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Organic fertilizer and microbial agents increase soil quality and maize yield on coastal saline-alkali land

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Abstract: To evaluate the effects of organic fertilizer and microbial agents on soil water and salt distribution, microorganisms, and crop yield on coastal saline-alkaline land, eight treatments were established, i.e., two maize varieties (Dajing Jiu 26 (J) and Quchen Jiu (Q)) and four organic fertilizer and microbial agent application methods (no organic fertilizer or microbial agent application (O_0M_0), single organic fertilizer application (O_1M_0), single microbial agent application (O_0M_1), and combined organic fertilizer and microbial agent application (O_1M_1)). The soil water content in the 40–50 cm soil layer under JO_1M_1 was 3.35% greater than that under JO_0M_0 at the mature stage. The soil organic carbon (SOC) and soil total nitrogen (STN) in the 0–10 cm soil layer under JO_1M_1 were 16.69% and 21.37% greater, respectively, than those under JO_0M_0 at the jointing stage. The actinomycete content was 58.79% greater in QO_1M_1 than in QO_0M_0. The urease activity was greater in O_1M_0 than in the other management practices. Compared with that in JO_0M_0 and QO_0M_0, the alkaline phosphatase activity in JO_1M_1 and QO_1M_1 was 47.36% and 33.97% higher, respectively. Compared with those of JO_0M_0, the catalase activity and sucrase activity of JO_1M_1 were 57.62% and 22.78% higher, respectively. Compared with JO_0M_0 and QO_0M_0, JO_1M_1 and QO_1M_1 increased the grain yield by 20.69% and 16.42%, respectively, and increased the biomass by 23.36% and 26.45%, respectively. In summary, organic fertilizer and microbial agents provide a scientific model for the rational use of saline soils and the development of their potential.

Keywords: organic material input; soil enzyme activities; soil organic carbon; water-salt dynamics

Salinization strongly affects soil quality and ecology and the growth of plants (Marsack & Connolly 2022; Nikolić et al. 2023; Zhang et al. 2023). Soil salinization has become one of the most severe agricultural hazards (Zhu 2001; Cuevas et al. 2019). The ecological environment of saline areas must urgently be improved, and saline and alkaline land resources need to be fully utilized (Li et al. 2014). Organic fertilizer is rich in organic components, has a high buffering capacity, regulates soil pH and is widely regarded as an effective soil amendment (Hou et al. 2025). Organic fertilizer increases the water-holding properties of surface soils, improves the saline soil environment (Schlegel et al. 2017; Cheng et al. 2023), and reduces the deep leakage of soil water (Oo et al. 2015). Different soil types have an optimal organic-to-inorganic

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fertilizer ratio that maximizes crop growth and yield (Hou et al. 2025). Overall, increasing the proportion of organic fertilizer application and reducing the amount of common fertilizer application reduces soil salinization (Tejada et al. 2006; Ning et al. 2021). The application of microbial agents to soil can increase the water content of saline soil, inhibit soil salinity, and reduce total salinity, which is beneficial for the accumulation of maize (Li et al. 2024).

Soil organic carbon (SOC) is fundamental to soil multifunctionality, as it affects soil fertility, food security and global climate change (Lal 2010; Zwetsloot et al. 2021). Saline soils have low organic matter and total nitrogen contents (Butturini et al. 2020), which affect plant growth. Organic fertilizer increases the soil organic matter content (Ren et al. 2024) and reduces C loss (Xu et al. 2023). Organic fertilizer improves the surface soil environment and increases the soil microbial biomass, microbial community and enzyme activity (Timo et al. 2004; Islam et al. 2009; Essalimi et al. 2022). Compared with traditional mineral fertilizers, microbial agents result in higher levels of SOC and soil total nitrogen (STN) (Böhme & Böhme 2006; Kong et al. 2021). Microbial agents regulate the C/N ratio of the soil under certain conditions, increasing the number of soil microorganisms and thus improving the soil environment (Stark et al. 2007). Microorganisms can reflect the level of soil fertility, and the number of soil microorganisms is an effective and sensitive indicator for evaluating soil quality (Liu et al. 2000). Microbial agents increase bacterial community diversity in farmland soil (Chen et al. 2021).

Increasing the application of organic fertilizer and reducing the share of mineral fertilizers can improve the yield of maize (Zhai et al. 2023). Microbial fertilizers are living organisms that can alleviate the negative impacts of fertilizers to promote plant growth and improve crop yields (Gong et al. 2018). When organic fertilizer is combined with microbial agents, the differences in soil quality and yield enhancement are significant (Peng et al. 2023). The appropriate application of organic fertilizers reduces the loss of soil nitrogen, delays the early decline of maize, improves the indicators of various maize economic traits, and increases maize yield (Liu et al. 2023). The mechanism by which organic fertilizer and microbial agents affect soil quality and crop growth in saline soils is still not fully understood.

