Postprint: Effect of Under-Mulch Integrated Irrigation-Drainage Technology on Soil Leaching Efficiency

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Date: 2021-08-12T00:00:00+00:00

Abstract

Drip irrigation under mulch combined with subsurface pipe drainage technology is a composite water-saving irrigation and drainage technology. To further investigate its effects in Xinjiang, a cotton field experiment was conducted in the Anjihai area of the 141st Regiment of Xinjiang Production and Construction Corps, with three treatments established: drip irrigation under mulch combined with subsurface pipe drainage (T1), drip irrigation under mulch without subsurface pipe drainage (T2), and no drip irrigation under mulch and no subsurface pipe drainage (T3). The results indicated: (1) Under the same soil layer, the variation amplitudes of soil moisture content for treatments T1, T2, and T3 were 6.32%, 10.03%, and 14.32%, respectively, i.e., T1<T2<T3; (2) The T1 treatment reduced soil salinity content throughout the 0–60 cm soil layer, with decreases of 63.06%, 60.62%, and 48.42% at depths of 20 cm, 40 cm, and 60 cm, respectively; during the late growth stage of cotton, the T2 treatment decreased soil salinity content at 20 cm and 40 cm depths but increased it at 60 cm depth, indicating that surface soil desalination could lead to deep soil salt accumulation; the T3 treatment exhibited surface salt return phenomenon at the end of the growth period; (3) At the end of the cotton growth period, soil organic matter content increased at 20 cm, 40 cm, and 60 cm depths under the T1 treatment, whereas it decreased in the T2 and T3 treatments without subsurface pipe drainage; (4) For the drip irrigation under mulch combined with subsurface pipe drainage technology, soil permeability improvement was enhanced with increasing soil depth within the 0–60 cm layer. (5) The pH and salinity content of subsurface pipe drainage water were both higher than those of irrigation water, demonstrating that subsurface pipe drainage simultaneously removed soil salts, thereby contributing to the amelioration of soil salinity and alkalinity.

Full Text

Effect of Drip Irrigation Under Mulch Combined with Subsurface Drainage on Soil Leaching Efficiency in Xinjiang

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Abstract

Drip irrigation under mulch combined with subsurface drainage technology represents a composite water-saving irrigation and drainage approach. To further investigate its effects in Xinjiang, we conducted cotton field experiments in the Anjihai region of the Xinjiang Production and Construction Corps, implementing three different treatments under identical soil layers: drip irrigation under mulch combined with subsurface pipe drainage (T1), drip irrigation under mulch without subsurface pipe drainage (T2), and conventional planting without either mulch or subsurface drainage (T3). The results demonstrated that under the same soil layer, the variation amplitudes of soil moisture content for T1, T2, and T3 treatments were 6.32%, 10.03%, and 14.32%, respectively, indicating that T1 maintained more stable soil moisture than T2 and T3. The water conservation effectiveness of different treatments followed the order T1 > T2 > T3. Soil salt content in the 0–60 cm layer decreased under T1 treatment, with reductions of 63.06%, 60.62%, and 48.42% in the 20 cm, 40 cm, and 60 cm layers, respectively. Under T2 treatment, soil salt content decreased in the 20 cm and 40 cm layers but increased in the 60 cm layer, demonstrating that surface desalination can cause deep soil salt accumulation. The T3 treatment exhibited surface salt return at the end of the growth period. At the end of the cotton growth period, soil organic matter content increased in the 20 cm, 40 cm, and 60 cm layers under T1 treatment, whereas it decreased in T2 and T3 treatments without subsurface pipes. Within the 0–60 cm depth range, soil permeability improved with increasing depth. The pH and salt content of water discharged from the subsurface pipes were higher than those of irrigation water, indicating that subsurface drainage simultaneously removed soil salts, thereby facilitating the improvement of saline-alkali soils. These findings provide a theoretical basis for the improvement and management of saline-alkali land in Xinjiang.

Keywords: cotton; drip irrigation under mulch; subsurface pipe drainage; salt leaching; Xinjiang

Introduction

Resource and environmental issues have received increasing attention during human development. As a developing country with a large population, China faces scarcity of per capita resources, with water shortage and soil salinization becoming critical factors affecting agricultural development. Xinjiang, as one of China' s major agricultural production regions, experiences severe water scarcity and soil salinization, which gradually reduce the area of arable land and its quality, consequently decreasing crop yields on saline-alkali soils and severely constraining sustainable agricultural and socio-economic development in the region. Improving agricultural water use efficiency and land quality is essential for increasing crop yields, ensuring sustainable land use, and reconciling the conflicts between human water demand and cultivated land to achieve harmonious and sustainable development.

