semi-arid climate which produces hot dry summers with an average temperature of 44 degrees Celsius and cool winters which have a temperature of 9 degrees Celsius and receives 120 millimeters of rain each year. Before planting, the composite soil samples were collected from 0 to 30 centimeters depth to examine essential physicochemical soil characteristics. The soil composition was identified as clay loam which displayed moderate salinity conditions with an initial ECe measurement of 5.8 dS m^{-1} and a pH level of 7.6 and a low organic matter content according to Table 1. The laboratory analyses utilized standard methods which included soil texture determination through hydrometer methods and Walkley–Black methods for organic matter measurement and Kjeldahl methods for nitrogen determination and Olsen methods for phosphorus measurement and flame photometry methods for potassium measurement according to Black 1965 and AOAC 2016.

Table 1
Initial physicochemical properties of the experimental soil (0–30 cm depth) at the Agricultural Research Station, University of Kufa, before the application of biofertilizer and humic acid treatments were added under saline irrigation conditions.

Parameter	Value	Method
Soil Texture	Clay Loam	Hydrometer
pH (1:2.5 soil:water)	7.6 ± 0.2	Glass electrode
ECe (dS m^{-1})	5.8 ± 0.3	Saturation extract
Organic Matter (%)	0.92 ± 0.03	Walkley–Black
Available N (mg kg^{-1})	49.6 ± 1.2	Kjeldahl
Available P (mg kg^{-1})	6.1 ± 0.2	Olsen
Available K (mg kg^{-1})	189 ± 4	Flame photometry
CEC ($cmol^{+}$ kg^{-1})	18.3 ± 0.8	Ammonium acetate (pH 7.0)

*Values are expressed as mean ± standard error (n = 3).

2.2. Experimental Design and Treatments

The experiment utilized a Randomized Complete Block Design (RCBD) to test four treatments which included T_0: Control (no amendment) and T_1: Biofertilizer and T_2: Humic acid and T_3: Biofertilizer plus humic acid. Plots which measured 3 m × 4 m (12 m^2) contained four maize rows which were spaced 75 cm apart while plants were spaced 25 cm within rows. All experimental plots received the same basal fertilization of 200 kg N ha^{-1} and 80 kg P_2O_5 ha^{-1} and 60 kg K_2O ha^{-1} which was applied as urea and single superphosphate and potassium sulfate to create equal nutrient conditions among all treatments.

2.3. Plant Materteral

The plant material used in this experiment was a cultivated hybrid maize (*Zea mays* L.) cultivar ‘Furat’, obtained from the Babylon Agriculture Division, Al-Mahawil, Iraq, and its collection and use complied with all relevant local and national agricultural guidelines; no special permissions or licenses were required.

2.4. Salinity Induction and Irrigation Management

Three different salinity levels were applied using irrigation water which had three different electrical conductivities (ECiw) values of S_0 (1.6 dS m^{-1}), S_1 (3.0 dS m^{-1}), and S_2 (6.0 dS m^{-1}). Saline water were monitored by dissolving NaCl and $CaCl_2$ and $MgCl_2$ in a 7:2:1 molar ratio to mimic the typical composition of salt-affected groundwater according to Liu, Xun [7]. The drip irrigation system was established weekly to deliver water to the fields and to sustain soil moisture levels at 80 percent of the field capacity. The salinity treatments were applied starting from the four-leaf stage and maintained throughout the entire growing season.

2.5. Biofertilizer and Humic Acid Application

The biofertilizer was contained *Klebsiella oxytoca* at a concentration of 10^8 CFU g^{-1}, which was extracted from the *Tamarix articulata* halophyte rhizosphere for testing its nitrogen fixation and phosphate solubilization and IAA production capabilities [11]. Pea-based slurry treatment was applied to maize seeds of cv. 5018 which contained 10 mL of biofertilizer for every kilogram of seed before they planted the seeds. Humic acid with 80% purity was applied to the soil through a drench method using 4 g L^{-1} concentration at two different times 25 and 45 days post-sowing (DAS). The integrated treatment was administered concurrently.

