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Interaction Effects of Irrigation Water Salinity and Sodium Adsorption Ratio on Cotton Growth and Yield Under Mulched Drip Irrigation (Postprint)

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Abstract

To alleviate the contradiction between water supply and demand and compensate for the shortage of freshwater resources, the utilization of brackish and saline water for irrigation has become an important approach to mitigate the water crisis. Meanwhile, under the same irrigation water salinity, different sodium adsorption ratios (SAR) of irrigation water also have varying effects on cotton growth and yield. Therefore, to further investigate the effects of irrigation water salinity and sodium adsorption ratio on cotton, this experiment used cotton as the research subject and designed three different irrigation water salinity levels: 3 g · L-1 (T3), 5 g · L-1 (T5), and 7 g · L-1 (T7). For each salinity level, three different sodium adsorption ratio (SAR) levels were designed: 10 (mmol · L-1)1/2 (S10), 15 (mmol · L-1)1/2 (S15), and 20 (mmol · L-1)1/2 (S20), with local freshwater irrigation as the control, totaling 10 treatments, to study the effects of different combinations of irrigation water salinity and SAR on soil salinity, cotton growth, plant ion accumulation, yield, and water use efficiency. The results showed that soil salinity increased with increasing irrigation water salinity or SAR, and exhibited a trend of first increasing then decreasing with soil depth. Plant Na+ content increased with increasing irrigation water salinity or SAR, and their interaction had an extremely significant effect on plant Na+ content, whereas plant K+ content, K+/Na+ ratio, and N content all decreased with increasing irrigation water salinity or SAR. Plant height, stem diameter, leaf area index, and dry matter mass all showed a decreasing trend with increasing irrigation water salinity or sodium adsorption ratio, and irrigation water salinity or sodium adsorption ratio extremely significantly inhibited dry matter accumulation. Irrigation water salinity or SAR had extremely significant effects on bolls per plant, boll weight, seed cotton yield, and water consumption (ET), while irrigation water SAR had an extremely significant effect on water use efficiency (WUE). Compared with the CK treatment, the yield and WUE of T3S10 increased by 3.27% and 1.09%, respectively, the yield and WUE of T5S10 increased by 2.54% and 0.47%, respectively, and the yield of T3S15 increased by 1.18%, indicating that moderately reducing irrigation water SAR can alleviate the degree of cotton yield reduction caused by increased salinity. Irrigation water with different salinities and SAR increased cotton plant Na+ content, decreased the absorption of K+ and N nutrients, and increased the K+/Na+ ratio; consequently, cotton plant height, stem diameter, leaf area, and dry matter accumulation gradually decreased with increasing irrigation water salinity or SAR. Compared with the CK treatment, the bolls per plant and boll weight of T3S10, T3S15, and T5S10 treatments increased. In conclusion, when using saline water with salinity of 3 g·L-1 and SAR < 15 (mmol·L-1)1/2 or salinity of 5 g·L-1 and SAR < 10 (mmol·L-1)1/2 for irrigation, cotton yield can be maintained without adverse effects. The research results can provide theoretical basis and data support for water resource management and sustainable agricultural development in Xinjiang and other arid regions.

Full Text

Effects of Irrigation Water Mineralization and Sodium Adsorption Ratio on Growth and Yield of Drip-Irrigated Cotton Under Film Mulch

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Abstract

To address the imbalance between water supply and demand and compensate for freshwater shortages, using brackish and saline water for irrigation has become an important approach to alleviate water crises. Simultaneously, under the same irrigation water mineralization, different sodium adsorption ratios (SAR) in irrigation water exert varying effects on cotton growth and yield. Therefore, to further investigate the combined effects of irrigation water mineralization and SAR on cotton, we conducted a field experiment with cotton as the test crop. The experiment employed three irrigation water mineralization levels: 3 $g \cdot L^{-1}$ (T3), 5 $g \cdot L^{-1}$ (T5), and 7 $g \cdot L^{-1}$ (T7). For each mineralization level, we designed three SAR levels: 10 $(mmol \cdot L^{-1})^1/^2$ (S10), 15 $(mmol \cdot L^{-1})^1/^2$ (S15), and 20 $(mmol \cdot L^{-1})^1/^2$ (S20), using local freshwater irrigation as a control (CK). Ten treatments were established to examine how different combinations of irrigation water mineralization and SAR affect soil salinity, cotton growth, plant ion accumulation, yield, and water use efficiency.

