Effects of Plastic Film Mulching on Water and Salt Dynamics in Coastal Saline Soil Under Spring Brackish Water Irrigation Conditions: Postprint

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Abstract

Two plots with significantly different initial water contents in the topsoil were selected in Haixing County, Cangzhou City, Hebei Province, to investigate the effects of plastic film mulching on water-salt dynamics in coastal saline soil under spring brackish water irrigation using local high-salinity brackish water (10~15 g L 1). Six treatments were established to explore the effects of different brackish water irrigation and mulching on soil water-salt dynamics: no brackish water irrigation and no mulching (control, CK), no brackish water irrigation with mulching (PM), brackish water irrigation on March 29 and April 13 without mulching (SE, SL), and brackish water irrigation with subsequent mulching (SE+PM, SL+PM). Additionally, at two locations with topsoil water content $ $20% (Xiaoshan Township, Haixing County) and <20% (Haixing County Farm), treatments of brackish water irrigation with mulching (SE+PM) and no irrigation with no mulching (CK) were established to investigate the influence of initial soil water content on soil water-salt dynamics under brackish water irrigation. The irrigation amount was 180 mm for all treatments, and the irrigation water was sourced from drainage ditches with salinities of 12.12 g L 1 and 11.53 g L 1. After the brackish water infiltration, oil sunflower was sown. The results showed that mulching after spring brackish water irrigation could effectively reduce topsoil salinity, and earlier implementation of this measure yielded better results with greater depth and higher rates of desalination. In this study, the SE+PM treatment exhibited the optimal desalination effect, achieving a desalination rate of 58.93% in the 0–5 cm layer after oil sunflower harvest, with soil salt content decreasing from 1.15% to 0.51%. Furthermore, desalination effectiveness was also influenced by initial soil water content. When topsoil water content was <20%, the spring brackish water irrigation with mulching treatment demonstrated better salt leaching effects, with an average desalination depth exceeding 40 cm, ensuring normal oil sunflower growth. The seedling emergence rate and yield of oil sunflower were 73.9% and 920 kg hm 2, respectively, and at harvest time, the soil salt content in the 0–20 cm layer decreased from 1.93% before irrigation to 0.32%, achieving a desalination rate of 84.07%. However, when topsoil water content was $ $20%, the desalination process was slow and shallow, and soil salinity remained high at sowing time, resulting in low seedling emergence rates and ultimately complete crop failure. This study demonstrates that utilizing spring high-salinity brackish water irrigation combined with plastic film mulching can effectively reduce topsoil salinity under conditions of spring drought and severe soil salt accumulation, providing suitable soil moisture conditions and a low-salt environment for crop sowing and seedling emergence.

Full Text

Effect of Plastic Film Mulch on Soil Moisture and Salt Dynamics Under Saline Water Irrigation in Coastal Saline Soils

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Abstract: Field experiments were conducted in Haixing County, Hebei Province, to investigate the effects of plastic film mulch on soil moisture and salt dynamics under saline water irrigation in coastal saline soils during spring. Two field sites with substantially different initial soil moisture contents in the plough layer were selected for spring irrigation with local high-salinity water (10–15 $g \cdot L^{-1}$) combined with plastic film mulching. Six treatments were established to examine the effects of different saline water irrigation and mulching combinations: no irrigation without plastic film mulch (control, CK), plastic film mulch without irrigation (PM), saline water irrigation on March 29 without mulch (SE), saline water irrigation on March 29 with mulch (SE+PM), saline water irrigation on April 13 without mulch (SL), and saline water irrigation on April 13 with mulch (SL+PM). Additionally, to assess the influence of initial soil moisture, two treatments—saline water irrigation with plastic film mulch (SE+PM) and no irrigation without mulch (CK)—were implemented at both a site with $ $20% initial soil moisture content (Xiaoshan Town) and a site with <20% initial moisture (Haixing Farm). The irrigation amount was 180 mm in all cases, and oil sunflower was sown after the saline water infiltrated.