Since its introduction to Xinjiang in 1996, mulched drip irrigation technology has been rapidly developed and widely applied, with the current application area exceeding 2 million hectares. Cotton cultivation under mulched drip irrigation in Xinjiang accounts for over 80% of the national planting area and approximately 90% of national production, making cotton the most extensively planted economic crop in the region. However, when mulched drip irrigation is applied on saline-alkali soils, the transport patterns of soil water and salt differ from conventional irrigation methods. While this technology can deliver water 定时、定量 to the crop root zone to achieve yield increase and water savings, it only provides limited regulation of soil salts. Salts accumulate at the wetting front edges, and long-term use of mulched drip irrigation without drainage leads to gradual salt accumulation in soils below 40 cm, threatening long-term stable and high yields and causing secondary salinization.

Research by Li Wenhao et al. demonstrated severe shallow soil salt accumulation after 15 years of continuous mulched drip irrigation. Yang Yuhui et al. showed that under current irrigation regimes and planting patterns in Xinjiang, the annual salt accumulation in the tillage layer reaches 0.36 $g \cdot kg^{-1}$, and that salt accumulation in moderately saline soils would reach severe levels (10–20 $g \cdot kg^{-1}$) within 15–40 years, posing potential threats to food security and the agricultural ecological environment in oasis areas. Similar deep soil salt accumulation phenomena exist in other arid and semi-arid regions worldwide.

To mitigate saline-alkali effects, periodic flood irrigation is typically employed for salt leaching based on the principle that "salt moves with water." However, surface leaching only transfers salts to deeper soil layers without reducing total salt content. Moreover, flood irrigation wastes scarce water resources in Xinjiang and exacerbates water shortages while raising groundwater levels, allowing salts in groundwater to return to the soil through capillary action. Therefore, effective measures to reduce soil salt content are crucial for preventing secondary salinization. Among traditional saline-alkali land improvement methods (hydraulic, agricultural, biological, and chemical), subsurface drainage technology in hydraulic engineering measures can effectively improve soil physicochemical properties, lower groundwater levels, and mitigate secondary salinization.

Previous studies have demonstrated the effectiveness of this approach. Shi Peijun et al. found that subsurface pipe drainage under mulched drip irrigation removed 28.90% of soil salt in the 0–80 cm layer after three irrigation leaching events. Liu Yuguang et al. reported desalination rates of 50.96% and 90.89% for light and moderate saline soils, respectively, when shallow subsurface drainage was combined with drip irrigation. Bahceci observed desalination rates exceeding 80% in shallow soils after subsurface drainage. Li Xianwei et al. conducted numerical simulations of mulched drip irrigation combined with subsurface salt drainage, successfully modeling water and salt movement during the leaching process. This study investigates the effects of different mulched drip irrigation and subsurface drainage (integrated irrigation-drainage) modes on soil moisture, salt, organic matter content, permeability coefficient, and leaching efficiency through field experiments, providing further reference for the application of this technology in saline-alkali lands of Xinjiang.

1. Materials and Methods

1.1 Study Area Overview The field experiment was conducted from April to October 2019 in the Anjihai area (85°21 47 E, 44°36 29 N, altitude 412 m) of the 141st regiment of the Xinjiang Production and Construction Corps, with a total planned area of 3.4 hm^2. The region is characterized by low rainfall, high evaporation, terrain sloping from south to north with a natural gradient of 3.4‰, accumulated temperature above 10°C of 3649°C, cotton growing season temperature of 6.8°C, average annual sunshine duration of 2700 h, and average annual evaporation of 1718 mm. The meteorological data during the cotton growth period are shown in [Figure 1: see original paper].

The test soil was sandy loam with average organic matter content of 1.20%-1.40% in the tillage layer, initial salt content of 1.80 $g \cdot kg^{-1}$, and soil porosity of 40.90%. The previous crop in the test area was cotton, and the test cotton variety was "Nongda 40," with a growth period of approximately 180 days, tower-type plant architecture, good ventilation and light transmission, and early maturity with high yield. The physical indicators of the test area soil are shown in .

1.2 Experimental Design The experiment included three treatments: T1 (mulched drip irrigation combined with subsurface pipe drainage, referred to as integrated irrigation-drainage), T2 (mulched drip irrigation without subsurface pipe drainage), and T3 (conventional control planting without mulched drip irrigation or subsurface pipe drainage). Each treatment had three replicates, with 15$\times 10 mexperimentalplots(totalarea450m\hat{}\{2\}$ per plot). All treatments adopted the "one film, three pipes, six rows" cotton planting pattern using single-wing labyrinth thin-walled drip tape with a flow rate of 2.6 $L \cdot h^{-1}$ and emitter spacing of 30 cm.