The results demonstrated that soil salinity increased with higher irrigation water mineralization or SAR, showing a trend of initial increase followed by decrease with soil depth, peaking at 60 cm. Plant Na^+ content increased with irrigation water mineralization or SAR, with their interaction exerting a highly significant effect. In contrast, plant K^+, K^+/Na^+ ratio, and N content decreased with increasing irrigation water mineralization or SAR. Plant height, stem diameter, leaf area index, and dry matter mass all exhibited declining trends with higher irrigation water mineralization or SAR, with significant inhibition of dry matter accumulation. Irrigation water mineralization and SAR significantly affected bolls per plant, boll weight, seed cotton yield, and water consumption (ET), while SAR alone significantly affected water use efficiency (WUE). Compared to CK, the T3S10 treatment increased yield and WUE by 3.27% and 1.09%, respectively; T5S10 increased them by 2.54% and 0.47%; and T3S15 increased yield by 1.18%. These results indicate that moderately reducing irrigation water SAR can mitigate cotton yield reduction caused by increased mineralization.

Different mineralization and SAR levels increased plant Na^+ content while reducing K^+ and N uptake, thereby decreasing the K^+/Na^+ ratio. Consequently, cotton plant height, stem diameter, leaf area, and dry matter accumulation gradually declined with increasing irrigation water mineralization or SAR. However, bolls per plant and boll weight increased in the T3S10, T3S15, and T5S10 treatments compared to CK. In conclusion, using brackish water with mineralization of 3 $g \cdot L^{-1}$ and SAR below 15 $(mmol \cdot L^{-1})^1/^2$, or mineralization of 5 $g \cdot L^{-1}$ and SAR below 10 $(mmol \cdot L^{-1})^1/^2$, can maintain cotton yield unaffected. These findings provide a theoretical basis and data support for water resource management and sustainable agricultural development in Xinjiang and other arid regions.

Keywords: cotton; irrigation water; mineralization; sodium adsorption ratio; dry matter accumulation; yield; water use efficiency

Introduction

Xinjiang is China' s largest cotton production base, with cotton output reaching 511.2 × 10^4 t, accounting for 90.99% of the national total. However, water scarcity has become a critical factor limiting sustainable cotton development in southern Xinjiang, where rainfall is scarce and evaporation is high. With decreasing water flow from the Tarim River main stream, irrigation water demand is increasingly strained. Southern Xinjiang possesses abundant brackish water resources, particularly in water-salt accumulation zones along the Tarim River, where soil salinization is relatively severe and large quantities of brackish groundwater exist. To resolve water supply-demand contradictions and compensate for freshwater shortages, using brackish and saline water for agricultural irrigation has become an important pathway to increase irrigation water sources and alleviate water crisis.

Numerous theoretical and practical production studies have validated the feasibility of saline water irrigation, providing theoretical foundations for different regions and conditions. However, saline water irrigation introduces salts into the soil, affecting the soil environment and consequently plant growth. Previous research on saline water irrigation mineralization thresholds has yielded varying results due to differences in climate, irrigation technology, and water quality factors across regions. Moreover, most studies have focused primarily on mineralization effects, while the ionic composition of saline water varies significantly across different ecological zones due to climate and geological conditions, inevitably affecting soil quality and crop growth after irrigation.

Previous research has shown that the sodium adsorption ratio (SAR) of irrigation water significantly impacts soil structure and crop growth. Column experiments by Wu et al. demonstrated that using micro-saline water with high SAR for infiltration damages soil structure. Xu et al. found that in typical agricultural areas of Xinjiang, micro-saline water irrigation with SAR ≤ 30 $(\mathrm{mmol} \cdot \mathrm{L}^{-1})^{1}/^{2}$ does not further damage soil structure, but the mechanism by which irrigation water ionic composition differences affect crop growth and development remains insufficiently understood and requires further investigation.

