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Article

Effects of Soil Texture on Soil Leaching and Cotton (*Gossypium hirsutum* L.) Growth under Combined Irrigation and Drainage

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Abstract: To further explore the effects of different soil textures on soil leaching and cotton (*Gossypium hirsutum* L.) growth using a combined irrigation and drainage technique and provide a theoretical basis for the improvement of saline alkali land in Xinjiang, we used a test pit experiment to test soil moisture, salinity, soil pH, permeability, cotton agronomic characteristics, cotton yield and quality, and water use efficiency in three soil textures (clay, loam, sand soil) under the combined irrigation and drainage (T1) and conventional drip irrigation (T2). We measured the soil moisture content in different soil layers of clay, loam and sandy soil under the T1 and T2 treatments. Clay and loam had better water retention than sandy soil, and the soil moisture under the combined irrigation and drainage treatment was slightly higher than that under conventional drip irrigation. Under T1, the average salt content and pH value in the 0–60 cm soil layer of clay, loam and sandy soil decreased by 14.09%, 14.21% and 12.35%, and 5.02%, 5.85% and 3.27%, respectively, compared with T2. Therefore, T2 reduced the salt content and pH value of shallow soil. Under T1 and T2, the relative permeability coefficient (K/K0) values in different soil textures at different growth stages of cotton were ranked as follows: sandy soil > loam > clay. Under T1, the K/K0 values for different soil textures at different growth stages of cotton were >1; therefore, T1 improved soil permeability. The yield and water use efficiency of seed cotton under T1 and T2 in different soil textures were ranked as follows: loam > clay > sand, and there were significant differences between the different treatments. In loam, the cotton yield and water use efficiency of the combined irrigation and drainage treatment were 6.37% and 13.70% higher than those for conventional drip irrigation treatment, respectively. By combining irrigation and drainage to adjust the soil moisture, salt, pH value and soil permeability of different soil textures, the root growth environment of crops can effectively be improved, which is of great significance to improving the utilization efficiency of water and fertilizer and promoting the growth of cotton.

Keywords: combined irrigation and drainage; soil texture; soil moisture; soil salinity; soil pH; permeability; cotton yield; WUE

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1. Introduction

Due to increasing requirements for agricultural development, a lack of resources and associated environmental problems has become increasingly prominent. China is a large agricultural country with a big population base and a shortage of resources. The scarcity of water resources and secondary salinization of soil have become important factors restricting agricultural development [1]. Xinjiang is located in an arid area of Northwest China and is the largest cotton (*Gossypium hirsutum* L.) growing area in China. Oasis farmland in Xinjiang is essential to the livelihoods of many members of the population and is critical to social and economic development in this part of the country [2]. The area experiences low levels of rainfall, high levels of evaporation and severe soil salinization. To alleviate water shortages and improve water use efficiency in Xinjiang, the area has aggressively been developing the use of drip irrigation under plastic film since 1996. The application of drip irrigation under plastic film improves the efficiency of water utilization. The application of drip irrigation technology has resulted in the reduction of field channel systems, which, coupled with the large-scale planting of crops and imperfect field drainage systems, have resulted in rising groundwater levels and the migration of soil salt in the water to the surface soil. However, due to a lack of field drainage infrastructure, the secondary salinization of oasis farmland (agriculture in arid and desert areas made possible through irrigation) has introduced new challenges. Over a third of the cultivated land in Xinjiang is endangered by different degrees of salinization and secondary salinization [3]. With the rapid development and increased use of drip–irrigation under film, secondary salinization of farmland has accelerated, therefore efforts to protect the soil and ecology of the area have been strengthened. Accordingly, projects to improve field water conservancy, field management, saline alkali soil, field drainage and salt discharge efficiency are being implemented so as to raise the yield and quality of crops and ensure the sustainable development of agriculture in the area.

