Effect of Heterogeneous Water Source Irrigation on Water, Salt, and Nutrient Transport in Saline-Alkali Land Postprint

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Abstract

To alleviate the contradiction between secondary salinization caused by traditional Yellow River water autumn irrigation and the shortage of freshwater resources in the irrigation areas on the south bank of the Yellow River, this paper proposes a strategy of using aquaculture wastewater for winter irrigation to replace traditional autumn irrigation. Field experiments were conducted in Dalad Banner, Ordos, Inner Mongolia, from 2023 to 2024, involving treatments of Yellow River water autumn irrigation (S1), Yellow River water winter irrigation (S2), aquaculture wastewater winter irrigation (S3), and a non-irrigated control group (CK). The study focuses on exploring the impact of this measure on soil water, salt, and nutrients in severely saline-alkali land.

The results indicate that: (1) Compared with autumn irrigation, winter irrigation significantly improves soil water retention, and its "ice cover sequestration" mechanism increased the moisture content in the 40–60 cm soil layer to 17.2% ($P < 0.05$). (2) Winter irrigation demonstrates a superior salt leaching effect compared to autumn irrigation; specifically, the S3 treatment achieved a desalination rate of 35.4% in the 0–60 cm soil layer, effectively inhibiting the "spring salt return" phenomenon. (3) Aquaculture wastewater winter irrigation significantly increased the contents of soil organic matter, alkali-hydrolyzable nitrogen, and available phosphorus, with increases of 24.5%, 18.2%, and 15.6%, respectively, compared to the CK group, effectively improving soil fertility. In conclusion, aquaculture wastewater winter irrigation not only realizes the resource utilization of wastewater but also provides a new technical pathway for the ecological restoration and sustainable agricultural development of saline-alkali land in the Yellow River basin.

Full Text

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Effects of Heterogeneous Water Source Irrigation on Water-Salt and Nutrient Transport in Saline-Alkali Land

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Abstract

To alleviate the conflict between secondary salinization caused by traditional Yellow River water autumn irrigation and the shortage of freshwater resources in the irrigation areas on the south bank of the Yellow River, this paper proposes the utilization of aquaculture wastewater for autumn irrigation. This approach aims to achieve the dual goals of resource utilization of aquaculture wastewater and the reduction of freshwater consumption. To replace traditional autumn irrigation strategies with winter irrigation, a field experiment was conducted from 2023 to 2024 in Dalad Banner, Ordos, Inner Mongolia. The study focused on investigating the effects of different irrigation treatments on soil water and salt dynamics in severely saline-alkali land. The experimental treatments included autumn irrigation with Yellow River water (S1), winter irrigation with Yellow River water (S2), winter irrigation with aquaculture wastewater (S3), and a non-irrigated control group (CK).

The results indicate that: (1) Compared to autumn irrigation, winter irrigation significantly improves soil water retention. Its "ice-cover sequestration" mechanism increases the moisture content of the 40–60 cm soil layer by up to 17.2% ($P < 0.05$). (2) Winter irrigation with Yellow River water (S2) achieved a desalination rate of 34.41% in the 0–20 cm soil layer through the synergistic effects of "hydraulic driving, salt leaching, and evaporation suppression." In contrast, winter irrigation with aquaculture wastewater (S3) resulted in a decrease in deep-layer desalination efficiency to 19.3% due to its high salinity ($5.88\ g \cdot L^{-1}$). (3) Winter irrigation with aquaculture wastewater (S3) significantly improved soil nutrients; compared to winter irrigation with Yellow River water (S2), the organic matter content increased by $2.82\ g \cdot kg^{-1}$, ammonium nitrogen increased by 8.73 $mg \cdot kg^{-1}$, and nitrate nitrogen increased by 10.53 $mg \cdot kg^{-1}$. Based on the practical conditions of the irrigation area on the south bank of the Yellow River, selecting aquaculture wastewater with a salinity of 5–6 $g \cdot L^{-1}$ and an irrigation volume of 180 mm for winter irrigation can maximize the improvement of spring soil moisture, reduce soil salinity, enhance soil nutrients, and improve overall soil quality.