The objectives of this research were (1) to explore the effects of organic fertilizer and microbial agents on water and salt distributions and soil microorganisms in coastal saline-alkaline land and (2) to provide a theoretical basis for improving soil quality and increasing crop yield in coastal saline-alkaline soils. We hypothesized that, compared with single organic fertilizer or microbial agents, the combination of organic fertilizer and microbial agents would increase the soil water content, improve the soil nutrients and microbial quantity structure, and contribute to the development of strategies to improve maize yields in coastal saline-alkaline land, thereby addressing the challenge of salinity hazards.

MATERIAL AND METHODS

Description of the experimental site. The experiment was established in 2020 in Wudi County, Binzhou City, Shandong Province, China (37°N, 118°E), which is characterized by a temperate continental monsoon climate with an average annual temperature of approximately 13 °C and an average annual precipitation of approximately 560 mm. The annual precipitation is mainly concentrated in July and August, which is essentially in line with the climatic characteristics of rain and heat occurring at the same time. The soil type was coastal saline tidal soil, which was classified as a Cambisol (IUSS Working Group WRB 2006). The soil was moderately saline. The soil texture was powdery clay loam. The groundwater level ranged from 1.0–1.5 m and the mineralization rate of groundwater ranged from approximately 10–40 g/L during the crop growth stage. At the beginning of the experiment, the basic properties of the 0–20 cm soil layer were as follows: sand, 40.88%; silt, 58.65%; clay, 0.26%; SOC, 12.21 g/kg; total nitrogen, 0.84 g/kg; phosphorus, 17.56 mg/kg; potassium, 133.1 mg/kg; and soil salinity, 3.32 g/kg; pH/H_2O 8.62. The entire experimental site was 100 m long and 38 m wide. Three replicates were established in each plot, and each plot was 15 m long and 5 m wide.

Experimental design. The experiment was conducted using a split-zone design. The four treatments included no application of organic fertilizer or microbial agent (control group, O_0M_0), a single application of organic fertilizer (O_1M_0), a single application of microbial agent (O_0M_1), and a combined application of organic fertilizer and microbial agents (O_1M_1). Two kinds of forage maize, the Dajing Jiu 26 variety (J) and the Quchen Jiu variety (Q), were used as test materials. The sowing density was 66 000 plants/ha. Slow-release

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fertilizer ($N : P_2O_5 : K_2O$ = 26 : 11 : 11, 450 kg/ha) and organic fertilizer (organic matter ≥ 45%, mass fraction of total nutrients (on a dry basis): $N + P_2O_5 + K_2O$ ≥ 5%, and number of active bacteria ≥ 0.2 billion/g) were used as basic fertilizers. The organic fertilizer was granular, applied at a rate of 15 t/ha and spread evenly on the soil surface. After the organic fertilizer was spread, the topsoil and organic fertilizer were ploughed to a depth of 15 cm. The concentration of the microbial agent, the bacterial strain *Bacillus polymyxa* SC2, was 75 L/ha. After the maize seedlings germinated, the microbial agent was sprayed into the field by dilution with water at a ratio of 1 : 500. The other management methods were consistent with those used in the field.

Soil sampling. The 5-point soil sampling method was used at the jointing stage, flowering stage and maturity stage of maize in 2021. The soil surface vegetation was subsequently removed, and soil samples were collected from the 0–100 cm soil layer, with one sample collected every 10 cm. The collected soil samples were divided into two portions: one portion was placed indoors to dry naturally, ground, passed through a 60-mesh sieve, and stored at less than 4 °C for the determination of soil physicochemical properties. The other fresh soil sample from the 0–40 cm layer was placed into a sterile self-sealing bag, temporarily stored in an insulated box with dry ice and subsequently placed into an ultralow-temperature freezer at –80 °C immediately after being returned to the laboratory for the determination of soil microorganisms.

Determination of soil physical and chemical properties. The soil mass water content was determined via the aluminium box drying method with the following formula: soil mass water content (%) = (mass of the aluminium box and soil sample before drying – mass of the aluminium box and soil sample after drying)/(mass of the aluminium box and soil sample after drying – mass of the empty aluminium box after drying) × 100%. SOC: one gram of soil was weighed and measured via the potassium dichromate oxidation–external heating method. STN: determination was performed via the semimicro Kjeldahl method. Soil salinity: several soil samples were selected and configured into a soil leachate with a water-soil ratio of 5 : 1, and their conductivity was determined using a DDSJ-308F conductivity meter (Shanghai Yidian Scientific Instrument Co., Ltd.) combined with the empirical formula for conductivity–salinity conversion in the region derived from previous research performed in the region:

$$\text{Soil salinity (g/kg)} = 3.1781 \times \text{EC } 5:1/1000 + 0.2853, \quad R^2 = 0.9411$$

Determination of soil enzyme activities. Catalase activity was determined via the $KMnO_4$ titration method. Sucrase activity was determined via the 3,5-dinitrosalicylic acid colorimetric method. Urease activity was determined via the indophenol blue colorimetric method. Alkaline phosphatase activity was determined via the colorimetric method via disodium benzyl phosphate.