2.6. Data Collection and Analytical Methods

Plant growth, physiological, and yield parameters were assessed utilizing standardized and recently validated methodologies. Plant height was recorded at the tasseling stage, and the leaf area index (LAI) was measured using advanced crop canopy assessment procedures often utilized in field research [12]. The chlorophyll content of leaves was assessed using a SPAD meter on the highest fully expanded leaf, a technique demonstrated to reliably indicate nitrogen status and photosynthetic capacity in cereal crops [13]. The net photosynthetic rate (Pn) and stomatal conductance (gs) were evaluated under natural field settings applying a LI-6400XT portable photosynthesis system, a recognized instrument for gas-exchange measurements in agronomic research [14]. The absorption of nitrogen, phosphorus, and potassium was evaluated from oven-dried shoot samples using Kjeldahl digestion, Olsen extraction, and flame photometry, in accordance with revised AOAC analytical standards [15]. Sodium and potassium levels were measured using a flame photometry, and the Na^+/K^+ ratio was processed as a measure of ionic homeostasis in response to salinity stress [16]. The soil organic matter after harvest was measured utilizing wet oxidation procedures commonly applied in contemporary soil fertility research [16]. Grain yield was measured from the central rows of each plot and they converted the results to 14% moisture content which allowed for accurate treatment comparison according to current maize yield evaluation standards[17].

2.7. Statistical Analysis

Prior to analysis, all collected data were evaluated for normality and homogeneity of variance employing the Shapiro–Wilk and Levene's tests, respectively. A two-way analysis of variance (ANOVA) was performed using SPSS software (version 27.0; IBM Corp., Armonk, NY, USA) to evaluate the main and interactive effects of treatments and growing season factors on measured variables. When significant differences were identified, treatment means were compared exploiting Tukey's honestly significant difference (HSD) test at a probability level of $p \leq 0.05$. Results are presented as means ± standard error (SE). Graphical representations were generated using OriginPro 2023 (OriginLab Corporation, Northampton, MA, USA).

3. Results and discussion

3.1. Grain Yield Enhancement Under Salinity Stress

Grain yield was significantly influenced by both salinity and amendment treatments (*p* < 0.01). As shown in Table 2, the combined application (T_3) consistently yielded the highest values across all salinity levels, with increases of 25.4%, 23.4%, and 20.7% over the control at S_0, S_1, and S_2, respectively. This synergistic yield improvement is visually supported by (Fig. 1), which illustrates a clear positive gradient from control to combined treatment across salinity levels. The results were consistent with the findings of Moro et al. 2025 who achieved a 22–30 percent yield improvement for maize crops through bio-organic amendments which applied multiple approaches under the same saline conditions. The combination treatment improves root biomass and nutrient availability together with osmotic adjustment, which prevents yield loss during high salinity conditions (S_2) [18].

Table 2
Grain yield (t ha^{-1}) of maize as influenced by individual and combined applications of *Klebsiella oxytoca* biofertilizer and humic acid under three irrigation water salinity levels (S_0: 1.6, S_1: 3.0, S_2: 6.0 dS m^{-1}) during the 2024 growing season.

Salinity (dS m^{-1})	Control	Biofertilizer	Humic Acid	Bio + Humic
S_0 (1.6)	7.10 ± 0.11	8.00 ± 0.16	8.30 ± 0.14	**8.90 ± 0.13**
S_1 (3.0)	6.40 ± 0.09	7.20 ± 0.09	7.50 ± 0.08	**7.90 ± 0.15**
S_2 (6.0)	5.80 ± 0.13	6.50 ± 0.14	6.70 ± 0.08	**7.00 ± 0.16**

Values are expressed as mean ± SE (n = 3). Different letters within rows imply significant differences at $p \leq 0.05$ using Tukey's HSD test.

The research results demonstrate that all treatments experienced decreased maize grain yield as salt stress increased from S_0 to S_2 according to the expected outcomes of salt-induced osmotic and ionic stress. The application of soil amendments decreased the lost treatment results efficiently, with the combination of biofertilizer and humic acid (Bio+Humic) treatment achieving the highest grain yield across all salinity treatments (8.9, 7.9, and 7.0 t/ha, respectively). The treatment demonstrated better performance than both the separate amendments and the control group, indicating that biofertilizer improved nutrient accessibility and root development while humic acid enhanced soil structure and cation exchange capacity and stress resistance. The improved effectiveness of the two substances works through known mechanisms which operate when microbial activity and organic chelation work together to reduce salt damage by improving nutrient uptake and reducing Na^+ poisoning while increasing plant physiological strength. The research results agreed with the findings of [19] and [19], who discovered that organic and biological treatment combinations produce similar advantages in decreasing salt stress impacts on cereal crops.

