Effects of Full-Season Saline Water Drip Irrigation on Soil Salt Accumulation and Cotton Growth: Postprint

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Abstract

By investigating the effects of different irrigation water salinity levels and nitrogen application rates on soil soluble salt ions, soil elements, enzyme activities, cotton growth, and yield, the relationships among these three factors were analyzed. The experiment was set up with three irrigation water salinity levels: 0.35 $dS \cdot m^{-1}$ (fresh water, FW), 4.61 $dS \cdot m^{-1}$ (brackish water, BW), and 8.04 $dS \cdot m^{-1}$ (saline water, SW); and nitrogen application rates of 0 $kg \cdot hm^{-2}$ (N0) and 360 $kg \cdot hm^{-2}$ (N360). The results showed that: (1) Compared with fresh water irrigation, brackish water and saline water irrigation significantly reduced cotton biomass and seed cotton yield; compared with the no nitrogen treatment, nitrogen application significantly increased cotton biomass and seed cotton yield. (2) With increasing irrigation water salinity, the contents of Na^+, Ca^{2+}, Cl^-, and Ca increased significantly, while the contents of ${SO_4}^{2-}$, ${HCO_3}^-$, Mg^{2+}, Na, Ni, Co, Cr, K, Fe, Se, and Cu decreased significantly; under nitrogen application conditions, the contents of Na^+, Ca^{2+}, Cl^-, and ${SO_4}^{2-}$ increased significantly, while the contents of ${HCO_3}^-$, Mg^{2+}, K^+, P, K, Ca, Fe, Se, Zn, Al, and Mg decreased significantly. (3) With increasing irrigation water salinity, the activities of invertase, catalase, dehydrogenase, polyphenol oxidase, hydroxylamine reductase, alkaline phosphatase, and aryl sulfatase decreased significantly, while the activities of nitrate reductase and nitrite reductase increased significantly; nitrogen application significantly increased soil enzyme activities. Comprehensive analysis revealed that saline water irrigation reduced the activities of soil invertase, catalase, dehydrogenase, polyphenol oxidase, hydroxylamine reductase, alkaline phosphatase, and aryl sulfatase, resulting in decreased seed cotton yield, and that the soluble salt ions Cl^-, ${SO_4}^{2-}$, Na^+, and Ca^{2+} in saline water were the main driving factors for the changes in enzyme activities.

Full Text

Effects of Saline Water Drip Irrigation on Soil Salt Accumulation and Cotton Growth During the Whole Growth Period

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Abstract: This study investigated the effects of different irrigation water salinity levels and nitrogen application rates on soil soluble salt ions, soil elements, enzyme activity, cotton growth, and yield, and analyzed the relationships among these factors. The experiment was conducted with three irrigation water salinity levels: 0.35 $\mathrm{dS \cdot m^{-1}}$ (freshwater, FW), 4.61 $\mathrm{dS \cdot m^{-1}}$ (brackish water, BW), and 8.04 $\mathrm{dS \cdot m^{-1}}$ (saline water, SW). Nitrogen application rates were 0 $\mathrm{kg \cdot hm^{-2}}$ (N0) and 360 $\mathrm{kg \cdot hm^{-2}}$ (N360). The results showed that: (1) Compared with freshwater irrigation, brackish water and saline water irrigation significantly reduced cotton biomass and seed cotton yield. Compared with the no-nitrogen treatment, nitrogen application significantly increased cotton biomass and seed cotton yield. (2) With increasing irrigation water salinity, the contents of Na^+, Ca^{2+}, Cl^-, and ${SO_4}^{2-}$ increased significantly, while the contents of K^+, Mg^{2+}, Na, Ni, Co, Cr, K, Fe, Se, and Cu decreased significantly. Under nitrogen application, the contents of Na^+, Ca^{2+}, Cl^-, and ${SO_4}^{2-}$ increased significantly, while the contents of K^+, Mg^{2+}, K, Ca, Fe, Se, Zn, Al, and Mg decreased significantly. (3) With increasing irrigation water salinity, the activities of sucrase, catalase, dehydrogenase, polyphenol oxidase, hydroxylamine reductase, alkaline phosphatase, and aryl sulfatase decreased significantly, while the activities of nitrate reductase and nitrite reductase increased significantly. Nitrogen application significantly increased soil enzyme activity. Comprehensive analysis indicated that saline water irrigation reduced the activities of soil sucrase, catalase, dehydrogenase, polyphenol oxidase, hydroxylamine reductase, alkaline phosphatase, and aryl sulfatase, thereby decreasing seed cotton yield. The soluble salt ions Cl^-, ${SO_4}^{2-}$, Na^+, and Ca^{2+} in saline water were the main driving factors for changes in enzyme activity.