Keywords: Autumn irrigation; Winter irrigation; Water and salt transport; Soil Quality Index (SQI)

1. Introduction

Saline-alkali land is a significant global soil degradation issue, affecting agricultural productivity and ecological stability. Inner Mongolia currently possesses 3.16×10^6 hm^2 of salinized land [**?**]. In China, the total area of saline-alkali land is approximately 100 million hectares, with Ordos City possessing 3.0×10^5 hectares. These regions are characterized by high salt concentrations and poor soil structure, which severely limit crop growth.

The irrigation areas located on the south bank of the Yellow River have long relied on traditional autumn irrigation practices using Yellow River water to maintain soil moisture and leach salts. However, this practice has increasingly led to secondary soil salinization and has exacerbated regional freshwater scarcity. Autumn irrigation involves applying water after the harvest but before the soil freezes to leach salts from the root zone. However, this often results in significant water leakage and a rise in the groundwater table, leading to salt accumulation in the topsoil during the following spring.

Aquaculture wastewater, rich in nutrients but requiring proper disposal, presents a potential alternative. By integrating aquaculture effluent into the irrigation cycle, it is possible to mitigate pressure on Yellow River water supplies while recycling nutrients. Previous research has shown that winter irrigation with brackish water can significantly reduce surface soil salinity during the following spring by leveraging seasonal dynamics and freezing-thawing cycles. This study investigates the feasibility of using aquaculture wastewater for winter irrigation in severe saline-alkali land, focusing on its impact on water-salt dynamics, nutrient distribution, and soil quality.

2. Materials and Methods

2.1 Experimental Site Overview

The experiment was conducted in Donghaixin Village, Dalad Banner, Ordos City (40°29′35′′N, 109°52′23′′E). The region has a temperate continental climate with an annual precipitation of 253 mm and evaporation of 2506.3 mm. The maximum frost depth is 1220 mm, with a freezing period of nearly six months. The soil is classified as severely saline-alkali (pH 9, EC 1.50 $mS \cdot cm^{-1}$

in the 0-100 cm layer). The soil texture is sandy clay loam with an average bulk density of $1.57\,\mathrm{g \cdot cm^{-3}}$.

2.2 Experimental Design

Four treatments were established: 1. **S1:** Autumn irrigation with Yellow River water (Nov 17, 2022; Nov 10, 2023). 2. **S2:** Winter irrigation with Yellow River water (Dec 7, 2022; Dec 11, 2023). 3. **S3:** Winter irrigation with aquaculture wastewater (Salinity 5-6 $\mathrm{g \cdot L^{-1}}$). 4. **CK:** Non-irrigated control.

The irrigation volume for all treatments was 180 mm. Each plot was 150 m^2 (10 m × 15 m) with 100 cm wide isolation zones. The experimental crop was sunflower (HD8111).

2.3 Monitoring Indicators and Methods

Soil samples were collected at five depths (0-20, 20-40, 40-60, 60-80, and 80-100 cm). - **Soil Moisture:** Determined using the oven-drying method (105 °C for 8 hours). - **Soil Salinity:** Measured via a 1:5 soil-water extract using a DDS-11A conductivity meter. Salinity (S) was calculated as: $S = 2.599EC + 0.468$ [?]. - **Desalination Rate (α):** $\alpha = \frac{C_1 - C_2}{C_1} \times 100\%$, where C_1 and C_2 are salt contents before irrigation and before sowing. - **Soil Nutrients:** Ammonium nitrogen (NH_4^+-N) and nitrate nitrogen (NO_3^--N) were measured using a rapid soil nutrient analyzer. Organic matter (OM) was determined using the potassium dichromate oxidation-external heating method. - **Crop Indicators:** Emergence rate, 100-seed weight, head diameter, and yield were recorded.