3.2. Growth and Biomass Accumulation

Plant height, leaf area index, and total dry matter were significantly improved by the combined treatment (Table 3). Under S_0, T_3 increased plant height by 19.5% and dry matter by 23.2% compared to the control. Even under S_2, growth suppression was reduced by approximately 40% relative to the unamended control. This growth promotion is likely due to HA-mediated stimulation of root proliferation (Santos et al., 2025), microbial production of growth-promoting hormones (Khan et al., 2024), and improved soil structure and water retention (Yassen et al., 2023).

Table 3
Vegetative growth parameters of maize plant height (cm), leaf area index (LAI), and total dry matter accumulation (t ha^{-1}) under different soil amendment treatments across three salinity stress regimes (S_0, S_1, S_2).

Salinity (dS m^{-1})	Treatment	Plant Height (cm)	Leaf Area Index	Total Dry Matter (t ha^{-1})
S_0 (1.6)	Control	176.0 ± 2.8	4.2 ± 0.11	12.0 ± 0.23
	Bio + Humic	210.3 ± 2.0	5.1 ± 0.10	14.8 ± 0.27
S_1 (3.0)	Control	150.2 ± 2.5	3.8 ± 0.12	10.8 ± 0.25
	Bio + Humic	178.8 ± 2.1	4.5 ± 0.12	12.7 ± 0.24
S_2 (6.0)	Control	138.0 ± 2.1	3.2 ± 0.10	9.3 ± 0.19
	Bio + Humic	158.1 ± 1.9	3.8 ± 0.08	11.0 ± 0.19

Values are expressed as mean ± SE (n = 3). Different letters within rows indicate significant differences at $p \leq 0.05$ using Tukey's HSD test

The Fig. 1 shows that nitrogen serves as the main constraint for maize yield because nitrogen uptake associates with grain output at an almost perfect degree ($R^2 = 0.96$). The relationship demonstrates that nitrogen accumulation explains 96% of the changes in yield production. The steep regression slope demonstrates that farmers will receive high yield returns from every nitrogen unit they successfully acquire which creates an essential agricultural need for farmers to enhance their nitrogen uptake performance. The combined Bio + Humic treatment shows its successful operation through its mechanism which demonstrates biofertilizer root function enhancement for nitrogen retrieval and humic acid soil nutrient retention ability and salinity stress reduction power optimize nitrogen uptake by plants. The results of the study verify basic physiological principles and agreed with the findings of [20] who studied nitrogen effects on cereal yield potential and agreed with Tejada with the findings of [21], which showed that organic amendments, especially humic substances, improve nitrogen uptake efficiency in plants during abiotic stress.

3.3. Photosynthetic Performance and Chlorophyll Content

The results as shown in the Table 4 demonstrate that the combined treatment of biofertilizer and humic acid (T_3) successfully reduced salinity stress which damages photosynthesis when compared to the control group. T_3 protected chlorophyll content (SPAD) and photosynthetic rate from salinity stress at the highest salinity level (S_2) showing only 12.1% and 9.3% decreases from the baseline values which occurred under non-saline conditions. The T_3 treatment produced superior results because humic acid worked with biofertilizer-derived microbial consortia to improve antioxidant defenses and stomatal control which preserved chloroplast structure and supported carbon dioxide uptake during salinity conditions. The results of this experiment are consistent with the results of [22] and [23], which show that organic amendments combined with other agricultural approaches helps plants sustain their photosynthetic capacity during periods of abiotic stress.

Table 4
Photosynthetic performance indicators chlorophyll content (SPAD units), net photosynthetic rate (Pn, μmol CO_2 m^{-2} s^{-1}), and stomatal conductance (gs, mmol H_2O m^{-2} s^{-1}) of maize leaves under biofertilizer, humic acid, and combined treatments at different levels of salinity.