Keywords: water salinity; nitrogen application rate; soil ions; soil enzyme activity; seed cotton yield

Introduction

Arid regions suffer from scarce freshwater resources but possess relatively abundant saline water resources, making saline water irrigation an effective approach to alleviate agricultural development constraints imposed by freshwater shortages. However, saline water has high mineralization, and consecutive years of irrigation can intensify soil salinization, deteriorate soil structure, alter soil physicochemical properties, and lead to soil salinization. Saline water irrigation introduces salt ions into the soil, changing the content and types of soil ions, causing deficiency or excess of soil mineral elements, and creating nutrient absorption imbalances in crops. Ion antagonism and synergism can also affect the soil, either promoting the formation of good soil structure and increasing soil fertility, or harming the soil and exacerbating soil degradation. Among these, Na^+ and Cl^- are the main ions causing soil salinization, which can induce K^+ efflux in crop roots and produce toxic effects. When Ca^{2+} and Na^+ coexist, they form an antagonistic relationship that affects soil element absorption.

In recent years, research on soil ions has focused on heavy metal ion pollution and the effects of salinity on soil soluble salt ions, but studies on the relationship between salinity and soil elements remain limited and require further investigation. Salt not only affects soil physicochemical properties, ion content, and microbial activity, but also changes soil enzyme types and activities. Soil enzyme activity is an indicator of soil nutrient status and plays an important role in the cycling of carbon, nitrogen, phosphorus, and sulfur elements, with salinity being a major factor affecting enzyme activity. Salinity affects soil nutrient availability and microbial activity by altering soil physicochemical properties and ion content, ultimately causing changes in soil enzyme types and activities. Salt stress-induced ion toxicity and osmotic stress can reduce soil microbial populations, thereby decreasing the amount of enzymes secreted by microorganisms. Related studies have shown that increased soil salinity content can inhibit urease, alkaline phosphatase, sucrase, and catalase activities, but under low-concentration salt ion conditions, salt ions can activate soil microorganisms and release large amounts of extracellular enzymes, causing soil urease, alkaline phosphatase, and catalase activities to first increase and then decrease.

Soil enzyme research has concentrated on the effects of different fertilization levels, exogenous additives, salinity, and heavy metal ions on enzyme activities, but studies on the relationship between salinity and soil elements, and the connection between soil ions and enzyme activities, remain incomplete and require in-depth research. Salinity can cause changes in topsoil by altering soil microbial populations and enzyme activities, restricting crop growth and development, and ultimately reducing seed cotton yield. Based on this research background, this study established different irrigation water salinity levels and nitrogen application rates in arid regions. By measuring soil soluble salt ion content, soil element content, enzyme activities related to carbon, nitrogen, phosphorus, and sulfur transformation, and cotton yield, we explored the internal relationships among irrigation water salinity, nitrogen fertilizer, soil soluble salt ions, enzyme activities, and yield, aiming to provide a theoretical basis for the rational use of saline water resources, increasing cotton yield, and maintaining soil nutrient balance in arid regions.

1 Materials and Methods

1.1 Experimental Site Overview

The study was conducted at the experimental station of the College of Agriculture, Shihezi University (44°33 N, 85°98 E). This region has scarce water resources and belongs to a typical arid desert climate, with annual precipitation of 180-270 mm and annual evaporation of 1000-1500 mm. The test crop was cotton (Gossypium hirsutum L.), cultivar Xinluzao 52. The soil type in the experimental plots was gray desert soil, with basic physicochemical properties as follows: soil salinity ($EC_{1:5}$) 0.13 $dS \cdot m^{-1}$, soil bulk density 1.27 $g \cdot cm^{-3}$, soil $pH_{1:2.5}$ 7.9, soil organic matter 16.8 $g \cdot kg^{-1}$, soil total nitrogen 1.1 $g \cdot kg^{-1}$, soil alkaline hydrolyzable nitrogen 52.38 $mg \cdot kg^{-1}$, soil available phosphorus 25.9 $mg \cdot kg^{-1}$, and soil available potassium 253 $mg \cdot kg^{-1}$.