All treatments received identical irrigation and fertilization regimes: total irrigation of 3600 $m^3 \cdot hm^{-2}$, nitrogen fertilizer of 225 $kg \cdot hm^{-2}$, and diammonium phosphate of 140 $kg \cdot hm^{-2}$. Mulched drip irrigation was applied with 7-10 day intervals: 1 irrigation during seedling stage (including seedling establishment), 2 during squaring stage, 8 during flowering-boll stage, and 1 during boll opening-maturity stage. Fertilizers were dissolved in water and applied through drip irrigation.

Each plot contained 6 subsurface pipes spaced at 15 m intervals with a designed slope of 3‰. Waterproof plastic was buried between different experimental plots to prevent mutual influence. The pipes were double-wall corrugated pipes with 80 mm diameter, 8 uniformly distributed holes in the same circumference, and wrapped with non-woven fabric to prevent soil particle entry. The cotton planting pattern is shown in [Figure 2: see original paper].

1.3 Measurement Methods 1.3.1 Soil Moisture Content

Soil moisture was measured during each growth period using the drying method. Soil samples were collected from cotton wide rows, narrow rows, and bare ground between films at 0-20 cm, 20-40 cm, and 40-60 cm depths using a soil auger. Samples were placed in aluminum boxes with three replicates per sampling point and dried at 105°C for 6-8 h to constant weight. Soil moisture content was calculated as:

$$w = \frac{m_1 - m_2}{m_2 - m_0} \times 100\%$$

where w is soil moisture content, m_1 is wet soil weight, m_2 is dry soil weight, and m_0 is aluminum box weight.

1.3.2 Soil Salinity Measurement

Soil salinity was measured using the electrical conductivity method. Before irrigation, soil samples were collected from wide rows, narrow rows, and bare ground at 0-20 cm, 20-40 cm, and 40-60 cm depths, dried, ground, and passed through a 1 mm sieve. A 1:5 soil-water mixture was prepared, shaken uniformly, left to stand for 5 min, then filtered. The supernatant EC value was measured using a DDSJ-318 conductivity meter. Irrigation water and subsurface drainage water were measured similarly. The relationship between EC ($S \cdot cm^{-1}$) and salt content S ($g \cdot kg^{-1}$) was established through field calibration:

$$S = 0.32 \times EC$$

1.3.3 Soil Organic Matter Measurement

Air-dried soil samples (5.00 g) from 0-20 cm, 20-40 cm, and 40-60 cm layers were placed in extraction bottles with 20 mL of pre-configured soil organic matter extractant, shaken thoroughly for 5 min, filtered, and measured using a TPY-7PC nutrient rapid tester.

1.3.4 Soil pH Measurement

Soil pH was measured by mixing soil samples with water at a 1:2.5 ratio, stirring for 20 minutes, then measuring immediately after stirring stopped using a pH meter.

1.3.5 Soil Permeability Coefficient

Soil permeability coefficient (K) was measured using the outdoor double-ring infiltration method:

$$K = \frac{QL}{F(H + Z + L)}$$

where Q is stable infiltration water volume ($m^3 \cdot min^{-1}$), F is infiltration area of inner ring (m^2), Z is water thickness in inner ring (m), H is capillary pressure (generally equal to half the soil capillary rise height, m), and L is water infiltration depth (determined by excavation after testing, m).

1.4 Data Processing Data were processed using Excel 2010, with statistical analysis performed using SPSS 20.0 and graphing using Origin 9.0.

2. Results

2.1 Effects of Different Integrated Irrigation-Drainage Modes on Soil Moisture Distribution [Figure 3: see original paper] shows that soil moisture distribution differed among treatments in the same soil layer, with moisture content varying from 6.01% to 23.54%. Throughout the cotton growth period, T1 treatment showed an increasing trend in soil moisture content, with more stable variation compared to T2 and T3. The T1 treatment maintained higher soil moisture than T2 and T3, with variation amplitudes of 6.32%, 10.03%, and 14.32% for T1, T2, and T3, respectively, in the same soil layer. This indicates that T1 treatment better maintained soil moisture stability. The water conservation effectiveness of different treatments was T1 > T2 > T3. The mulched drip irrigation combined with subsurface drainage improved soil salinity content and structure, increased liquid and gas distribution, changed soil physicochemical properties to reduce compaction, enhanced soil aeration, improved the three-phase ratio, and consequently increased soil water holding capacity during cotton growth, benefiting crop growth and yield improvement. Therefore, mulched drip irrigation combined with subsurface drainage has a greater promoting effect on soil water holding capacity than T2 and T3 treatments. The sudden increase in soil moisture content around September 20 was due to rainfall effects.