The results demonstrated that plastic film mulch effectively reduced soil salinity in the plough layer, with earlier implementation yielding superior outcomes in both desalination depth and efficiency. The SE+PM treatment achieved the optimal desalination effect, reducing soil salt content in the 0–5 cm layer from 1.15% to 0.51% (a 58.93% desalination rate) by harvest. Desalination efficacy was also contingent upon initial soil moisture content. When plough layer moisture was $<20\%$, the combined saline irrigation and mulching treatment produced superior salt leaching, with an average desalination depth exceeding 40 cm, ensuring normal oil sunflower growth. At harvest, the 0–20 cm layer salt content decreased from 1.93% to 0.32%, achieving an 84.07% desalination rate, with emergence rate and yield reaching 73.9% and 920 $kg \cdot hm^{-2}$, respectively. Conversely, when initial moisture \$ \$20%, desalination proceeded slowly and shallowly, leaving high soil salinity at sowing and resulting in poor emergence and complete crop failure. This study demonstrates that spring irrigation with high-salinity water combined with plastic film mulching can effectively reduce plough layer salinity under conditions of spring drought and severe salt accumulation, providing suitable moisture conditions and a low-salt environment for crop germination.

Keywords: Heavy saline soil; Saline water irrigation; Plastic film mulching; Soil salinity; Soil moisture content; Soil water-salt dynamics

Introduction

Freshwater scarcity and soil salinization are primary constraints on agricultural development and ecological improvement in the Bohai Rim region. Utilizing limited water resources rationally while exploiting available saline water resources represents a critical challenge for saline-alkali land improvement in this area. Research by Wang Zunqin et al. indicates that salt movement in soil exhibits distinct seasonal patterns, with salt accumulation occurring in spring, autumn, and winter, and desalination in summer. Spring accumulation is particularly severe, coinciding with the salt-sensitive period of crop emergence and early growth. Therefore, creating low-salt conditions in the plough layer during spring is crucial for saline-alkali land improvement in this region.

Given freshwater shortages, the abundant subsurface saline water in the Bohai Rim region constitutes a potentially valuable resource. Extensive research on saline water irrigation has been conducted both domestically and internationally. Wang Weiguang et al. note that the suitability of saline water for irrigation depends primarily on salinity level and composition, though irrigation method and timing, crop salt tolerance, and regional climate characteristics also significantly influence outcomes. Rational saline water irrigation can increase soil moisture without increasing salinity, ensuring normal crop growth and yield improvement. Conversely, improper use can damage soil structure and cause secondary salinization. Chen Xiuling et al., conducting saline water irrigation experiments in Nanpi County, Hebei, identified maintaining soil salinity below crop tolerance thresholds as the key to successful saline water irrigation. Wu

Zhongdong et al. proposed 3 g·L^{-1} as the upper salinity limit for local irrigation water to ensure sustained high yields. Zhao Gengmao et al. found that three years of seawater irrigation in coastal Shandong did not cause salt accumulation and could improve yields under appropriate irrigation and drainage conditions. Bnyamini et al. studied drainage system configurations for optimizing soil water-salt regulation in the Jezre' el Plain, while Kass et al. demonstrated that rational saline water irrigation in Israel' s coastal areas could achieve safe irrigation and crop yield increases.

However, in the low-lying plains of the Bohai Rim region, subsurface saline water typically exhibits high salinity (averaging 7-22 g·L^{-1}), presenting new challenges for saline water utilization. Recent research has systematically explored high-salinity water resources. Shi Peijun et al. obtained freshwater from sea ice melting in Bohai Bay, while Guo Kai et al. acquired brackish water and freshwater from freezing-thawing processes of saline water in winter, achieving plough layer desalination in saline soils. Combined with subsequent mulching for salt suppression, these approaches provided suitable low-salt conditions for crops. These methods achieve saline water desalination through natural solid-liquid phase transitions. Saline water can also be desalinated through gas-liquid phase transitions. Furthermore, plastic film mulching represents an important saline-alkali land improvement measure, offering advantages including reduced vertical water evaporation, decreased soil water loss, improved soil moisture content and water use efficiency, and mitigated surface salt accumulation. Compared with other mulching methods, plastic film also facilitates condensation of soil water vapor and its reflux infiltration for salt leaching.