1.2 Experimental Design

This study had been conducted for three consecutive years (2018-2020) with brackish and saline water drip irrigation field experiments. The experiment included three irrigation water salinity levels: 0.35 $dS \cdot m^{-1}$ (freshwater, FW), 4.61 $dS \cdot m^{-1}$ (brackish water, BW), and 8.04 $dS \cdot m^{-1}$ (saline water, SW). Nitrogen application rates were 0 $kg \cdot hm^{-2}$ (N0) and 360 $kg \cdot hm^{-2}$ (N360). The experiment adopted a completely randomized block design with six treatments, each replicated three times, totaling 18 experimental plots. Each plot measured 66 m^2 (6.6 m × 10 m). Cotton was planted using the dry-seed wet-emergence method in late April each year and harvested in late September. The film-mulched cultivation technique was employed with one film covering four rows, with row spacing of (66+10) cm. The irrigation quota during the cotton growth period was 450 mm (2.22$×10^{3}$ $m^3 \cdot hm^{-2}$), with a total of 11 irrigation events and an irrigation cycle of 7-10 days. No salt leaching measures were taken before irrigation. Nitrogen fertilizer (urea, N$ 46.4*{2}O{5})applicationratewas105kg · hm^{-2},andpotassium(K{2}O)applicationratewas60kg·hm^{-2}.Otherfieldmanagementpracticesfollowedlocalp* to freshwater, maintaining consistent irrigation water salinity for each event. The chemical properties of the three irrigation water types are shown in .

1.3 Sample Collection and Processing

Soil samples were collected from the 0-30 cm tillage layer using a tube auger during the cotton flowering and boll-setting stage in 2020. The diagonal sampling method was used. Collected soil samples were mixed uniformly, debris was removed, and the samples were divided into three portions. One portion of fresh soil was passed through a 2 mm sieve and stored at 4°C for enzyme activity determination. Another portion was passed through a 2 mm sieve for soil soluble salt ion content determination. The remaining portion was air-dried, ground, and passed through a 0.149 mm sieve for soil total element content determination. Cotton seed cotton yield was measured during the boll-opening stage using the quadrat method and actual harvest recording.

1.4 Soil Ion Content Determination

Soil soluble salt ion determination methods followed the Soil Agrochemical Analysis Methods. K^+ and Na^+ contents were determined by flame photometry. Ca^{2+} and Mg^{2+} contents were determined by EDTA complexometric titration. ${CO_3}^{2-}$ and ${HCO_3}^-$ contents were determined by double indicator neutralization titration. Cl^- content was determined by silver nitrate titration. ${SO_4}^{2-}$ content was determined by indirect complexometric titration. Heavy metal elements (Ni, Co, Cr, Cu, Zn, As, Cd, Pb) were classified as trace nutrient elements (Fe, Mn, Cu, Zn, Mo, B, Ni, Co, Cr, Se), medium nutrient elements (Ca, Mg, S), and beneficial elements (Si, Na, Al, Se).

1.5 Soil Enzyme Activity Determination

Soil enzyme activities were determined using methods provided by Guan Songyin. Sucrase (SC) activity was determined by the 3,5-dinitrosalicylic acid colorimetric method. Dehydrogenase (DHA) activity was determined by the triphenyltetrazolium chloride spectrophotometric method. Catalase (CAT) activity was determined by the potassium permanganate titration method. Hydroxylamine reductase (HR) activity was determined by the ferric ammonium sulfate-phenanthroline method. Urease (UE) activity was determined by the indophenol blue colorimetric method. Nitrate reductase (NR) activity was determined by the sulfanilamide colorimetric method. Polyphenol oxidase (PPO) activity was determined by the pyrogallol colorimetric method. Alkaline phosphatase (ALP) activity was determined by the disodium phenyl phosphate colorimetric method. Nitrite reductase (NiR) activity was determined by the p-aminobenzenesulfonic acid colorimetric method. Aryl sulfatase (ASF) activity was determined by the p-nitrophenyl sulfate method.

1.6 Data Analysis

SPSS 26.0 statistical software was used for data calculation, statistical analysis, and graphing. Excel 2016 was used for analysis and plotting. Two-way ANOVA and correlation analysis were performed, with a significance level of $P<0.05$. Tukey' s method was used for multiple comparisons among treatments ($P<0.05$). RDA redundancy analysis was conducted using the vegan package.