Soil microbiology. Soil microflora counts were determined via the plate dilution method with beef paste peptone medium for bacteria, Martin-Bertani red agar medium for fungi, and modified Gow's 1 agar medium for actinomycetes.

Maize sampling and determination. For the field emergence rate, 10 m rows were selected from each plot at the seedling stage to investigate the seedling emergence rate, and the process was repeated three times. Biomass: samples were dried in an oven at 105 °C for 30 min, dried at a constant temperature of 80 °C until a constant weight was reached, and weighed using an electronic balance with an accuracy of 0.01 g. Yield: at the time of maize harvest, maize cobs were taken from the central portion of each plot in 5 m double rows, and three replications were performed. The ears were subsequently threshed and weighed, after which the maize yield was calculated.

Statistical analysis. Microsoft Excel 2019 and Origin 2022 software were used for graphing. SPSS Ver. 22 software was used for statistical analysis. The data were statistically analysed via analysis of variance (ANOVA). Variance analysis and treatment mean values (n=3) were compared with Fisher's least significant difference (LSD) test at the 5% level. Correlations between the yield of maize and the soil parameters were analysed in R (Ver. 3, R Core Team 2016).

RESULTS

Soil water content. JO_1M_1 and QO_1M_1 presented the highest water contents from 50–60 cm at the flowering stage (Figure 1A). The decrease in the soil water content of the Dajing Jiu 26 variety was greater than that of the Quchen Jiu variety at 70–90 cm at the flowering stage (Figure 1B). The soil water content in the mature stage reached a maximum in the 40–50 cm soil layer (Figure 1C).

Soil salinity. QO_1M_1 had a lower salt content (13.51%) than did QO_0M_0 at 20–30 cm (Table 1). The

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salt content of JO_1M_1 was 13.16% lower than that of JO_0M_0 at 30–40 cm. The salt content of JO_1M_1 was 12.16% lower than that of JO_0M_0 at 30–40 cm, and the salt content of the Quchen Jiu variety in QO_1M_1 was 12.81% lower than that in QO_0M_0 in the 20–30 cm soil layer (Table 1). QO_1M_1 had a 12.17% lower salinity than did QO_0M_0 from 20–30 (Table 1).

Soil organic carbon. The SOC content at 0–10 cm under JO_1M_1 and JO_1M_0 was 16.69% and 14.69% greater than that under JO_0M_0 at the jointing stage (Figure 2A). The SOC in the 0–10 cm layer under JO_1M_1 was 13.14% greater than that under JO_0M_0 at the flowering stage (Figure 2B).

Soil total nitrogen. The STN in the 0–10 cm layer under JO_1M_1 and QO_1M_1 was 21.37% and 20.16% greater than that under JO_0M_0 and QO_0M_0 at the jointing stage (Figure 3A). The STN in the 0–10 cm layer under JO_1M_1 was 40.75% greater than that under JO_0M_0 at the flowering stage (Figure 3B). The STN in the 0–10 cm layer under QO_1M_1 was 36% greater than that under QO_0M_0.

Table 1. Effects of organic fertilizer and microbial agents on soil salinity at the jointing, flowering and mature stages (in g/kg)