Salinity (dS m^{-1})	Treatment	SPAD Value	Pn (μmol CO_2 m^{-2} s^{-1})	gs (mmol H_2O m^{-2} s^{-1})
S_0 (1.6)	Control	46.6 ± 0.8	23.6 ± 0.9	278 ± 11
	Bio + Humic	54.3 ± 0.5	27.4 ± 0.7	310 ± 8
S_1 (3.0)	Control	43.1 ± 0.6	20.5 ± 0.8	252 ± 10
	Bio + Humic	49.6 ± 0.5	24.4 ± 0.7	282 ± 7
S_2 (6.0)	Control	41.2 ± 0.6	18.6 ± 0.8	240 ± 9
	Bio + Humic	46.8 ± 0.5	21.4 ± 0.7	263 ± 7

Values are expressed as mean ± SE (n = 3). Different letters within rows indicate significant differences at $p \leq 0.05$ using Tukey's HSD test

3.4. Nutrient Uptake and Ionic Homeostasis

The data presented in Table 5 highlights that the combined Bio+Humic application method functions as a complementary salinity stress relief method which simultaneously improved macronutrient uptake (N, P, and K) and reduced ionic toxicity through a pronounced decrease in the Na^+/K^+ ratio. The severe salinity condition S_2 resulted in nutrient acquisition of N increasing by 24.8% and P by 21.3% and K by 19.7% which demonstrates successful nutrient acquisition under salinity limits. The 31.1% drop in the Na^+/K^+ ratio demonstrates that ionic balance restoration leads to proper enzymatic activity and cellular osmotic regulation. The combined response occurs because biofertilizer microorganisms solubilize nutrients which increase soil cation exchange capacity and humic acid allows for better K^+ retention and root membrane stability under saline conditions. The results demonstrate that salinity tolerance for plants depends on specific ion uptake according to established frameworks their results validate evidence from [24] which shows that applying both PGPR and humic substances increases nutrient use efficiency while reducing sodium accumulation in salt-stressed crops. These improvements are due to biofertilizer-mediated nutrient solubilization [7], HA-induced increases in CEC and K^+ selectivity [2], and microbial production of chelating agents [7].

Table 5
Nutrient uptake (N, P, K) and leaf ionic balance (Na^+/K^+ ratio) in maize plants grown under salinity stress and amended with biofertilizer, humic acid, or their combination.

Salinity (dS m⁻¹)	**Treatment**	**N Uptake (kg ha⁻¹)**	**P Uptake (kg ha⁻¹)**	**K Uptake (kg ha⁻¹)**	**Na^+/K^+ Ratio**
S_0 (1.6)	Control	145.2 ± 2.6	28.3 ± 0.7	163.5 ± 3.2	0.32 ± 0.01
	Bio + Humic	178.0 ± 3.2	35.2 ± 0.9	206.5 ± 3.4	0.25 ± 0.01
S_1 (3.0)	Control	132.8 ± 2.4	25.6 ± 0.6	149.2 ± 3.1	0.38 ± 0.02
	Bio + Humic	167.5 ± 3.0	31.2 ± 0.8	179.4 ± 3.2	0.27 ± 0.01
S_2 (6.0)	Control	118.4 ± 2.3	22.1 ± 0.5	137.6 ± 2.7	0.45 ± 0.02
	Bio + Humic	147.8 ± 2.8	26.8 ± 0.6	164.7 ± 2.9	0.31 ± 0.01

Values are expressed as mean ± SE (n = 3). Different letters within rows indicate significant differences at $p \leq 0.05$ using Tukey's HSD test

3.5. Soil Fertility Improvement

The post-harvest soil assessment results from Table 6 demonstrate that the Bio + Humic treatment T_3 combination produced the highest soil fertility improvement across different salinity levels. The treatment T_3 at non-saline conditions S_0 increased soil organic matter by 31.6% while raising available nitrogen to 27.2%, phosphorus to 27.9%, and potassium to 22.8% when compared to control samples. The two amendments work together to bring about these improvements because humic acid enhances soil aggregation combined with cation exchange capacity which results in better nutrient retention and fewer nutrient losses, while biofertilizer microbial consortium speeds up organic matter decomposition and makes nutrients, especially P and K, available for plants to absorb. The soil biosphere enhancement of fertilities and structural properties creates a cycle that helps plants absorb more nutrients and photosynthesize better and produce more grain, which works even when salt is present in the environment. The results of this study agreed with the established principles of soil fertility management and are agreed by the findings of [25], who demonstrated the critical role of organic amendments in restoring soil quality, and [26], who documented that integrated bio-organic strategies sustainably enhance microbial activity, nutrient cycling, and crop productivity.