2 Results

2.1 Effects of Irrigation Water Salinity and Nitrogen Application on Soil Soluble Salt Ions

Irrigation water salinity, nitrogen application rate, and their interaction had significant effects on soil ion contents (Figure 1). Compared with the FW treatment, the BW and SW treatments significantly increased soil Na^+, Ca^{2+},

Cl^-, and $SO_4{}^{2-}$ contents, which increased by 1048.15% and 772.00% for Na^+, 166.67% and 1268.00% for Ca^{2+}, 80.30% and 1362.96% for Cl^-, and 25.40% and 40.48% for $SO_4{}^{2-}$, respectively. However, these treatments significantly reduced soil K^+ and Mg^{2+} contents, which decreased by 7.95% and 22.84% for K^+, and 22.29% and 18.28% for Mg^{2+}, respectively. Compared with the N0 treatment, the N360 treatment significantly increased Na^+, Ca^{2+}, Cl^-, and $SO_4{}^{2-}$ contents, which increased by 24.53%, 31.58%, 11.11%, and 29.47%, respectively, but significantly reduced K^+ and Mg^{2+} contents, which decreased by 22.84% and 18.28%, respectively. The interaction effects showed that under FW and BW conditions, nitrogen application significantly reduced K^+ content but had no significant effect on Mg^{2+} content. Under SW conditions, nitrogen application significantly increased Na^+, Ca^{2+}, Cl^-, and $SO_4{}^{2-}$ contents but had no significant effect on K^+ and Mg^{2+} contents.

Irrigation water salinity and the interaction significantly affected soil Ca^{2+} content, while nitrogen application rate significantly affected soil K^+ content (Figure 1). Compared with the FW treatment, the BW and SW treatments significantly reduced soil K^+ content by 55.47% and 40.88%, respectively, but significantly increased soil Ca^{2+} content by 31.10% and 30.88%, respectively. Compared with the N0 treatment, the N360 treatment significantly reduced soil K^+ content by 12.98% and increased soil Ca^{2+} content by 20.70%. Soil Mg^{2+} content was not detected.

2.2 Effects of Irrigation Water Salinity and Nitrogen Application on Soil Elements

Irrigation water salinity, nitrogen application rate, and their interaction significantly affected the contents of most soil elements (Table 2). Compared with the FW treatment, the BW and SW treatments significantly reduced the contents of Na, Ni, Co, Cr, K, Fe, Se, and Cu, which decreased by 0.13% and 10.90% for Na, 0.38% and 7.73% for Ni, 0.13% and 6.25% for Co, 6.61% and 9.50% for Cr, 3.27% and 3.29% for K, 15.37% and 6.36% for Fe, 17.18% and 3.32% for Se, and 7.03% and 9.12% for Cu, respectively. However, these treatments significantly increased the contents of Ca and Mg, which increased by 3.62% and 7.14% for Ca, and 1.60% and 1.17% for Mg, respectively. Compared with the N0 treatment, the N360 treatment significantly reduced the contents of Na, Ni, Co, Cr, K, Fe, Se, Cu, and Mg, which decreased by 7.87% for Na, 10.60% for Ni, 12.80% for Co, 7.87% for Cr, 9.65% for K, 7.42% for Fe, 6.86% for Se, 7.80% for Cu, and 3.46% for Mg, respectively, but significantly increased the contents of Ca and Zn, which increased by 4.54% and 0.21%, respectively. The interaction effects showed that under FW conditions, nitrogen application had no significant effect on element contents. Under BW conditions, nitrogen application significantly reduced the contents of Na, Ni, Cr, Fe, Se, and Cu but had no significant effect on Co, K, Ca, Zn, Mg, and Al contents. Under SW conditions, nitrogen application significantly increased Ca content but had no significant effect on other element contents.

Irrigation water salinity and nitrogen application rate significantly affected soil P content, while irrigation water salinity significantly affected soil Zn content, and the interaction significantly affected soil Al content (Table 2). Compared with the FW treatment, the BW and SW treatments significantly increased soil P content by 13.68% and 6.86%, respectively, but significantly reduced soil Zn content by 1.47% and 9.67%, respectively. Compared with the N0 treatment, the N360 treatment significantly increased soil P content by 2.26% but had no significant effect on soil Zn and Al contents.

2.3 Effects of Irrigation Water Salinity and Nitrogen Application on Enzyme Activities

Irrigation water salinity, nitrogen application rate, and their interaction significantly affected sucrase activity (Figure 2). Compared with the FW treatment, the BW and SW treatments significantly reduced sucrase activity by 2.32% and 3.52%, respectively. Compared with the N0 treatment, the N360 treatment significantly increased sucrase activity by 37.91%. The interaction effect showed that nitrogen application significantly increased sucrase activity under different irrigation water treatments, but the increase varied significantly among treatments, with increases of 26.55% under FW, 20.52% under BW, and 0.67% under SW.