Treatment	Soil depth (cm)									
	0–10	10–20	20–30	30–40	40–50	50–60	60–70	70–80	80–90	90–100
Jointing stage										
JO_1M_1	2.27^c	2.18^c	2.08^c	1.98^c	1.88^c	1.81^c	1.89^c	2.05^b	2.10^b	1.99^c
JO_1M_0	2.37^b	2.28^b	2.22^b	2.13^b	2.01^b	1.92^b	1.95^c	2.08^b	2.11^b	2.02^b
JO_0M_1	2.31^b	2.22^b	2.17^b	2.06^b	1.94^b	1.85^c	2.07^b	2.11^b	2.15^b	2.05^a
JO_0M_0	2.52^a	2.43^a	2.35^a	2.28^a	2.16^a	2.04^a	2.18^a	2.26^a	2.31^a	2.09^a
QO_1M_1	2.23^c	2.12^c	1.92^c	1.89^c	1.84^c	1.79^c	1.95^c	2.07^b	2.15^b	2.02^c
QO_1M_0	2.29^b	2.22^b	2.19^a	2.08^a	1.99^b	1.83^b	2.06^b	2.11^b	2.16^b	2.08^b
QO_0M_1	2.26^c	2.18^b	2.07^b	1.96^b	1.86^c	1.76^c	1.98^c	2.09^b	2.11^c	2.03^c
QO_0M_0	2.44^a	2.33^a	2.22^a	2.07^a	2.01^a	1.92^a	2.17^a	2.25^a	2.31^a	2.22^a
Flowering stage										
JO_1M_1	2.22^c	2.09^c	2.05^c	1.95^c	1.77^c	1.73^c	1.79^c	1.91^c	2.04^b	1.95^b
JO_1M_0	2.32^b	2.13^c	2.09^b	2.01^b	1.94^b	1.83^b	1.96^b	2.03^b	2.08^b	1.98^b
JO_0M_1	2.30^b	2.25^b	2.11^b	2.04^b	1.98^b	1.77^c	1.94^b	2.04^b	2.09^b	1.97^b
JO_0M_0	2.48^a	2.36^a	2.30^a	2.22^a	2.08^a	1.98^a	2.08^a	2.15^a	2.21^a	2.07^a
QO_1M_1	2.10^b	2.03^c	1.84^c	1.89^b	1.77^c	1.72^c	1.89^c	1.98^c	2.07^c	2.01^c
QO_1M_0	2.19^b	2.11^b	2.08^a	1.91^b	1.89^b	1.78^b	1.98^b	2.02^b	2.08^c	2.03^c
QO_0M_1	2.18^b	2.09^b	1.99^b	1.93^b	1.75^c	1.71^c	2.02^b	2.05^b	2.11^b	2.06^b
QO_0M_0	2.33^a	2.23^a	2.11^a	2.01^a	1.97^a	1.89^a	2.15^a	2.23^a	2.29^a	2.19^a
Mature stage										
JO_1M_1	2.38^c	2.27^c	2.21^c	2.12^c	2.00^b	2.05^c	2.08^b	2.12^c	2.06^c	2.01^b
JO_1M_0	2.48^b	2.36^b	2.30^b	2.21^b	2.02^b	2.09^b	2.13^b	2.16^b	2.08^c	2.04^b
JO_0M_1	2.41^c	2.33^b	2.25^b	2.13^c	2.04^b	2.10^b	2.15^b	2.19^b	2.14^b	2.07^b
JO_0M_0	2.62^a	2.54^a	2.43^a	2.35^a	2.26^a	2.32^a	2.34^a	2.37^a	2.30^a	2.24^a
QO_1M_1	2.29^c	2.23^c	2.02^c	1.96^c	1.94^b	2.01^b	2.05^c	2.09^c	2.06^b	2.03^c
QO_1M_0	2.39^b	2.33^b	2.17^b	2.15^a	2.09^a	2.16^a	2.19^b	2.23^a	2.18^a	2.13^b
QO_0M_1	2.36^b	2.29^b	2.15^b	2.03^b	1.96^b	2.04^b	2.10^c	2.15^b	2.09^b	2.07^c
QO_0M_0	2.54^a	2.44^a	2.30^a	2.14^a	2.11^a	2.18^a	2.24^a	2.27^a	2.21^a	2.18^a

JO_1M_1 – combined application of organic fertilizer and microbial agents, Dajing Jiu 26 variety; JO_1M_0 – single application of organic fertilizer, Dajing Jiu 26 variety; JO_0M_1 – single application of microbial agent, Dajing Jiu 26 variety; JO_0M_0 – no application of organic fertilizer or microbial agent, Dajing Jiu 26 variety; QO_1M_1 – combined application of organic fertilizer and microbial agents, Quchen Jiu variety; QO_1M_0 – single application of organic fertilizer, Quchen Jiu variety; QO_0M_1 – single application of microbial agent, Quchen Jiu variety; QO_0M_0 – no application of organic fertilizer or microbial agent, Quchen Jiu variety; different letters in the same column represent significant differences among treatments for the same variety ($P < 0.05$)

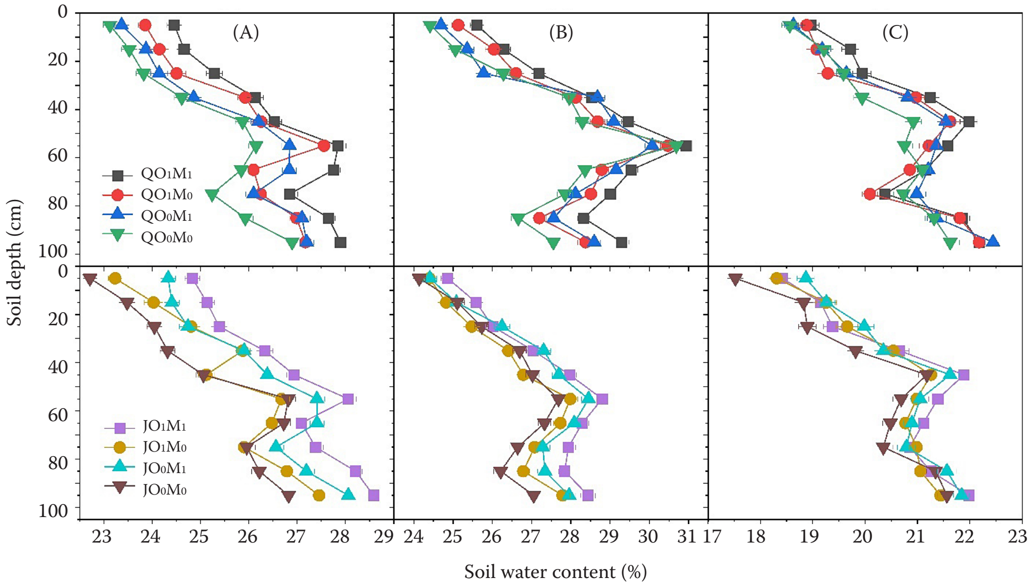

Figure 1. Effects of organic fertilizers and microbial agents on the soil water content at the jointing (A), flowering (B) and mature (C) stages of maize