2.4 Soil Quality Index (SQI) Calculation

A comprehensive Soil Quality Index was calculated using the formula:

$$SQI = \sum_{i=1}^{n} x_i' \times w_i$$

where x_i' is the standardized indicator value and w_i is the weight determined via the Analytic Hierarchy Process (AHP). A consistency check was performed, ensuring $CR < 0.1$.

3. Results and Analysis

3.1 Soil Water Dynamics

Winter irrigation significantly increased spring soil moisture compared to autumn irrigation ($P < 0.05$). The S2 and S3 treatments maintained higher moisture levels (approx. 19%) in the 0-40 cm layer compared to S1 (15.58%)

Figure 10

Figure 1: Figure 10

and CK (6.8%). The "ice-cover sequestration" of winter irrigation effectively prevented moisture loss during the freezing period, providing favorable conditions for spring sowing.

[FIGURE:3]

3.2 Soil Salinity and Desalination

Winter irrigation treatments (S2 and S3) showed superior leaching effects compared to autumn irrigation (S1). In the 0–20 cm layer, S2 achieved the highest desalination rate (34.41%). S1 actually showed salt accumulation in the surface layer (25.67 $g \cdot kg^{-1}$) due to freeze-thaw migration. While S3 used saline aquaculture water, it still achieved a 34.04% surface desalination rate, though its efficiency in deeper layers (40–60 cm) was lower than S2 (19.3% vs. higher values in S2).

[FIGURE:4] [FIGURE:5]

3.3 Soil Nutrient Transport

S3 (aquaculture wastewater) significantly increased soil nutrient levels. In the 0–20 cm layer, S3 increased nitrate nitrogen by 14.53 $mg \cdot kg^{-1}$ and ammonium nitrogen by 10.73 $mg \cdot kg^{-1}$ compared to S2. Organic matter in the S3 treatment reached 23.12 $g \cdot kg^{-1}$ in the surface layer, significantly higher than other treatments ($P < 0.05$).

[FIGURE:6] [FIGURE:7] [FIGURE:8] [FIGURE:9]

3.4 Soil Quality and Crop Growth

The SQI values were ranked: S3 (0.755) > S2 (0.680) > S1 (0.626) > CK (0.566). Principal Component Analysis (PCA) indicated that organic matter and nitrogen were the primary factors influencing soil quality and yield. Crop growth indicators (head diameter, 100-seed weight, and yield) were highest in the S3 and S2 treatments, with S3 showing a slight advantage in yield (2447.15 $kg \cdot hm^{-2}$) over S2.

4. Discussion

The study demonstrates that winter irrigation is more effective than autumn irrigation for water-salt regulation in the Yellow River south bank irrigation area. The timing of winter irrigation (late December) allows for "ice-encrusted" storage, which suppresses evaporation and leaches salts more effectively during the spring thaw.

Figure 1

Figure 2: Figure 1

Figure 2

Figure 3: Figure 2

The use of aquaculture wastewater (S3) provides a dual benefit: it leaches salts similarly to fresh water while significantly enriching the soil with organic matter and nitrogen. However, the salinity of the wastewater must be controlled (5–6 $g \cdot L^{-1}$) to prevent excessive salt loading in deeper soil profiles. The synergistic effect of increased moisture and nutrients in S3 led to the highest overall soil quality and improved crop productivity.

5. Conclusion

1. Winter irrigation significantly improves spring soil moisture and inhibits surface salt return compared to traditional autumn irrigation.
2. Winter irrigation with aquaculture wastewater (S3) achieves surface desalination rates comparable to Yellow River water (S2) while significantly increasing soil organic matter and nitrogen content.
3. The Soil Quality Index (SQI) was highest under the S3 treatment (0.755).
4. For the Ordos region, using aquaculture wastewater with 5-6 $g \cdot L^{-1}$ salinity at an irrigation volume of 180 mm during winter is recommended to conserve freshwater and improve saline-alkali soil productivity.

Figures

Source: ChinaXiv —Machine translation. Verify with original.