Irrigation water salinity, nitrogen application rate, and their interaction significantly affected polyphenol oxidase activity (Figure 2). Compared with the FW treatment, the BW and SW treatments significantly reduced polyphenol oxidase activity by 41.10% and 50.47%, respectively. Compared with the N0 treatment, the N360 treatment significantly increased polyphenol oxidase activity by 91.93%. The interaction effect showed that nitrogen application significantly increased polyphenol oxidase activity under different irrigation water treatments, with increases of 13.59% under FW, 106.68% under BW, and 30.49% under SW.

Irrigation water salinity, nitrogen application rate, and their interaction significantly affected catalase activity (Figure 2). Compared with the FW treatment, the BW and SW treatments significantly reduced catalase activity by 24.36% and 2.90%, respectively. Compared with the N0 treatment, the N360 treatment significantly increased catalase activity by 40.06%. The interaction effect showed that nitrogen application significantly increased catalase activity under different irrigation water treatments, with increases of 44.21% under FW, 87.12% under BW, and 26.5% under SW.

Irrigation water salinity, nitrogen application rate, and their interaction significantly affected dehydrogenase activity (Figure 2). Compared with the FW treatment, the BW and SW treatments significantly reduced dehydrogenase activity by 6.98% and 7.57%, respectively. Compared with the N0 treatment, the N360 treatment significantly increased dehydrogenase activity by 35.25%. The interaction effect showed that nitrogen application significantly increased dehydrogenase activity under different irrigation water treatments, with increases of

32.49% under FW, 150.08% under BW, and 47.17% under SW.

Irrigation water salinity, nitrogen application rate, and their interaction significantly affected urease activity (Figure 3). Compared with the FW treatment, the BW treatment significantly increased urease activity by 15.85%, while the SW treatment significantly reduced it by 51.05%. Compared with the N0 treatment, the N360 treatment significantly increased urease activity by 69.96%. The interaction effect showed that nitrogen application significantly increased urease activity under different irrigation water treatments, with increases of 10.63% under FW, 51.05% under BW, and 18.62% under SW.

Irrigation water salinity, nitrogen application rate, and their interaction significantly affected nitrite reductase activity (Figure 3). Compared with the FW treatment, the BW and SW treatments significantly increased nitrite reductase activity by 31.29% and 39.58%, respectively. Compared with the N0 treatment, the N360 treatment significantly increased nitrite reductase activity by 77.17%. The interaction effect showed that nitrogen application significantly increased nitrite reductase activity under FW and BW conditions, with increases of 33.26% and 28.76%, respectively, but showed no significant difference under SW conditions.

Irrigation water salinity, nitrogen application rate, and their interaction significantly affected nitrate reductase activity (Figure 3). Compared with the FW treatment, the BW and SW treatments significantly increased nitrate reductase activity by 13.09% and 36.94%, respectively. Compared with the N0 treatment, the N360 treatment significantly increased nitrate reductase activity by 27.03%. The interaction effect showed that nitrogen application significantly increased nitrate reductase activity under FW and BW conditions, with increases of 35.73% and 20.84%, respectively, but had no significant effect under SW conditions.

Irrigation water salinity, nitrogen application rate, and their interaction significantly affected hydroxylamine reductase activity (Figure 3). Compared with the FW treatment, the BW and SW treatments significantly reduced hydroxylamine reductase activity by 19.88% and 19.69%, respectively. Compared with the N0 treatment, the N360 treatment significantly increased hydroxylamine reductase activity by 40.06%. The interaction effect showed that nitrogen application significantly increased hydroxylamine reductase activity under FW and BW conditions, with increases of 44.21% and 87.12%, respectively, but had no significant effect under SW conditions.

Irrigation water salinity, nitrogen application rate, and their interaction significantly affected alkaline phosphatase activity (Figure 4). Compared with the FW treatment, the BW and SW treatments significantly reduced alkaline phosphatase activity by 7.57% and 19.69%, respectively. Compared with the N0 treatment, the N360 treatment significantly increased alkaline phosphatase activity by 40.06%. The interaction effect showed that nitrogen application significantly increased alkaline phosphatase activity under FW and BW conditions, with increases of 44.21% and 87.12%, respectively, but had no significant effect under SW conditions.

Irrigation water salinity, nitrogen application rate, and their interaction significantly affected aryl sulfatase activity (Figure 4). Compared with the FW treatment, the BW and SW treatments significantly reduced aryl sulfatase activity by 7.57% and 19.69%, respectively. Compared with the N0 treatment, the N360 treatment significantly increased aryl sulfatase activity by 40.06%. The interaction effect showed that nitrogen application significantly increased aryl sulfatase activity under FW and BW conditions, with increases of 44.21% and 87.12%, respectively, but had no significant effect under SW conditions.