JO_1M_1 – combined application of organic fertilizer and microbial agents, Dajing Jiu 26 variety; JO_1M_0 – single application of organic fertilizer, Dajing Jiu 26 variety; JO_0M_1 – single application of microbial agent, Dajing Jiu 26 variety; JO_0M_0 – no application of organic fertilizer or microbial agent, Dajing Jiu 26 variety; QO_1M_1 – combined application of organic fertilizer and microbial agents, Quchen Jiu variety; QO_1M_0 – single application of organic fertilizer, Quchen Jiu variety; QO_0M_1 – single application of microbial agent, Quchen Jiu variety; QO_0M_0 – no application of organic fertilizer or microbial agent, Quchen Jiu variety

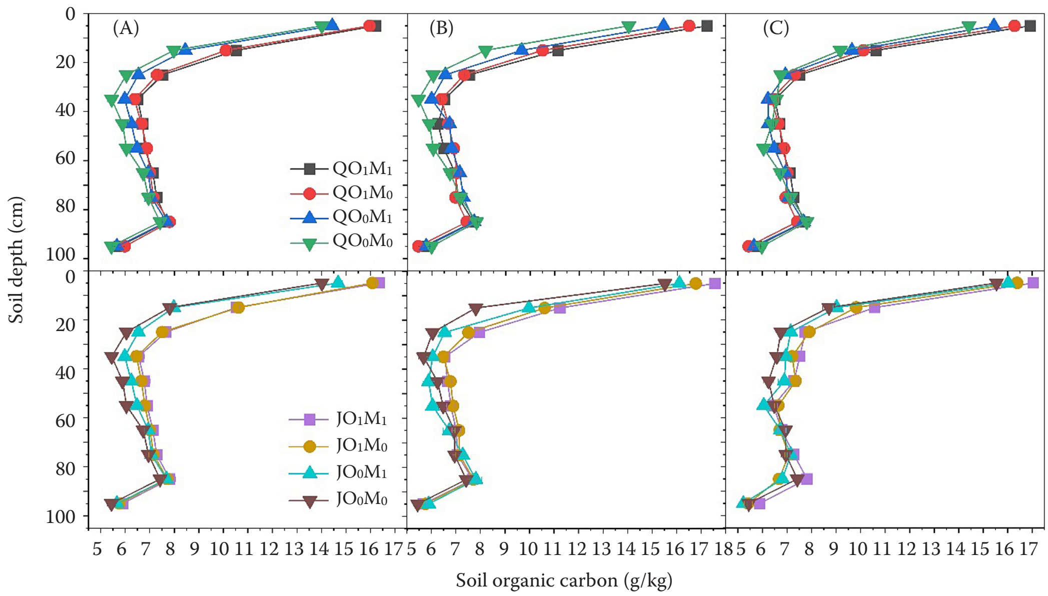

Figure 2. Effects of organic fertilizers and microbial agents on soil organic carbon at the jointing (A), flowering (B) and mature (C) stages of maize

For the treatment explanation see Figure 1

Soil enzyme activities. Urease activity was greater in JO_1M_1 and JO_1M_0 than in JO_0M_1 and JO_0M_0, whereas the values in QO_1M_1 and QO_1M_0 were greater than those in QO_0M_1 and QO_0M_0 (Figure 4A). The soil catalase activity was highest in both the organic fertilizer and microbial agent treatments, with that

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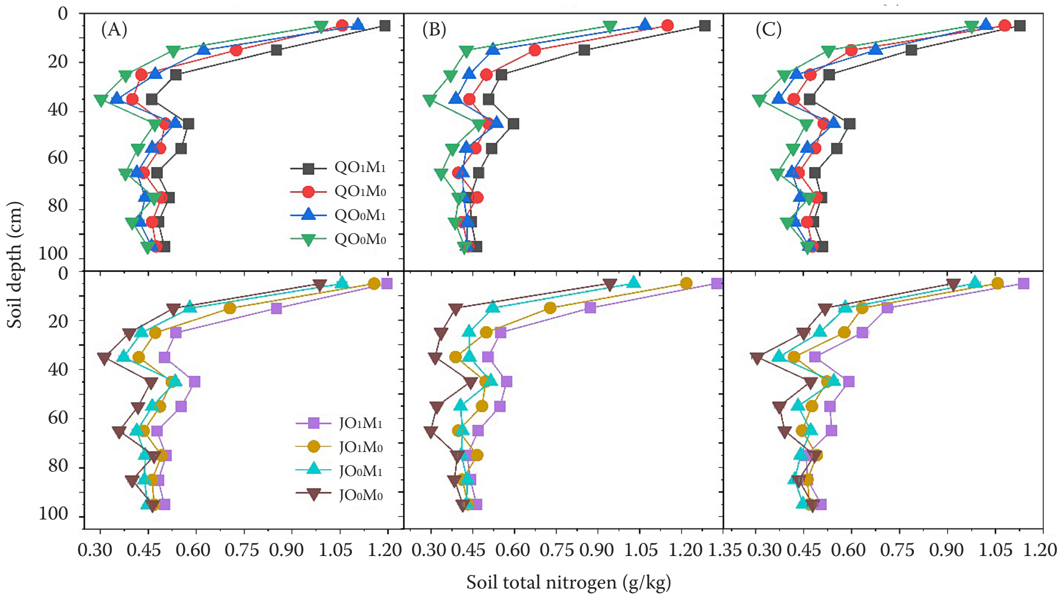