2.2 Effects of Different Integrated Irrigation-Drainage Modes on Soil Salt Leaching [Figure 4: see original paper] shows the variation trend of soil salt content at different depths under the same treatment. In the T1 treatment, soil salt content in the 20 cm, 40 cm, and 60 cm layers all decreased, with reductions of 63.06%, 60.62%, and 48.42%, respectively. The T2 treatment showed decreased salt content in the 20 cm and 40 cm layers but increased salt content in the 60 cm layer, indicating that surface desalination caused deep soil salt accumulation. In the T3 treatment, soil salt content in all layers showed an increasing trend due to reduced precipitation and strong evaporation in the late cotton growth period, causing deep soil salts to migrate upward with water and resulting in severe surface salt accumulation. Soil salt content in different layers under T1 treatment showed alternating changes before the squaring stage and similar trends after squaring. At the end of the cotton growth period, soil salt content in different layers was lower than the initial salt content, indicating an overall decreasing trend. This demonstrates that mulched drip irrigation combined with subsurface drainage technology can reduce soil salt content because "salt moves with water" —mulched drip irrigation infiltrates water while carrying salts into deep soil layers, and subsurface pipes remove salts while draining water. Comparing initial salt content with that at the end of the growth period revealed significant desalination in all layers under T1 treatment, indicating that under integrated irrigation-drainage mode, reducing surface soil salt content also reduces subsurface soil salt content, confirming the excellent desalination effect of this technology.

2.3 Effects of Different Integrated Irrigation-Drainage Modes on Soil Organic Matter Content at Different Depths [Figure 5: see original paper] illustrates the temporal variation of soil organic matter content at different depths under different integrated irrigation-drainage modes. Soil organic matter is a primary indicator of soil fertility. Analysis of T1 treatment data showed that soil organic matter content in different layers was mainly between 0–6 $g \cdot kg^{-1}$, indicating relatively low soil fertility. Overall, soil organic matter content under different integrated irrigation-drainage modes showed an initial increase followed by a decrease during the cotton growth period. At the end of the cotton growth period, soil organic matter content in the 20 cm, 40 cm, and 60 cm layers under T1 treatment increased by 39.76%, 14.49%, and 7.26%, respectively. This increase occurred because mulched drip irrigation combined with subsurface drainage improved soil permeability, creating conditions for microbial decomposition of plant residues and thereby increasing soil organic matter content. In contrast, T2 treatment showed increased organic matter content during the mid-growth period due to fertilization during the flowering-boll stage, but decreased organic matter content in the late growth period compared to the seedling stage because cotton continuously consumed soil organic matter in plots without subsurface pipes, where poor soil aeration and slow microbial activity could not timely decompose plant residues into organic matter.

2.4 Effects of Integrated Irrigation-Drainage on Soil Permeability Soil permeability coefficient is a primary physical parameter indicating soil permeability strength. [Figure 6: see original paper] shows the soil permeability coefficients of T1 treatment at seedling and boll opening-maturity stages. The results indicate that soil permeability decreased with increasing soil depth (20 cm > 40 cm > 60 cm), with significant differences among different layers. Soil permeability coefficients at the boll opening-maturity stage were greater than at the seedling stage, indicating improved permeability in the later period. The permeability coefficients in the 20 cm, 40 cm, and 60 cm layers increased by 42.87%, 89.30%, and 97.50%, respectively. Within the 0–60 cm depth range, soil permeability improvement was better with increasing depth. This demonstrates that mulched drip irrigation combined with subsurface drainage technology can effectively enhance soil permeability, benefiting crop growth and yield improvement.

2.5 Effects of Integrated Irrigation-Drainage on Subsurface Drainage Water Quality [Figure 7: see original paper] shows the pH and salt content of irrigation water and subsurface drainage water. The pH and salt content of subsurface drainage water were higher than those of irrigation water, with significant differences between them. The salt content of subsurface drainage water increased by 33.87%, 24.88%, and 54.59% on July 15, August 15, and September 15, respectively, indicating that subsurface pipes removed soil salts while draining water, helping reduce soil salt content and improve saline-alkali soils. This demonstrates that the mulched drip irrigation combined with subsurface drainage mode is a better choice for crop planting on saline-alkali land and can improve saline-alkali soils to a certain extent by effectively reducing soil salt content.