2.4 Effects of Irrigation Water Salinity and Nitrogen Application on Cotton Growth and Seed Cotton Yield

Irrigation water salinity, nitrogen application rate, and their interaction significantly affected cotton growth and seed cotton yield (Figure 5). Compared with the FW treatment, the BW and SW treatments significantly reduced cotton stem dry weight, leaf dry weight, boll dry weight, and seed cotton yield, with reductions of 34.94% and 28.15% for stem dry weight, 30.96% and 26.79% for leaf dry weight, 19.01% and 9.21% for boll dry weight, and 24.18% and 54.03% for seed cotton yield, respectively. Compared with the N0 treatment, the N360 treatment significantly increased cotton stem dry weight, leaf dry weight, boll dry weight, and seed cotton yield, with increases of 65.21% and 82.86% for stem dry weight, 37.58% and 131.78% for leaf dry weight, 72.63% and 99.40% for boll dry weight, and 32.88% and 93.94% for seed cotton yield under FW and BW conditions, respectively. The interaction effect showed that with increasing irrigation water salinity, the yield-increasing effect of nitrogen fertilizer was enhanced. Under SW conditions, nitrogen application increased cotton stem dry weight, leaf dry weight, boll dry weight, and seed cotton yield by 120.20%, 102.57%, 140.02%, and 200.76%, respectively.

2.5 Correlation Between Soil Soluble Salt Ions and Enzyme Activities

RDA analysis of soil soluble salt ions and enzyme activities showed that the first axis explained 59.99% of the variation, the second axis explained 13.55%, and together they explained 73.54% of the total variation (Figure 6). Soil enzyme activities were significantly correlated with Cl^- (explanatory degree 19.43%), ${SO_4}^{2-}$ (explanatory degree 17.15%), Na^+ (explanatory degree 2.87%), and Ca^{2+} (explanatory degree 2.69%). Sucrase activity was significantly negatively correlated with Cl^- (P=0.001) and ${SO_4}^{2-}$ (P=0.034), and significantly positively correlated with Na^+ (P=0.001). Polyphenol oxidase activity was significantly negatively correlated with Cl^- (P=0.005) and ${SO_4}^{2-}$. Catalase activity was significantly negatively correlated with Cl^- and ${SO_4}^{2-}$, and significantly positively correlated with Na^+. Dehydrogenase activity was significantly negatively correlated with Cl^- and ${SO_4}^{2-}$, and significantly positively correlated with Na^+. Urease activity was significantly negatively correlated with Cl^- and ${SO_4}^{2-}$. Nitrate reductase activity was significantly positively correlated with Cl^- and ${SO_4}^{2-}$, and significantly negatively correlated with Na^+. Nitrite reductase activity was significantly positively correlated with Cl^- and ${SO_4}^{2-}$, and significantly negatively correlated with Na^+. Hydroxylamine reductase activity was significantly negatively correlated with Cl^- and ${SO_4}^{2-}$, and significantly positively correlated with Na^+. Alkaline phosphatase activity was significantly negatively correlated with Cl^- and ${SO_4}^{2-}$, and significantly positively correlated with Na^+. Aryl sulfatase activity was significantly negatively correlated with Cl^- and ${SO_4}^{2-}$, and significantly positively correlated with Na^+.

2.6 Correlation Analysis Between Enzyme Activities Related to C, N, P, and S Transformation and Seed Cotton Yield

Correlation analysis between enzyme activities and cotton seed cotton yield showed that sucrase activity was extremely significantly positively correlated with cotton seed cotton yield ($P<0.001$). Catalase activity was extremely significantly positively correlated with cotton seed cotton yield ($P<0.001$). Dehydrogenase activity was extremely significantly positively correlated with cotton seed cotton yield ($P<0.001$). Polyphenol oxidase activity was extremely significantly positively correlated with cotton seed cotton yield ($P<0.001$). Urease activity was significantly positively correlated with cotton seed cotton yield ($P<0.05$). Hydroxylamine reductase activity was significantly positively correlated with cotton seed cotton yield ($P<0.05$). Alkaline phosphatase activity was extremely significantly positively correlated with cotton seed cotton yield ($P<0.001$). Aryl sulfatase activity was extremely significantly positively correlated with cotton seed cotton yield ($P<0.001$). However, nitrate reductase and nitrite reductase activities showed no significant correlation with cotton seed cotton yield. Brackish and saline water irrigation introduced salt ions into the soil, altering the original contents of soluble ions and elements, thereby affecting enzyme activities. Among these, Cl^- was the dominant factor changing soil structure, deteriorating cotton growth conditions. Changes in soil element contents and enzyme activities caused soil nutrient imbalances, ultimately leading to reduced cotton yield. Nitrogen application increased soil nitrogen nutrients while also changing the contents of soil soluble ions, soil elements, and enzyme activities, thereby increasing cotton yield.