Figure 3. Effects of organic fertilizers and microbial agents on soil total nitrogen at the jointing (A), flowering (B) and mature (C) stages of maize

For the treatment explanation see Figure 1

of JO_1M_1 being 57.62% greater than that in JO_0M_0 and representing the greatest difference (Figure 4B). The alkaline phosphatase activity in JO_1M_1 and QO_1M_1 was 47.36% and 33.97%, respectively, higher than that in JO_0M_0 and QO_0M_0 (Figure 4C). The sucrase activity in JO_1M_1 was 7.33%, 6.02%, and 22.78% greater than those in JO_1M_0, JO_0M_1, and JO_0M_0, respectively (Figure 4D).

Soil microorganisms. The values of both QO_1M_0 and QO_0M_1 were 57.24% and 63.16% greater than those of QO_0M_0 (Figure 5B). The number of actinomycetes was greater than that of fungi under organic fertilizer and microbial agent treatment. The actinomycete concentration differed among the treatments, with all the microbial agent applications being greater, i.e., JO_0M_1 was 31.21% greater than

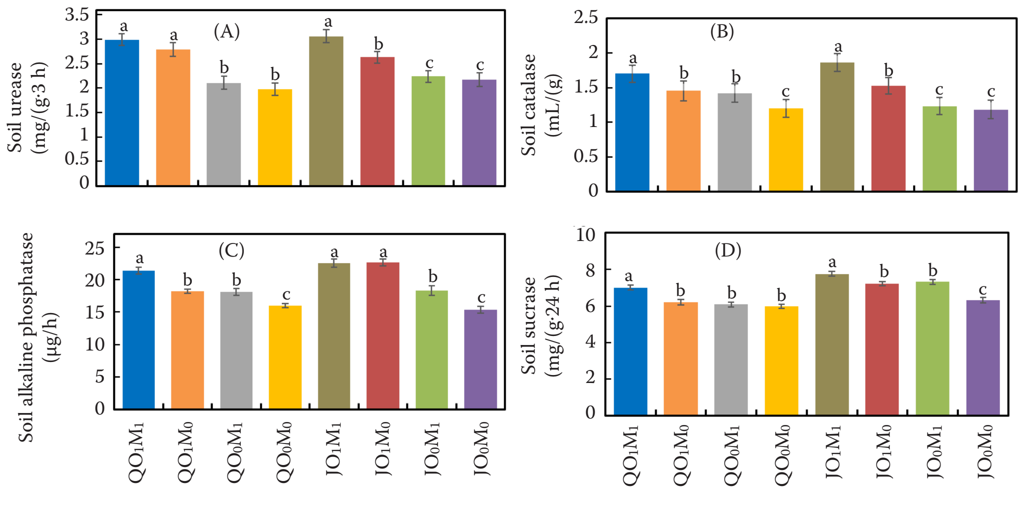

Figure 4. Effects of organic fertilizers and microbial agents on soil enzyme activities

For the treatment explanation see Figure 1; different letters in the same group represent significant differences among treatments for the same variety ($P < 0.05$)

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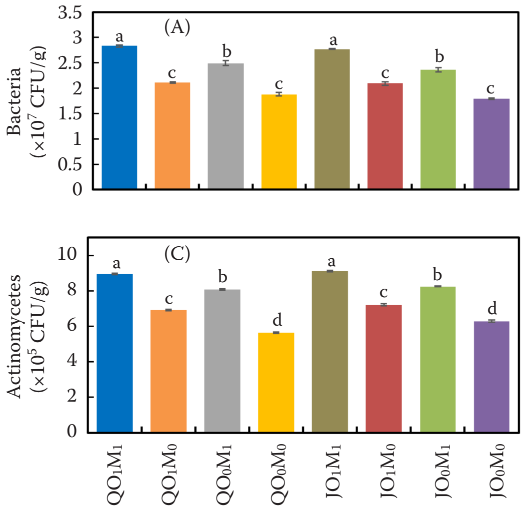

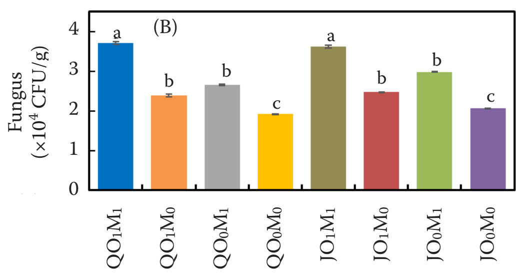

Figure 5. Effects of organic fertilizers and microbial agents on the number of soil microorganisms

For the treatment explanation see Figure 1; different letters in the same group represent significant differences among treatments for the same variety ($P < 0.05$)

JO_0M_0, and QO_1M_1 was 58.79% greater than QO_0M_0 (Figure 5C).