Based on this analysis, this study proposes direct spring irrigation with high-salinity water combined with plastic film mulching to leverage these processes. Saline water irrigation increases soil moisture, and subsequent mulching after complete infiltration—taking advantage of high spring evaporation rates and large diurnal temperature variations—causes soil moisture to vaporize, condense on the film surface, and reflux as freshwater to leach surface soil salts, thereby creating suitable low-salt conditions for crop emergence. Accordingly, we established experiments on spring saline water irrigation combined with plastic film mulching under different initial soil moisture conditions to investigate salt leaching effectiveness, evaluate the technology' s efficacy and applicable areas, and provide new approaches for utilizing high-salinity water in the low-lying plains of the Bohai Rim region.

1.1 Study Area Description

The experiment was conducted in coastal heavy saline-alkali land in Haixing County, Hebei Province (37°56 10 -38°17 31 N, 117°18 33 -117°50 57 E, elevation 1.3-3.6 m). The region features a warm temperate semi-humid continental monsoon climate with an average annual temperature of 12.1°C. January averages -4.5°C, with extreme minimum temperatures of -19.9°C. First frost typically occurs in late October, with final frost in mid-April. Mean annual precipitation is 582.3 mm, concentrated in July–August (74% of annual total), while winter precipitation accounts for only 5-7%. Soil salts are dominated by NaCl, with Cl^- comprising 70-80% of total anions and Na^+ exceeding 90% of total cations; salt composition shows minimal vertical variation in the profile. Groundwater salinity and depth vary seasonally: during July-September rainfall recharge, the water table rises to approximately 1 m depth. In spring and autumn with less rainfall and high evaporation, the water table deepens to about 2.2 m during spring drought periods. Groundwater salinity ranges from 7-22 $g \cdot L^{-1}$ with significant interannual variation. [Figure 1: see original paper] shows annual temperature and rainfall variation in Haixing County during 2016. Monthly mean temperatures during the experimental period (March–June) were 8.50°C, 14.06°C, 20.86°C, and 25.40°C, respectively. Notable rainfall events during the experimental period are illustrated in [Figure 1: see original paper]. March diurnal temperature differences were approximately 10°C.

1.2 Experimental Design

Since salt movement in soil is driven by water movement, which is closely related to soil moisture content, two plots with substantially different initial soil moisture levels in spring 2016 (Xiaoshan Town and Haixing Farm) were selected for experiments on salt leaching under spring saline water irrigation and plastic film mulching. Xiaoshan Town had shallow groundwater depth (~1 m) and higher spring soil moisture (>20%), while Haixing Farm had deeper groundwater (>2.5 m) and drier spring soil (<20%). Initial soil water and salt contents for both sites (measured March 6) are shown in .

At Xiaoshan Town, six treatments were established: no irrigation without plastic film mulch (control, CK), plastic film mulch without irrigation (PM), saline water irrigation on March 29 without mulch (SE), saline water irrigation on March 29 with mulch (SE+PM), saline water irrigation on April 13 without mulch (SL), and saline water irrigation on April 13 with mulch (SL+PM). Each treatment had six replicates. Mulched plots were covered immediately after irrigation. Plot size was 4 m × 5 m with a randomized block design. To prevent lateral seepage, 1 m-deep plastic film separated adjacent plots.

At Haixing Farm, two treatments were established: saline water irrigation with plastic film mulch on March 29 (SE+PMN) and no irrigation without plastic film mulch (control, CKN). Each treatment had six replicates with the same plot dimensions and design as Xiaoshan Town.