3 Discussion

3.1 Effects of Irrigation Water Salinity and Nitrogen Application on Soil Ion and Element Contents

Soil ions can serve as components and activators of biological molecules such as enzymes, hormones, and coenzymes, participating in a series of metabolic processes within crops and in soil nutrient cycling and transformation. Long-term saline water irrigation and nitrogen fertilizer application alter soil physicochemical properties, thereby affecting soil ion contents. This study showed that with increasing irrigation water salinity, Na^+, Ca^{2+}, Cl^-, and ${SO_4}^{2-}$ contents increased significantly, while K^+ and Mg^{2+} contents decreased significantly. This is because brackish and saline water contain large amounts of Na^+, Ca^{2+}, Cl^-, and ${SO_4}^{2-}$, which enter the soil through irrigation and increase their contents. When Cl^- content exceeds a certain concentration, it inhibits crop absorption of K^+ and Mg^{2+}, thereby reducing their contents. Changes in salt ion contents may also be related to soil adsorption processes or dissolution and redistribution of irrigation water. This study also showed that nitrogen application significantly increased Na^+, Ca^{2+}, Cl^-, and ${SO_4}^{2-}$ contents but significantly reduced K^+ and Mg^{2+} contents. This may be because nitrogen application is closely related to soil salt accumulation, and increased Na^+ content can cause soil salinization to develop toward sodic soil, easily causing single-salt toxicity, harming crop roots, and producing antagonistic effects with other ions, leading to nutrient element imbalances. Changes in soil ions affect enzyme activities.

Saline water irrigation and nitrogen fertilizer application also affect soil element contents. This study found that among soil elements, Na, Ni, Co, Cr, K, Fe, Se, and Cu contents decreased with increasing irrigation water salinity, while Ca and Mg contents increased. This may be because under salt stress, crop root sensitivity limits nutrient absorption, causing element content changes. Under nitrogen application conditions, soil element contents of Na, Ni, Co, Cr, K, Fe, Se, Zn, Al, and Mg were significantly lower than in the no-nitrogen treatment. Related studies have shown that long-term nitrogen fertilizer application can increase soil ion contents and reduce soil element contents. This may be because nitrogen application promotes crop growth, accelerates crop nutrient absorption and utilization, thereby reducing ion contents.

3.2 Effects of Irrigation Water Salinity and Nitrogen Application on Enzyme Activities

Soil enzymes are one of the active components in the soil micro-ecosystem, and their activities can reflect soil fertility status and are important indicators for evaluating soil quality. Salinity and nitrogen application rate are important factors affecting soil enzyme activity. This study found that saline water irrigation reduced the activities of sucrase, catalase, dehydrogenase, polyphenol oxidase, hydroxylamine reductase, alkaline phosphatase, and aryl sulfatase. This may be because Ca^{2+} and Na^+ ions in saline water cause soil compaction, deteriorate the soil environment, inhibit crop root growth and microbial populations, thereby reducing enzyme activities. This study also found that saline water irrigation could increase nitrate reductase and nitrite reductase activities, although related studies have shown that salinity has little effect on nitrate reductase activity but inhibits nitrite reductase activity. This may be because changes in soil physicochemical properties affect nitrate reductase and nitrite reductase activities. For urease, saline water irrigation inhibited its activity, while brackish water irrigation promoted its activity, possibly because brackish water could stimulate urease and increase its activity.

Nitrogen fertilizer application can improve soil quality, promote crop and microbial growth, increase enzyme production, and improve enzyme activities. This study also found that under nitrogen application conditions, soil enzyme activities were enhanced. This may be because nitrogen application inhibits soil salt accumulation, improves soil conditions, provides a suitable living environment for soil enzymes, and is beneficial for increasing their activities. It may also be because nitrogen application increases soil organic matter content, stimulates crop rhizosphere metabolism, increases root exudate content, promotes crop growth, provides nitrogen and carbon sources for soil microorganisms, changes crop root environment and microbial community structure, forms nutrient pools in the rhizosphere, and thereby increases soil enzyme activities. Other studies have found that soil enzyme activities show different trends during different crop growth stages, and the effect of nitrogen application on yield also varies. Rice yield in coastal saline-alkali tidal flats shows an increasing trend under low nitrogen conditions but a decreasing trend under high nitrogen conditions.