Emergence rate and yield of maize. The yield and biomass of JO_1M_1 were 20.69% and 23.36% greater, respectively, than those of JO_0M_0 (Table 2). The yield and biomass of QO_1M_1 were 16.42% and 26.45% greater, respectively, than those of QO_0M_0.

Relationships among the soil physicochemical properties, microorganisms, and maize yield. The soil salinity was negatively correlated with all the other parameters (Figure 6). There was a poor correlation between emergence rate and soil water content. There were positive correlations between the yield of maize and soil organic carbon, total nitrogen, soil urease, soil alkaline phosphatase, soil sucrase, fungus, actinomycetes, and biomass. SOC was positively correlated with soil urease, soil alkaline phosphatase, soil sucrase, fungi, actinomycetes and STN.

Table 2. Effects of organic fertilizers and microbial agents on maize yield

Treatment	Field emergence rate (%)	Grain yield (t/ha)	Biomass (t/ha)
JO_1M_1	80.57[a]	9.04[a]	16.26[a]
JO_1M_0	81.25[a]	8.18[b]	14.79[b]
JO_0M_1	76.67[b]	8.53[b]	15.02[b]
JO_0M_0	77.08[b]	7.49[c]	13.18[c]
QO_1M_1	77.08[b]	8.24[a]	15.25[a]
QO_1M_0	80.42[a]	7.69[b]	14.28[b]
QO_0M_1	75.83[b]	7.14[c]	12.72[c]
QO_0M_0	74.56[c]	6.82[c]	12.06[c]

For the treatment explanation see Figure 1; different letters in the same column represent significant differences among treatments for the same variety ($P < 0.05$)

DISCUSSION

Effects of organic fertilizer and microbial agents on water-salt dynamics, soil organic carbon and total nitrogen. Owing to the evaporation of groundwater as well as the infiltration of precipitation, the soil water content reached a maximum at 50–60 cm depth during the jointing stage. The soil salt content migrates to the surface as water evaporates (Li et al. 2024). The salinity in each treatment reached a minimum in the 50–60 cm soil layer at the jointing and flowering stages. The soil salinity had the greatest negative correlation with the soil water content (Figure 6). The higher the water content is, the lower the solute content (Rezaei et al. 2021). The movement of soil salts with seasonal changes is an important cause of soil salinization, and water and salt regulation is a mainly soil hydrological process, i.e., the movement of soil water drives the movement of salts to achieve salinity equilibrium (Meiri et al. 1995). O_0M_0 lost high amounts of water and exhibited poor water retention performance compared with O_1M_0. Organic fertilizer significantly reduces the salt content and alkalinity (Zhang et al. 2014; Cheng et al. 2023). This is because the application of organic fertilizer improves the soil structure, increases water retention and the discharge of soil salts and inhibits salt return (Duan et al. 2023; Wang et al. 2023). QO_0M_1 had a significantly lower salt content than did QO_0M_0 in the 0–20 cm soil layer

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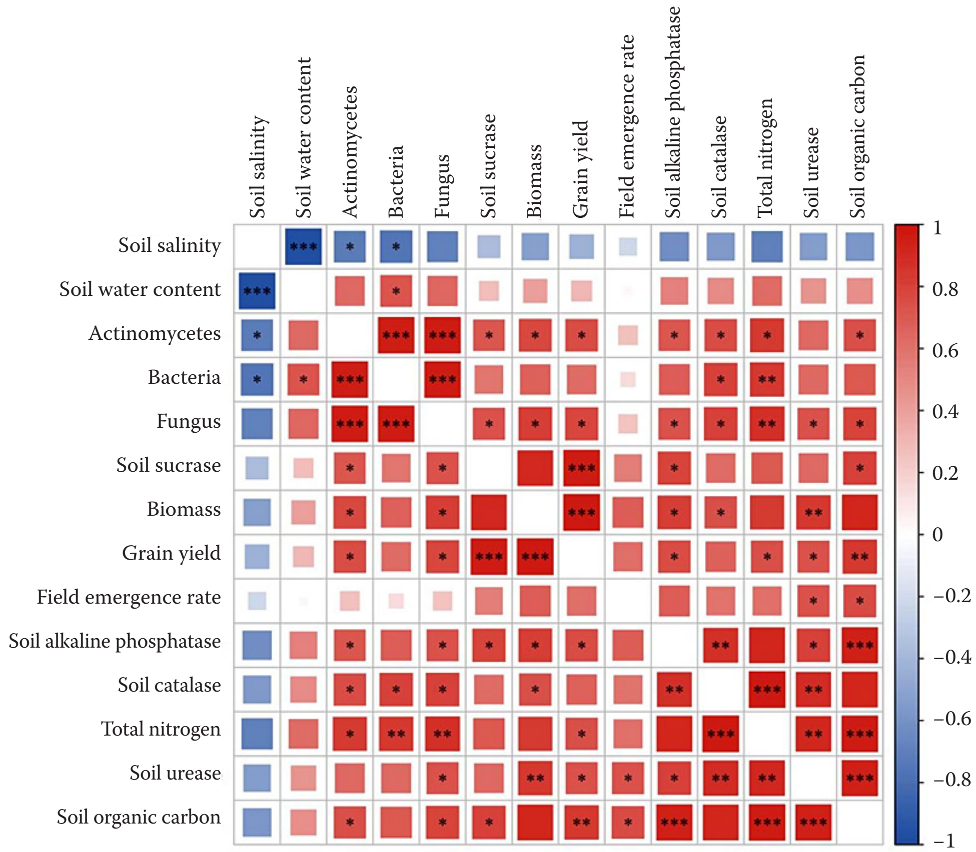