Irrigation water for both sites was sourced from drainage ditches with salinity levels of 12.12 $g \cdot L^{-1}$ for Xiaoshan Town and 11.53 $g \cdot L^{-1}$ for Haixing Farm. The irrigation amount was 180 mm at both sites. Salinity levels and ionic compositions of irrigation water are presented in .

Oil sunflower (Helianthus annuus 'G101'), a shallow-rooted crop, was planted on June 1-2 at both sites with row spacing of 0.5 m, plant spacing of 0.3 m, and density of 3.9×10^4 plants $\cdot$ hm^{-2}. Sowing was performed manually along marked lines. During the growth period, topdressing and irrigation were applied (control plots received only topdressing). Emergence rates and yields were investigated at the seedling and maturity stages, respectively.

1.3 Measurement Indicators and Methods

1) Soil sampling: Background values were measured before irrigation (March 28, 2016) by sampling at 0–20 cm, 20–40 cm, and 40–60 cm depths. Post-irrigation sampling occurred at the same depths every 7 days until May 4, with additional samples taken at sowing (June 1) and 20 days after sowing. The final sampling occurred on June 22, after which only mature oil sunflower yields were measured.

Soil moisture content was determined by the oven-drying method. Soil solution extracts were prepared at a 1:5 soil-to-water ratio. Salt ion composition was analyzed using: double-indicator titration for HCO_3^-, $AgNO_3$ titration for Cl^-, EDTA indirect complexometric titration for SO_4^{2-}, and EDTA titration for Ca^{2+} and Mg^{2+}. K^+ + Na^+ content was calculated by charge balance, and total salt content was determined by summing all ion concentrations.

2) Crop emergence and yield: Emergence rates were calculated by counting all seedlings in each plot. At maturity, 20 plants from the middle rows (excluding border rows and row ends) were randomly harvested, dried, cleaned, and weighed for yield determination.

3) Meteorological data: Rainfall and temperature data were obtained from an automatic weather station at the Xiaoshan Town experimental site.

1.4 Data Processing and Statistical Methods

Data analysis was performed using SPSS 16.0, and figures were generated using Sigmaplot 12.0.

Results

2.1.1 Dynamic Changes in Soil Salt Content Across Different Layers

As shown in [Figure 2: see original paper], in the 0–5 cm layer, soil salt content in non-mulched treatments generally exhibited fluctuating increases until oil sunflower planting (June 1). The CK and SE treatments showed two peaks on April 6 and April 20, with salt content increasing by 40.13% and 113.70% for CK, and 66.32% and 65.70% for SE, respectively. The SL treatment, influenced by rainfall on April 18, showed a consistent decreasing trend due to rain leaching, with salt content declining 37.96% by June 1 relative to initial values. Mulched treatments showed overall decreasing trends: PM initially increased then decreased, while SE+PM and SL+PM decreased with fluctuations. By June 1, salt content had decreased by 21.26% and 52.97% for PM and SE+PM, respectively. The SL+PM treatment, with later irrigation and mulching, showed only a 10.30% decrease. The SE+PM treatment achieved the highest desalination efficiency, reducing salt content from 1.10% to 0.52% (53.6% desalination rate). However, at this point, no treatment had reduced salinity to the level required for oil sunflower emergence, resulting in extremely poor emergence at this experimental site.

By June 22 (post-emergence), rainfall had increased. Compared with June 1, CK salt content increased 21.00%, while SE and SL decreased 1.22% and 1.86%, respectively, indicating that heavy saline irrigation had some salt-suppressing effect but insufficient for desalination. Among mulched treatments without supplemental irrigation, only SE+PM maintained desalination effects, decreasing 0.69% relative to June 1, while PM and SL+PM increased 12.90% and 40.38%, respectively. During the emergence period, with increased rainfall and no additional irrigation, non-mulched treatments showed superior desalination due to rain leaching. By experiment conclusion, SE+PM again showed the highest desalination efficiency, reducing salt content from 1.10% to 0.51% (53.6% desalination rate).