Table 6
Post-harvest soil fertility parameters organic matter content (%), available nitrogen (N), phosphorus (P), and potassium (K) as affected by biofertilizer and humic acid applications under saline irrigation regimes.

Salinity (dS m^{-1})	Treatment	OM (%)	Available N (mg kg^{-1})	Available P (mg kg^{-1})	Available K (mg kg^{-1})
S_0 (1.6)	Control	0.92 ± 0.03	49.6 ± 1.2	6.1 ± 0.2	189 ± 4
	Bio + Humic	1.21 ± 0.03	63.1 ± 1.6	7.8 ± 0.3	232 ± 6
S_1 (3.0)	Control	0.85 ± 0.03	46.5 ± 1.1	5.7 ± 0.2	176 ± 4
	Bio + Humic	1.10 ± 0.03	58.0 ± 1.5	7.1 ± 0.3	215 ± 5
S_2 (6.0)	Control	0.76 ± 0.02	41.8 ± 1.0	5.1 ± 0.2	162 ± 4
	Bio + Humic	0.99 ± 0.03	51.4 ± 1.3	6.3 ± 0.3	195 ± 5

Values are expressed as mean ± SE (n = 3). Different letters within rows indicate significant differences at $p \leq 0.05$ using Tukey's HSD test

3.6. Integrated Trait Correlations

The correlation analysis shown in Fig. 3 clarifies the integrated processes by which the combined Bio + Humic treatment enhances maize performance under saline conditions. The study found strong positive correlations between soil fertility indicators and key physiological attributes which included chlorophyll content and photosynthetic rate and nutrient uptake. The parameters demonstrated positive relationships with grain yield which showed the most evident soil–plant continuum in the combined treatment. The leaf Na^+/K^+ ratio exhibited strong negative correlations with yield and physiological traits which demonstrated how ionic imbalance under salinity stress affects plant health. The results show that Bio + Humic synergy operates through multiple pathways which connect to each other and enhance academic writing by improving physicochemical and biological properties while restoring ionic balance and advancing plant physiological performance. The resulting system provides combined advantages which help plants take in nutrients and build biomass and produce their yields. These findings are consistent with the integrated soil–plant feedback framework described by [27] and align with reports by [28], who showed that combined microbial inoculants and humic substances enhance root functionality, microbial activity, photosynthetic performance, and ionic regulation in salt-stressed crops.

4. Conclusion

Overall, this study shows that combining biofertilizer with humic acid is an effective and practical approach for improving maize performance under saline conditions. Compared with using either amendment alone, their joint application consistently produced higher grain yield, better plant growth and photosynthetic activity, and improved soil fertility, including greater organic matter and N, P, and K availability. The microorganisms found in biofertilizers establish beneficial relationships with plant roots which enable plants to better absorb nutrients from the soil. The application of humic acid to soil enhances its structural properties while maintaining nutrients in the soil, which results in a decrease of sodium toxicity and restoration of ionic balance through its action on Na^+/K^+ ratio reduction. The combination of improved nutrient uptake with greater photosynthetic efficiency leads to increased biomass production and crop yield, which remains effective under all salinity conditions. The strong relationships between soil organic matter, nutrient uptake, chlorophyll content, and yield and their negative association with Na^+/K^+ confirm this integrated soil–plant response. Taken together, the findings demonstrate that the Bio + Humic strategy strengthens the resilience of the soil–plant system as a whole and represents a sustainable option for enhancing maize productivity in salt-affected soils.

Abbreviations

CEC (Cation Exchange Capacity), CFU (Colony Forming Units), DAS (Days After Sowing), EC (Electrical Conductivity), ECe (Electrical Conductivity of the Saturation Extract), ECiw (Electrical Conductivity of Irrigation Water), gs (Stomatal Conductance), HA (Humic Acid), IAA (Indole-3-Acetic Acid), LAI (Leaf Area Index), OM (Organic Matter), PGPM (Plant Growth-Promoting Microorganisms), Pn (Net Photosynthetic Rate), RCBD (Randomized Complete Block Design), and SPAD (Soil Plant Analysis Development). Salinity levels are denoted as S_0 (1.6 dS m^{-1}), S_1 (3.0 dS m^{-1}), and S_2 (6.0 dS m^{-1}), while treatments are labeled T_0 (Control), T_1 (Biofertilizer only), T_2 (Humic acid only), and T_3 (Biofertilizer + HA). ROS (Reactive Oxygen Species) All abbreviations are defined upon first use and applied consistently throughout the text.