Therefore, this study used cotton as the research object, employing irrigation water SAR to characterize saline water ionic composition. We conducted field plot experiments combining different mineralization levels and SAR ratios to investigate their interactive effects on soil salinity, cotton growth, plant ion accumulation, yield, and water use efficiency. The objective was to clarify cotton growth, yield, and water use efficiency responses to different mineralization levels and SAR ratios, and to propose suitable brackish water irrigation thresholds that maintain cotton yield stability, providing theoretical foundations for saline water utilization in arid regions.

1 Materials and Methods

1.1 Experimental Site Description

The field experiment was conducted from April to October 2023 at the Xinjiang Aral Modern Agriculture Comprehensive Experimental Station (81°17 56.52 E, 40°32 36.90 N). The experimental area features a temperate continental climate with annual precipitation of approximately 50 mm and average annual temperature of 14.49°C. The soil texture is sandy loam with bulk density of 1.58 $g \cdot cm^{-3}$ in the 0–100 cm soil layer and field capacity of 18%. The average groundwater depth is approximately 100 cm. The test cotton variety was "Tahe 2," sown in late April, topped in mid-July, and harvested using machine-picking cultivation mode (one film, three drip tapes, six rows) with film width of 2.28 m. The row spacing configuration was 10 cm + 66 cm + 10 cm + 66 cm + 10 cm. Drip tapes were placed inside the two outer rows and beside the middle row, totaling three drip tapes per film [Figure 1: see original paper].

1.2 Experimental Design

A split-plot design was employed with irrigation water mineralization as the main factor and SAR as the sub-factor. Three mineralization levels were established: 3 $g \cdot L^{-1}$ (T3), 5 $g \cdot L^{-1}$ (T5), and 7 $g \cdot L^{-1}$ (T7). Three SAR levels were designed: 10 $(mmol \cdot L^{-1})^1/^2$ (S10), 15 $(mmol \cdot L^{-1})^1/^2$ (S15), and 20 $(mmol \cdot L^{-1})^1/^2$ (S20), with local freshwater irrigation as control (CK). This resulted in 10 treatments, each replicated three times, totaling 30 plots with dimensions of 6.48 m × 7 m. Different mineralization levels and SAR ratios were configured using local well water as the source by adding $CaCl_2$ and NaCl. To precisely control irrigation amounts for each treatment, individual drip systems consisting of mixing tanks, pressure gauges, water meters, valves, and small self-priming pumps were used [Figure 2: see original paper].

Irrigation was scheduled based on crop evapotranspiration (ETc), calculated using the FAO-56 recommended single crop coefficient method. Cotton crop coefficients were derived from our research group' s 2023 experimental data, with average values of 0.4 during the budding stage and 1.05 during the flowering-boll stage. The irrigation cycle was 7 days, with total irrigation events of 13 throughout the growth period. All treatments received identical irrigation quotas. Fertilization followed local conventional practices , with 84 $kg \cdot hm^{-2}$ of NPK compound fertilizer applied as base fertilizer before cultivation, and top-dressing applied with each irrigation according to local standard rates.

1.3 Measurement Items and Methods

1.3.1 Soil Salinity Soil salinity was measured using the oven-drying method. Soil samples were collected during the late flowering-boll stage at depths of 0–10 cm, 10-20 cm, 20–40 cm, 40–60 cm, 60–80 cm, and 80–100 cm. After oven-drying and crushing, 20 g of soil was placed in a triangular flask with 100 mL distilled water, shaken for 15 minutes, filtered, and the electrical conductivity of the

1:5 soil-water extract was measured using a DDSJ-308A portable conductivity meter (Shanghai Yidian).

1.3.2 Plant Ions and Nutrients During the late flowering-boll stage, three uniformly sized plants per treatment were randomly selected and separated into stems, leaves, and bolls. Plant Na^+ and K^+ contents were determined using flame photometry after concentrated H_2SO_4-H_2O_2 digestion. Plant N content was measured using a continuous flow analyzer (Germany).