In the 5–10 cm layer, salt dynamics were consistent with the 0–5 cm layer. By June 22, CK, PM, SE, SL, and SL+PM treatments showed salt content increases of 42.66%, 11.06%, 90.01%, 12.08%, and 25.36%, respectively, while SE+PM decreased 7.8%. In the 10–40 cm layer, variation was minimal, with only SE+PM maintaining a desalination trend (17.40% decrease) by June 22; all other treatments showed slight increases.

2.1.2 Dynamic Changes in Soil Water Content Across Different Layers

In the 0–5 cm layer, water content variation was pronounced ([Figure 3: see original paper]). All mulched treatments showed initial increases followed by gradual decreases, while non-mulched treatments exhibited fluctuating decreases due to temperature and rainfall. On June 1, with minimal rainfall and high evaporation, mulched treatments showed increased surface moisture due to vapor condensation on film and reflux infiltration: PM, SE+PM, and SL+PM increased 11.92%, 7.41%, and 40.04%, respectively. Non-mulched treatments (CK, SE, SL) decreased 16.86%, 12.60%, and 13.87%, respectively, demonstrating the water conservation effect of mulching, particularly when combined with saline water irrigation. Subsequently, with increased rainfall, mulched treatments received less infiltration, and by June 22, SE+PM and SL+PM had decreased 17.06% and 8.71%, respectively, relative to June 1.

The 5–10 cm layer showed similar patterns, with minimal variation except around rainfall events. Post-irrigation, mulched treatments maintained stable moisture at 22–26%, while non-mulched treatments fluctuated substantially. The 10–40 cm layer had high initial moisture (22–24%) with later fluctuations around 9%, showing consistent trends across treatments. SE+PM consistently maintained higher moisture than other treatments, with mulched treatments generally outperforming non-mulched treatments.

2.2 Effects of Spring Saline Water Irrigation and Plastic Film Mulching on Soil Water-Salt Dynamics Under Different Initial Soil Moisture Conditions

Results from Xiaoshan Town indicated that when initial soil moisture >20%, saline irrigation with mulching achieved shallow desalination (only ~5 cm depth) with poor salt leaching efficiency. High initial moisture filled soil macropores, causing water infiltration at saturated hydraulic conductivity rates and slow salt leaching with shallow desalination layers. Therefore, concurrent experiments were conducted under <20% initial moisture conditions at Haixing Farm.

As shown in [Figure 4: see original paper], after saline irrigation with mulching (April 13), both treatments showed stable salt content across all layers, no longer influenced by shallow saline groundwater. Compared with pre-irrigation (March 28), SE+PMN treatment substantially reduced salt content throughout the profile: 76.70% and 74.45% decreases in 0–10 cm and 10–20 cm layers, respectively, with a 75.06% average decrease across 0–60 cm. In contrast, CKN treatment increased salt content throughout the profile: 22.56% and 29.69% increases in 0–10 cm and 10–20 cm layers, respectively, with a 19.76% increase across 0–60 cm. At this time, SE+PMN had a mean salt content of 0.49%, 71.91% lower than CKN.

At oil sunflower planting (June 1-2), SE+PMN maintained low salt levels. By June 22 (post-emergence), CKN had a mean salt content of 1.05% across 0–60 cm, while SE+PMN had 0.13%—far below CKN and meeting oil sunflower emergence requirements.

As shown in [Figure 5: see original paper], pre-irrigation moisture differences between treatments were minimal. Post-irrigation (April 13), SE+PMN showed significantly higher moisture than CKN: 20.93% and 17.53% increases in 0–10 cm and 10–20 cm layers, respectively. Below 20 cm, differences between treatments were negligible.