Declarations

Supplementary Information

Supplementary Material

Additional supporting data, including raw datasets, detailed statistical outputs, supplementary tables, and extended figures, are available from the corresponding author upon reasonable request.

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Author Contributions

W.F.H.: Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Software; Validation; Visualization; Writing – Original draft; Writing – review & editing; Funding acquisition; Project administration; Writing – review & editing. M.H.D.: Formal analysis; Investigation; Methodology; Supervision; Writing – review & editing.

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Data Availability

The datasets generated and analyzed during this study are available from the corresponding author upon reasonable request.

Ethics Approval and Consent to Participate

Not applicable.

Consent for Publication

Not applicable.

Competing Interests

The authors declare no competing interests.

Clinical trial number

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Figures

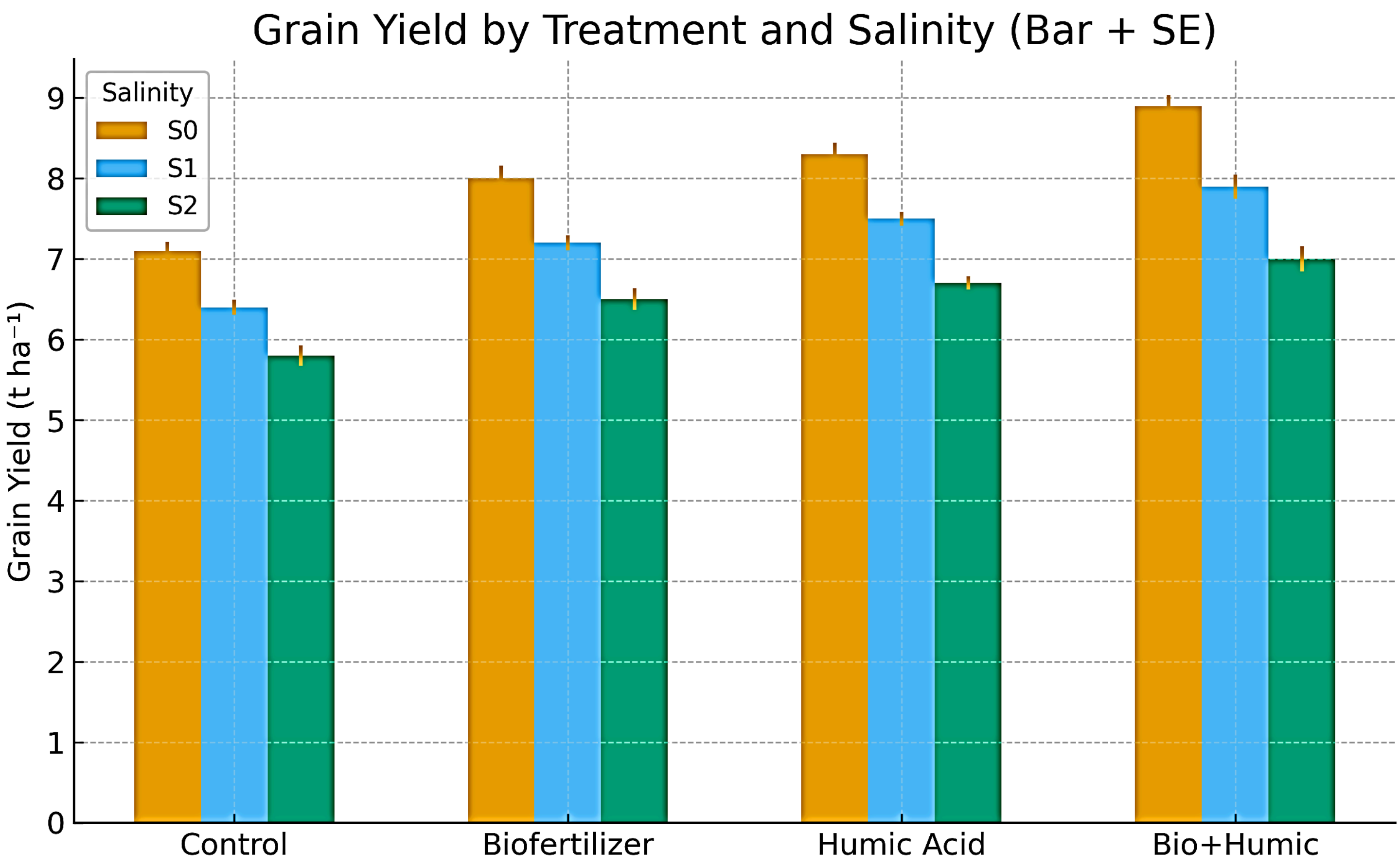

Figure 1

Grain yield response of maize to biofertilizer, humic acid, and their combination under different salinity levels (S_0, S_1, S_2).

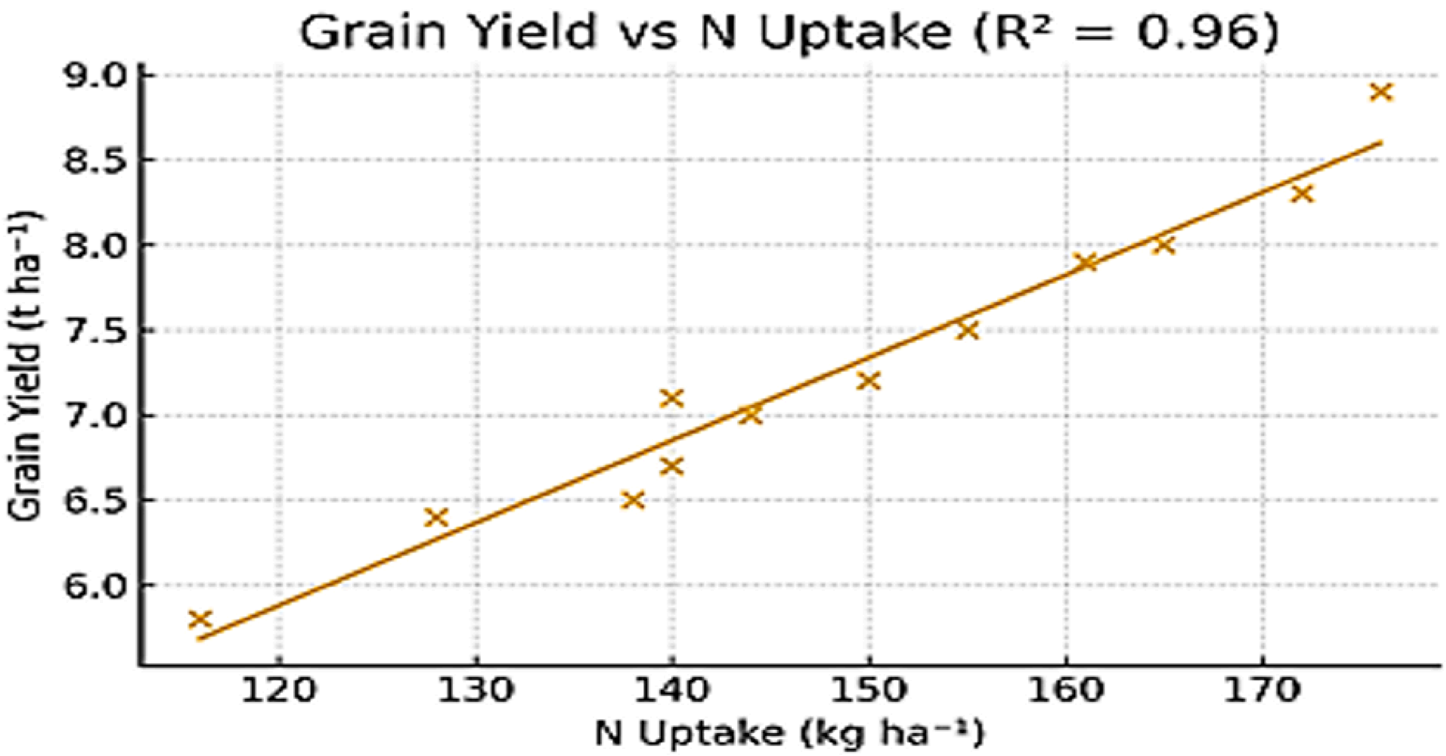

Figure 2

Growth response of maize plants under different treatments and salinity levels.