1.3.3 Growth Indicators Growth indicators including plant height, stem diameter, and leaf area were measured during the late flowering-boll stage on three representative plants per treatment. Plant height was measured from base to apex using a ruler. Stem diameter was measured at 5 cm above ground using calipers in a cross pattern. Leaf area was calculated using the length-width conversion coefficient method, then used to compute leaf area index based on planting density. For dry matter accumulation, three uniform plants per treatment were separated into stems, leaves, and bolls, then oven-dried at 105°C for 30 minutes and subsequently at 75°C to constant weight.

1.3.4 Yield Yield was measured when cotton boll opening rate exceeded 95%. In each plot, a 2.28 m × 2.9 m sample area was selected to measure open boll weight. One hundred bolls were randomly collected to determine boll weight. Boll number per plant and plant density were recorded, with remaining bolls calculated using 0.8 times single boll weight to estimate theoretical total yield.

1.3.5 Water Consumption and Water Use Efficiency Cotton field water consumption was calculated using the water balance equation [1]. Water use efficiency (WUE) was computed as the ratio of seed cotton yield to water consumption [2].

1.4 Data Analysis

Data were processed using Microsoft Excel 2019. Analysis of variance and significance testing were performed using SPSS 27.0, with figures created using Origin software.

2 Results

2.1 Effects of Saline Water Irrigation on Soil Salinity

Soil salinity increased with irrigation water mineralization or SAR, showing a pattern of initial increase followed by decrease with soil depth, peaking at 60 cm [Figure 3: see original paper]. At 3 $g \cdot L^{-1}$ mineralization, average soil salinity in the 0–100 cm layer increased by 2.86%, 15.78%, and 42.84% in T3S15 and T3S20 compared to T3S10, respectively. At 5 $g \cdot L^{-1}$ mineralization, T5S15 and T5S20 increased salinity by 21.53% and 47.27% compared to T5S10. At 7 $g \cdot$

L^{-1} mineralization, T7S15 and T7S20 increased salinity by 31.42% and 64.84% compared to T7S10, while T7S20 increased by 73.57% compared to T7S10.

2.2 Effects of Saline Water Irrigation on Plant Ions

2.2.1 Effects on Plant K^+ and Na^+ Content Plant Na^+ content was significantly affected by irrigation water mineralization or SAR, with their interaction being highly significant. Under the same mineralization, plant Na^+ content increased with SAR, decreasing by 11.32%, 16.69%, and 31.90% in T3S15 and T3S20 compared to T3S10, respectively. Under the same SAR, plant Na^+ content increased with mineralization, decreasing by 8.95%, 15.29%, and 25.31% in T5S10 and T7S10 compared to T3S10. Organ Na^+ content ranked as: leaves > stems > bolls, indicating primary accumulation in leaves.

Plant K^+ content was significantly affected by mineralization, SAR, and their interaction. Under the same mineralization, plant K^+ content increased with SAR, rising by 25.40%, 33.81%, and 47.65% in T3S15 and T3S20 compared to T3S10. Under the same SAR, plant K^+ content increased with mineralization, rising by 20.29%, 32.97%, and 53.60% in T5S10 and T7S10 compared to T3S10. T3S20 significantly reduced K^+ content by 1.55% compared to T5S10, demonstrating that reducing SAR can mitigate K^+ reduction at 5 $g \cdot L^{-1}$ mineralization. Organ K^+ content ranked as: leaves > bolls > stems [Figure 4: see original paper].

2.2.2 Effects on Plant K^+/Na^+ Ratio The K^+/Na^+ ratio was significantly affected by mineralization or SAR, but not by their interaction. Under the same mineralization, the ratio decreased with increasing SAR, declining by 35.47%, 43.33%, and 50.70% in T3S15 and T3S20 compared to T3S10. Under the same SAR, the ratio decreased with mineralization, declining by 32.15%, 40.71%, and 56.64% in T5S10 and T7S10 compared to T3S10. Organ K^+/Na^+ ratio ranked as: bolls > leaves > stems [Figure 5: see original paper].