Discussion

Oil sunflower, a relatively salt-tolerant shallow-rooted oil crop, remains sensitive to salt stress during germination and seedling stages. The spring saline water irrigation and plastic film mulching model can create a desalinated plough layer in spring, providing suitable low-salt conditions for oil sunflower emergence. This study demonstrates that spring saline irrigation with mulching can reduce soil profile salinity and achieve surface salt leaching, even meeting the soil requirements for oil sunflower emergence and seedling growth. This combined approach shows considerable promise for arid and semi-arid saline regions. However, spring saline irrigation effectiveness depends on initial soil moisture content. Water infiltration profiles are substantially affected by soil moisture; only at low initial moisture does infiltration create an approximately trapezoidal profile with most salts accumulating at the wetting front. At higher initial moisture, water primarily infiltrates through macropores, leaving salts in micropores insufficiently leached. Ma Donghao et al. reported that lower soil moisture results in smaller salt content in the upper layer and larger salt content in the lower layer after saline water infiltration, indicating higher leaching efficiency. These findings align with our results: at Xiaoshan Town with high initial moisture, spring saline irrigation with mulching only desalinated the 0–5 cm layer with low efficiency; at Haixing Farm with low initial moisture, the same treatment achieved salt leaching across 0–60 cm, with >70% desalination rate in 0–20 cm, reducing salt content to <0.2% and enabling normal oil sunflower cultivation. Therefore, to achieve optimal desalination, saline irrigation with mulching should be implemented at sites with low soil moisture during spring. Furthermore, while spring saline irrigation with mulching achieves salt leaching through water infiltration and vapor condensation-reflux processes, further quantitative research is needed on the respective contributions of irrigation and mulching to salt leaching.

Many studies indicate that high-salinity water is difficult to use directly for irrigation. However, regionally adapted research exists for extreme conditions. Ma Xuexi et al. reported that *Tamarix chinensis* achieved 75% survival under 28 $g \cdot L^{-1}$ saline irrigation in the Taklamakan Desert, with 80% survival under 20 $g \cdot L^{-1}$. Shi Peijun et al. utilized sea ice collection, storage, and melting for seawater resource utilization and saline soil improvement. Guo Kai et al. achieved utilization of high-salinity subsurface water in coastal areas through winter saline ice irrigation. This study demonstrates that high-salinity water irrigation combined with plastic film mulching during spring drought and peak salt accumulation periods can also achieve surface salt leaching. Additionally, during saline irrigation, salt-water-soil interactions promote soil flocculation, improve soil structure, and enhance aeration and permeability. Higher irrigation water salinity accelerates infiltration rates, providing favorable conditions for freshwater condensed on the film to infiltrate—an important reason for the effective salt leaching achieved by spring high-salinity water irrigation with mulching. Earlier implementation of this measure is more beneficial for salt leaching.

Severe freshwater scarcity and soil salinization constrain agricultural production in the Bohai Rim region. Based on regional water resources and climate characteristics, and addressing seasonal spring drought and explosive salt accumulation, this study investigated spring saline water irrigation combined with plastic film mulching. Results show this approach can effectively increase soil moisture and reduce surface salinity during spring. Initial soil moisture content significantly affects salt leaching efficacy, with low moisture conditions enabling deeper leaching and higher desalination rates while supporting growth of shallow-rooted salt-tolerant crops like oil sunflower. Thus, spring saline irrigation with plastic film mulching represents an effective method for utilizing high-salinity water and leaching plough layer salts in coastal saline areas, providing new insights for saline water resource utilization in coastal saline zones.

However, spring saline irrigation combined with plastic film mulching involves complex dynamic processes including freshwater vapor condensation-reflux and water-salt movement in soil, influenced by numerous factors such as vapor evaporation quantity, groundwater depth and quality, irrigation timing and amount. Further research is needed to address these aspects.

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Note: Figure translations are in progress. See original paper for figures.