3. Discussion

Mulched drip irrigation is considered an irrigation method with small wetting range, no deep percolation, and frequent shallow irrigation, which cannot remove salts from soil layers into groundwater, leading to soil salt accumulation with long-term use. Combined with freshwater shortage and use of brackish water irrigation, salt content in soil layers is further exacerbated. To alleviate the impacts of water shortage and secondary salinization on agricultural production, numerous scholars have studied the effects of mulched drip irrigation combined with subsurface drainage on soil physicochemical properties, groundwater levels, and desalination effects under different conditions. Shi Peijun et al. found that subsurface pipe salt discharge accounted for 28.90% of soil salt content in the 0–80 cm layer. Liu Hongguang et al. reported that at 80 cm pipe depth and 0–200 cm sampling point, total soil salt decreased by 42.99% and root zone salt content decreased by 36.84%. In this study, mulched drip irrigation combined with subsurface drainage reduced soil salt content in the 20 cm, 40 cm, and 60 cm layers by 63.06%, 60.62%, and 48.42%, respectively, indicating that water infiltration under drip irrigation carries salts into deep soil layers, which are then removed by subsurface drainage.

Yang Yuhui et al. found that soil salt content at the end of the cotton growth period decreased by 16%-43% with subsurface pipe installation. Liu Yuguang et al. found that without subsurface pipes, surface desalination caused deep soil salt accumulation, and surface salt return occurred at the end of the growth period. This study found similar results: under T2 treatment, surface desalination caused deep soil salt accumulation, while T3 treatment showed surface salt return at the end of the growth period. At the end of the cotton growth period, soil organic matter content in the 20 cm, 40 cm, and 60 cm layers increased under T1 treatment, but decreased in T2 and T3 treatments without subsurface pipes. Soil permeability improved with increasing depth within 0-60 cm. The pH and salt content of subsurface drainage water were higher than those of irrigation water, indicating that subsurface drainage removed soil salts and reduced soil salt content, providing a theoretical basis for saline-alkali land improvement.

Tajiguli Dawut et al. found that the mineralization and electrical conductivity of subsurface drainage water were 2.77% and 4.20% higher than irrigation water, respectively, with significant differences, indicating that subsurface drainage removed soil salt ions and reduced soil salt content. Ai Tiancheng concluded that subsurface drainage effectively lowered groundwater levels and improved topsoil physical environment. This study found that soil permeability coefficients at the later growth stage improved compared to the seedling stage, with increases of 42.87%, 89.30%, and 97.50% in the 20 cm, 40 cm, and 60 cm layers, respectively, and that permeability improvement was better with increasing depth within 0-60 cm. The leaching effect of subsurface drainage is influenced by multiple factors including pipe diameter, spacing, and burial depth, and reasonable pipe installation parameters should be developed for different salinization degrees to achieve effective desalination.

4. Conclusions

This study investigated the effects of different integrated irrigation-drainage modes on soil moisture, salt content, permeability, and leaching efficiency through field experiments, yielding the following conclusions:

1) Under the same soil layer, the variation amplitudes of soil moisture content for T1, T2, and T3 treatments were 6.32%, 10.03%, and 14.32%, respectively. The T1 treatment better maintained soil moisture stability, and the water conservation effectiveness of different treatments was T1 > T2 > T3. This is because mulched drip irrigation combined with subsurface drainage technology can improve soil physicochemical properties and the solid-liquid-gas three-phase ratio, increasing soil aeration.

2) Mulched drip irrigation combined with subsurface drainage reduced soil salt content because "salt moves with water" —subsurface pipes removed salts while draining water. Soil salt content decreased in the 0-60 cm

layer, with reductions of 63.06%, 60.62%, and 48.42% in the 20 cm, 40 cm, and 60 cm layers, respectively. Under T2 treatment, soil salt content decreased in the 20 cm and 40 cm layers but increased in the 60 cm layer, indicating that surface desalination caused deep soil salt accumulation. The T3 treatment showed surface salt return at the end of the growth period.

3) At the end of the cotton growth period, soil organic matter content increased in the 20 cm, 40 cm, and 60 cm layers under T1 treatment, whereas it decreased in T2 and T3 treatments without subsurface pipes. Within the 0–60 cm depth range, soil permeability improved with increasing depth. The pH and salt content of subsurface drainage water were higher than those of irrigation water, indicating that subsurface drainage simultaneously removed soil salts, providing a theoretical foundation for saline-alkali land improvement.

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