2.2.3 Effects on Plant N Content Plant N content was significantly affected by mineralization or SAR, but not by their interaction. Under the same mineralization, plant N content decreased with SAR, declining by 10.75%, 16.16%, and 21.07% in T3S15 and T3S20 compared to T3S10. Under the same SAR, plant N content decreased with mineralization, declining by 10.11%, 15.39%, and 22.47% in T5S10 and T7S10 compared to T3S10. T5S10 significantly increased N content by 4.29% compared to T3S20, while T5S20 increased by 5.28% compared to T7S10, indicating that reducing SAR does not decrease plant N content despite higher mineralization. Organ N content ranked as: leaves > bolls > stems, with stems having the lowest content [Figure 6: see original paper].

2.3 Effects of Saline Water Irrigation on Cotton Growth

2.3.1 Effects on Plant Height, Stem Diameter, and Leaf Area Index

Plant height, stem diameter, and leaf area index were significantly affected by mineralization or SAR, with their interaction significantly affecting plant height but not stem diameter or leaf area index. Under the same mineralization, these parameters decreased with SAR, declining by 19.07%, 26.99%, and 28.73% in T3S15 and T3S20 compared to T3S10. Under the same SAR, they decreased with mineralization, declining by 16.9%, 24.1%, and 33.8% in T5S10 and T7S10 compared to T3S10. T3S10 significantly increased stem diameter, indicating improved stem thickness under low mineralization and SAR conditions. No significant differences in stem diameter were observed between T3S20 and T5S10, suggesting low mineralization does not reduce stem thickness. Similarly, no significant differences in leaf area index between T5S10 and T5S15 indicate that reducing SAR under low-to-medium mineralization does not affect leaf area index [Figure 7: see original paper].

2.3.2 Effects on Cotton Dry Matter Accumulation Dry matter accumulation was significantly affected by mineralization, SAR, and their interaction. Under the same mineralization, aboveground biomass decreased with SAR, declining by 31.67% and 42.84% in T3S15 and T3S20 compared to T3S10. Under the same SAR, biomass decreased with mineralization, declining by 9.64%, 19.35%, and 33.01% in T5S10 and T7S10 compared to T3S10. T3S20 and T5S10 significantly increased biomass by 22.68% and 17.24%, respectively, compared to T7S10, demonstrating that moderately reducing SAR can promote aboveground biomass accumulation under medium-high mineralization. Organ dry matter ranked as: bolls > leaves > stems, with all organs decreasing as mineralization or SAR increased. Bolls accounted for the highest proportion of total dry matter, indicating they are the primary nutrient-absorbing organs during the late flowering-boll stage [Figure 8: see original paper].

2.4 Effects of Saline Water Irrigation on Yield and Water Use Efficiency

2.4.1 Cotton Yield Mineralization and SAR significantly affected yield components, though their interaction did not affect bolls per plant or boll weight. Under the same mineralization, bolls per plant and boll weight decreased with SAR. Compared to T3S10, T3S15 and T5S10 increased bolls per plant and boll weight by 0.92% and 8.44%, respectively, indicating that reducing SAR under low-to-medium mineralization can improve yield components. Under the same SAR, yield decreased with mineralization, declining by 2.17%, 7.94%, and 19.04% in T5S10 and T7S10 compared to T3S10. No significant differences in seed cotton yield were observed between T3S10, T3S15, and T5S10 .

2.4.2 Water Consumption (ET) Mineralization, SAR, and their interaction significantly affected ET. Under the same mineralization, ET decreased with SAR, declining by 1.57%, 4.00%, and 9.95% in T3S15 and T3S20 compared to T3S10. Under the same SAR, ET decreased with mineralization, declining by 0.53%, 4.41%, and 10.59% in T5S10 and T7S10 compared to T3S10 .