3.3 Effects of Irrigation Water Salinity and Nitrogen Application on Cotton Biomass and Seed Cotton Yield

Saline water irrigation disrupts the soil water-salt balance, causing salt accumulation on the soil surface, forming secondary salinized soil, and causing crop yield reduction. Studies have shown that brackish and saline water irrigation significantly reduces cotton biomass and seed cotton yield because increased salinity changes soil structure, causes soil compaction, increases bulk density, reduces salt leaching capacity, and causes salt accumulation, making salt stress inhibition of crops more significant and reducing crop biomass and yield. Salinity can inhibit crop water absorption, limit crop growth and development, and ultimately affect yield. Studies have shown that salinity can change rice panicle traits and affect rice yield, and can also affect wheat root respiration, reduce its antioxidant capacity and nutrient absorption capacity, and cause wheat yield reduction.

Nitrogen is an essential nutrient element for crop growth and can increase crop yield. This study showed that nitrogen application significantly increased cotton biomass and seed cotton yield, possibly because nitrogen application can promote crop root growth, promote nutrient absorption and utilization, and improve nutrient use efficiency. It may also be because nitrogen application can enhance crop photosynthetic capacity, thereby increasing crop yield. Related studies have shown that in low-salt and medium-high-salt areas, nitrogen fertilizer has a greater promoting effect on tomato physiology and yield, and nitrogen application can also increase the yield of forage crops.

3.4 Relationships Between Soil Enzyme Activity and Soil Ions/Seed Cotton Yield

Soil enzymes originate from microorganisms, humus, crop roots, and their secretions, and play important roles in the cycling of nutrients such as carbon, nitrogen, phosphorus, and sulfur in soil, promoting crop growth and thereby affecting crop yield. This study found that soil soluble salt ions are closely related to enzyme activities. Among the soluble salt ions, Cl^-, SO_4^{2-}, Na^+, and Ca^{2+} have significant effects on enzyme activities, possibly because the content, type, and valence state of ions in soil differ, affecting the soil environment and crop growth differently, and enzymes have different sensitivities to soil ions. By analyzing the relationship between soil enzyme activities and cotton yield, it was found that except for nitrate reductase and nitrite reductase, other enzyme activities have significant positive correlations with cotton seed cotton yield. Related studies have shown that soil enzyme activities affect crop yield by changing soil nutrient contents. Among them, sucrase and polyphenol oxidase can participate in lignin degradation and the transformation of aromatic compounds in organic components, serving as a medium for humification. Dehydrogenase can catalyze the dehydrogenation of soil organic matter and reflect the intensity of anaerobic decomposition of soil organic matter. Urease participates in soil nitrogen transformation and can provide nitrogen nutrition for crops. Alkaline phosphatase is beneficial for the mineralization of soil organic phosphorus and increases crop phosphorus absorption capacity. Catalase can resist drought stress and is beneficial for crop growth and development in arid environments. Aryl sulfatase can affect sulfur metabolism, convert organic sulfur into available sulfur, and improve crop resistance to adversity.

4 Conclusions

1) With increasing irrigation water salinity, cotton biomass and yield decreased significantly; with increasing nitrogen application rate, cotton biomass and yield increased significantly.

2) With increasing irrigation water salinity, the contents of Na^+, Ca^{2+}, Cl^-, and SO_4^{2-} increased significantly, while the contents of K^+, Mg^{2+}, Na, Ni, Co, Cr, K, Fe, Se, and Cu decreased significantly. Nitrogen application significantly increased the contents of Na^+, Ca^{2+}, Cl^-, and SO_4^{2-}, but significantly reduced the contents of K^+, Mg^{2+}, K, Ca, Fe, Se, Zn, Al, and Mg.

3) With increasing irrigation water salinity, the activities of nitrate reductase and nitrite reductase increased significantly, while the activities of sucrase, catalase, dehydrogenase, polyphenol oxidase, hydroxylamine reductase, alkaline phosphatase, and aryl sulfatase decreased significantly. Nitrogen application significantly increased the activities of sucrase, catalase, dehydrogenase, polyphenol oxidase, urease, nitrate reductase, nitrite reductase, hydroxylamine reductase, alkaline phosphatase, and aryl sulfatase, but significantly reduced the activity of hydroxylamine reductase.

4) The soluble salt ions Cl^-, SO_4^{2-}, Na^+, and Ca^{2+} in saline water are the main driving factors of soil enzyme activity changes.

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