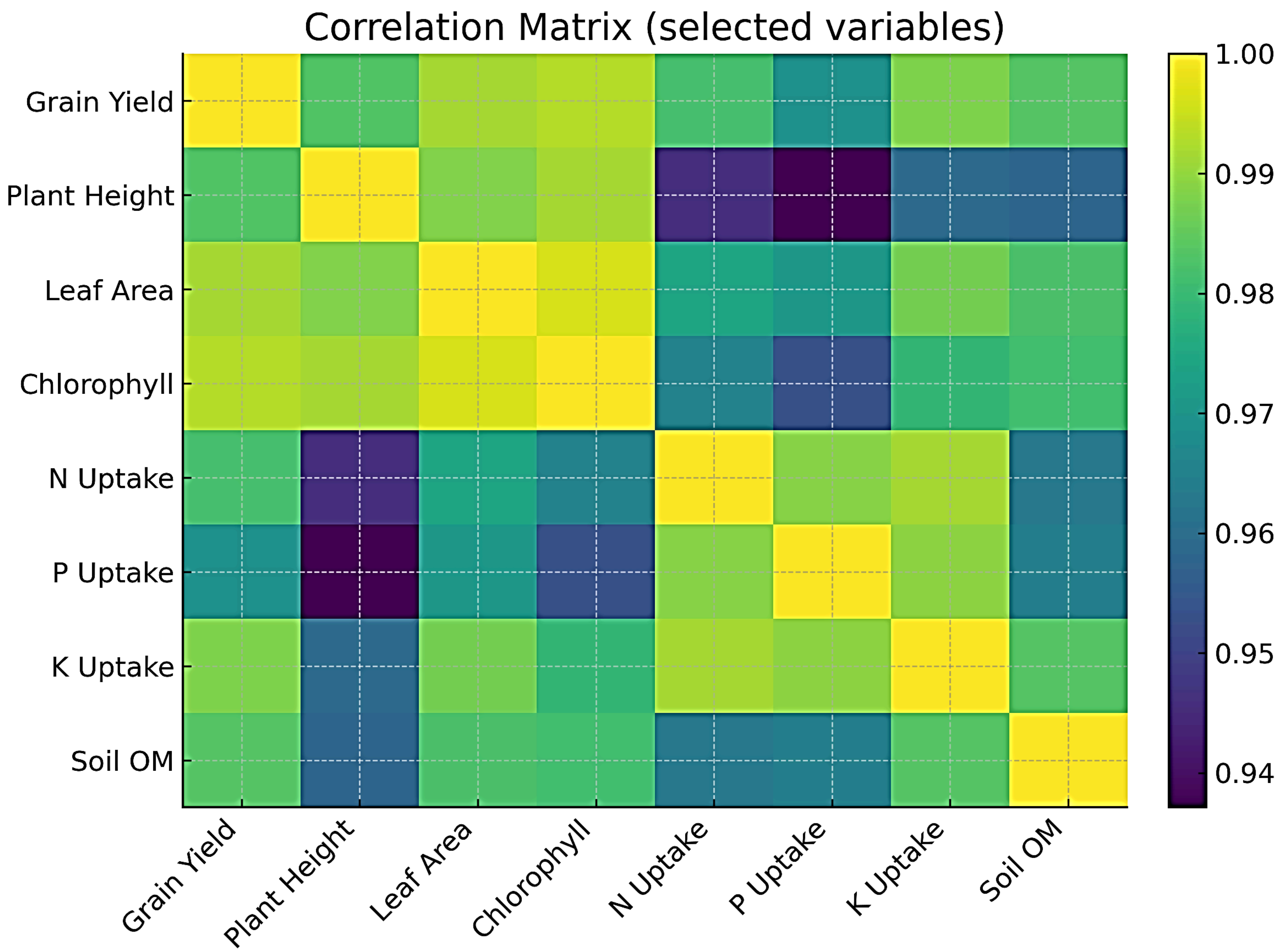

Figure 3

Correlation heatmap illustrating relationships among soil properties, plant physiological traits, nutrient uptake, and grain yield under different treatments. Red indicates positive correlations; blue indicates negative correlations. The combined treatment (Bio + Humic) cluster shows the strongest positive linkages between soil fertility indicators and yield-related traits.