2.4.3 Water Use Efficiency (WUE) SAR significantly affected WUE, though the interaction with mineralization did not. Under the same mineralization, WUE decreased with SAR, declining by 0.70% in T3S15 compared to T3S10. Under the same SAR, WUE decreased with mineralization, declining by 4.22%, 10.14%, and 2.56% in T5S10 and T7S10 compared to T3S10 .

3 Discussion

Saline water irrigation introduces salts into the soil, affecting plant ions and nutrients, with Na^+ having particularly significant impacts that can cause nutritional disorders. The K^+/Na^+ ratio serves as an important indicator of cotton salt tolerance. Plant height and stem diameter are crucial growth parameters vulnerable to saline water irrigation. Leaf area index is a key indicator of canopy structure, with optimal values enhancing light use efficiency and yield. This study found that soil salinity increased with irrigation water mineralization or SAR, peaking at 60 cm depth, consistent with Wang et al. Saline water irrigation inhibited nutrient absorption, causing reductions in plant height, stem diameter, and leaf area with increasing mineralization or SAR, aligning with Gong et al. but differing from Zhang et al., possibly due to regional climate variations and rainfall patterns affecting salt leaching.

Plant organ Na^+ content ranked as leaves > stems > bolls, consistent with Liu et al., as leaves are primary photosynthetic sites where Na^+ accumulates after transport via stems. Organ K^+ content ranked as leaves > bolls > stems, differing from Min et al., possibly due to measurement timing differences. Organ N content ranked as leaves > bolls > stems, with leaves and bolls storing substantial nitrogen to support vegetative and reproductive growth. Most treatments increased stem N content compared to CK, except T7S20, indicating that moderate salt stress hinders N accumulation in stems.

The K^+/Na^+ ratio decreased with increasing mineralization or SAR, consistent with Jiang et al., as saline water irrigation reduces cotton' s ability to exclude Na^+ and absorb/transport K^+. Dry matter accumulation decreased with mineralization or SAR, with bolls comprising the highest proportion of total dry matter, as salt stress inhibits vegetative growth and affects dry matter allocation. Bolls per plant and boll weight decreased with SAR due to elevated root zone salt concentrations limiting water absorption and shortening the flowering-boll period. ET decreased with mineralization or SAR because salt stress reduces crop water consumption. WUE declined with mineralization as both yield and ET decreased.

The T3S20 and T5S10 treatments showed interesting interactions: despite both experiencing salt stress, their small difference in Ca^{2+} content significantly affected yield. Ca^{2+} plays vital roles in maintaining membrane structure, stabilizing cell walls, regulating ion transport, and controlling enzyme activities. The higher dry matter, bolls per plant, and boll weight in T5S10 resulted in significantly higher yield than T3S20, while its lower ET led to significantly higher WUE. This study elucidated the interactive effects of irrigation water mineralization and SAR on soil salinity, plant ion accumulation, cotton growth, yield, and WUE, though long-term effects require further investigation across multiple seasons.

4 Conclusion

This study investigated the effects of irrigation water mineralization and SAR on cotton growth and yield, yielding the following main conclusions:

1) Soil salinity increased with irrigation water mineralization or SAR. At 3 $g \cdot L^{-1}$ mineralization, average soil salinity in the 0–100 cm layer increased by 2.86% with SAR at 15 $(mmol \cdot L^{-1})^1/^2$ compared to 10 $(mmol \cdot L^{-1})^1/^2$. Soil salinity initially increased then decreased with depth, peaking at 60 cm.

2) Plant Na^+ content increased with irrigation water mineralization or SAR, while K^+, N, and K^+/Na^+ ratio decreased. This inhibited nutrient absorption, significantly reducing plant height, stem diameter, leaf area index, and dry matter accumulation. As mineralization increased, reducing SAR alleviated growth inhibition.

3) The study identified brackish water irrigation thresholds that do not affect cotton growth and yield: when SAR < 15 $(mmol \cdot L^{-1})^1/^2$, mineralization should be below 3 $g \cdot L^{-1}$; when SAR < 10 $(mmol \cdot L^{-1})^1/^2$, mineralization should be below 5 $g \cdot L^{-1}$.

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