Figure 6. Relationships among the yield of maize and soil parameters

*Significant differences (Tukey's test, $P < 0.05$) between the two parameters; **significant differences (Tukey's test, $P < 0.01$); ***significant differences (Tukey's test, $P < 0.001$) between the two parameters; red and blue represent positive and negative correlations, respectively

at the flowering stage, which suggested that microbial agents act as buffers against soil salinity by increasing microbial activity.

Organic fertilizer and microbial agents increase SOC (Figure 2) and STN (Figure 3) (Kong et al. 2021). Organic fertilizer contains a large amount of organic matter, which can be decomposed and transformed by microorganisms to form humus (Zang et al. 2022), providing sufficient C and N sources for saline soils (Yang et al. 2014). Microbial agents activate soil nutrients, improve soil physicochemical properties and increase soil fertility by increasing SOC and STN (Kong et al. 2021). SOC and STN increased at the flowering stage compared with those at the jointing stage. Because macromolecular organic nutrients must be converted into inorganic or small molecules through mineralization and decomposition before they can be absorbed and utilized by plants, the fertilizer efficiency of organic fertilizer is relatively slow (Fan et al. 2005).

Effects of organic fertilizer and microbial agents on soil enzyme activity, microorganisms and maize yield. Organic fertilizer has been shown to change microbial biomass, activity and population by improving soil physicochemical properties (Deng et al. 2023), promoting the activation of microorganisms and mineral decomposition in the soil and creating a nutrient-enriched soil microbial ecosystem environment (Stark et al. 2007). Compared with O_1M_0, O_1M_1 increased the number of bacteria, fungi and actinomycetes. The microbial agents contained abundant beneficial flora, activated native microorganisms, and enriched the nutrient sources of the original microorganisms, thus increasing the number of bacteria in the soil and optimizing the microbial community structure (Yun et al. 2021). No microbial agent or organic fertilizer results in high salinity, and the soil microorganism abundance tends to decrease with increasing soil salinity because saline and alkaline stress reduce

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the soil microbial carbon and nitrogen contents (Song et al. 2023).

Organic fertilizer increases the activities of soil enzymes, including urease, sucrase, catalase, and alkaline phosphatase (Liu et al. 2024). The present study revealed that under organic fertilizer and microbial agent application, soil sucrase activity was elevated due to the input of organic fertilizer and the stabilizing carbon source of the microbial agents. While soil urease activity reflects the fertility of the soil, the input of organic fertilizer increases the nitrogen source, whereas microbial agents perform poorly (Yun et al. 2021; Wang et al. 2023),which is possibly due to the insufficient supply of nutrients in the soil; thus, the strains cannot colonize the soil well, which leads to differential changes in the activity of soil urease between different treatments. The application of organic fertilizer increases soil microorganism abundance and enzyme activity, improves soil structure and vitality (Liang et al. 2012), and promotes the utilization of nutrients by maize (Yang et al. 2024), thus increasing maize yield (Al-Huqail et al. 2023). Microbial agents increase maize yields by decreasing soil salinity, increasing microbial activity (Song et al. 2023) and increasing nitrogen utilization (Gavilanes et al. 2023). On the basis of the results of this study, it was recommended that both organic fertilizer and microbial agents be applied to coastal saline-alkali soils to improve maize yields. If only organic fertilizer or microbial agents were used alone for economic reasons, the application of microbial agents would be more beneficial to maize similar to the Dajing Jiu 26 variety, and the application of organic fertilizer would be more beneficial to maize similar to the Quchen Jiu variety.

CONCLUSION

In this study, the effects of the addition of different external materials on soil quality and crop yield were evaluated. The combination of organic fertilizer and microbial agents increased the soil water content; soil organic carbon; total nitrogen; and the numbers of soil bacteria, fungi, and actinomycetes, as well as the enzyme activities in the topsoil, thus increasing the yield and biomass of maize. This finding was consistent with our hypothesis. The application of organic fertilizers and microbial agents compensates for the shortcomings of a single organic fertilizer or a single microbial agent and is a feasible measure to increase crop yield on saline-alkali land.

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