Soil is an important part of the agricultural ecological environment. Protecting soils and improving the ecological structure of the area guarantees the sustainable development of oasis agriculture [4]. Texture is a physical property of soil and refers to the different sizes of the mineral particles [5]; it is an important index that reflects the potential productivity of the soil. Soil texture is significantly related to soil moisture, nutrient content, pH, salt content and aeration as well as farming difficulty [6]. The measures of aeration, fertility and thermal characteristics of soils with different textures vary greatly [7]. The moisture content, temperature, pH and salt distribution in different textures of soil affect the physiological indexes of crop growth, including the retention capacity for water and fertilizer and the water use efficiency [8]. Previous reports have described the effects of different soil textures on soil leaching and crop growth. For example, Li Chaohai et al. [9] investigated the biological activity of rhizospheres in different soil textures and concluded that the biological activity in the maize rhizosphere is affected by the growth of the crop and the soil texture. Coarse textured soils led to the least amount of available water and an increased soil drought index [10]. Moreover, soil pH affects the forms, availability, migration and transformation of various elements in soil [11]. In studying the effect of texture on soil physical properties, previous researchers concluded that when the sand content of soil is 30–70%, the addition of organic matter can significantly improve the soil water holding capacity [12]. There is a good quantitative relationship between the thermal properties of soils with different textures and soil water suction [13]. Previous studies on the effects of soil texture on cotton growth and yield have been carried out on crops grown using a traditional drip irrigation under film method. Luo Xinning et al. [14] studied the dynamics of cotton nutrient accumulation and fertilizer utilization efficiency in sandy and heavy loam, while the effects of different soil textures on cotton yield and boll distribution were also studied. It was concluded that the boll setting capacity in loam soil was greater than that in clay or sandy soil [15]. Salt transport when using drip irrigation under film in cotton fields was also studied with respect to different soil textures. It was subsequently pointed out that flood irrigation should be carried out regularly and alkali drainage channels should be restored [2]. In recent years, many scholars have recognized the importance of field drainage [16,17]. Research shows that the construction of drainage channels, including shaft drainage and concealed pipe drainage, can improve the drainage efficiency of farmland and have significant effects on inhibiting soil salinity and promoting crop growth [18–20]. When using concealed pipe drainage, the soil salt status changes from "high salt heterogeneity" to "low salt homogeneity", which effectively reduces the amount of soil salt ions [21]. Li Xianwei previously carried out a numerical simulation and analysis of combining drip irrigation under plastic film and salt drainage through concealed pipes and was able to simulate the movement of water and salt during the process of salt drainage [22]. The coordinated regulation of flood irrigation, leaching and concealed pipe drainage has achieved remarkable results in improving saline alkali soil. Reasonable irrigation and concealed pipe layout spacing can improve leaching efficiency [23]. However, there have been few studies on the effects of soil texture on soil leaching and cotton growth when irrigation and drainage are linked.

Irrigation is very important to the sustainable development of agriculture in Xinjiang, but the construction and development of field drainage projects and advances in drainage and salt removal efficiency also play very important roles in improving the farmland soil environment and crop growth [24]. With the increase in the area of farmland under plastic film undergoing drip irrigation and the acceleration of farmland secondary salinization, it is important to explore the water and salt distribution in different textures of soil and crop growth responses under combined irrigation and drainage in order to popularize and apply this technology. It is critical to explore the impact of drip irrigation under plastic film combined with concealed pipe drainage on soil leaching and cotton growth in soils with different textures. However, there are few previous studies on the effects of combined irrigation and drainage in different soil textures on soil leaching and crop growth. The purpose of this study was to determine the effects of different soil textures on soil leaching and cotton growth under combined irrigation and drainage so as to provide new ideas for promoting agricultural water saving and improving saline alkali land. Our research group hypothesized that combined irrigation and drainage technology can improve the growth environment for cotton roots, reduce soil salt and improve cotton yield and quality compared with traditional drip irrigation under plastic film. Therefore, it is essential to study the effects of different soil textures on soil leaching and cotton growth using combined irrigation and drainage technology to provide information about the application of this method in soils with different soil textures.

2. Materials and Methods

2.1. Experimental Site

The experiment was conducted at the Key Laboratory of Modern Water-Saving Irrigation of the Xinjiang Production and Construction Corps (85°59′ E, 44°19′ N, altitude 412 m) from April to November 2018 at Shihezi University in Xinjiang, China (Figure 1). The region experiences a typical arid continental climate, with an average annual rainfall of 210 mm, an average annual evaporation of 1600 mm, air temperature of 7.2 °C, sunshine duration of 2865 h and frost-free period lasting 171 days [25]. The active accumulated temperature above 10 °C and 15 °C were 3463 °C and 2960 °C, respectively. Changes in precipitation, reference crop evapotranspiration (ET_0, the ET_0 is calculated by Penman-Monteith [26]) and maximum atmospheric temperature in the cotton-growing season (from April to November) in 2018 is presented in Figure 2. A total of 153.8 mm of rain fell during the cotton-growing season. Air temperature, precipitation, wind speed, humidity and other meteorological data were recorded by an automatic weather station (TRM-ZS2 type, Jinzhou Sunshine Meteorological Technology Co., Ltd., Jinzhou, China). The weather station was set up at our experiment site.

The experimental area comprised 0.0216 ha. The regional ground-water table remained at a depth of 8 m. The cotton cultivar 'Nong feng 133' was used, which is suitable for dense planting, good ventilation, light transmission among populations, early maturity and high yield. This cultivar is also suitable for machine planting and harvesting. The soil particle composition and physical indexes (e.g., dry bulk density and nutrient content) of the 0–100 cm soil layers in the test area are shown in Table 1.

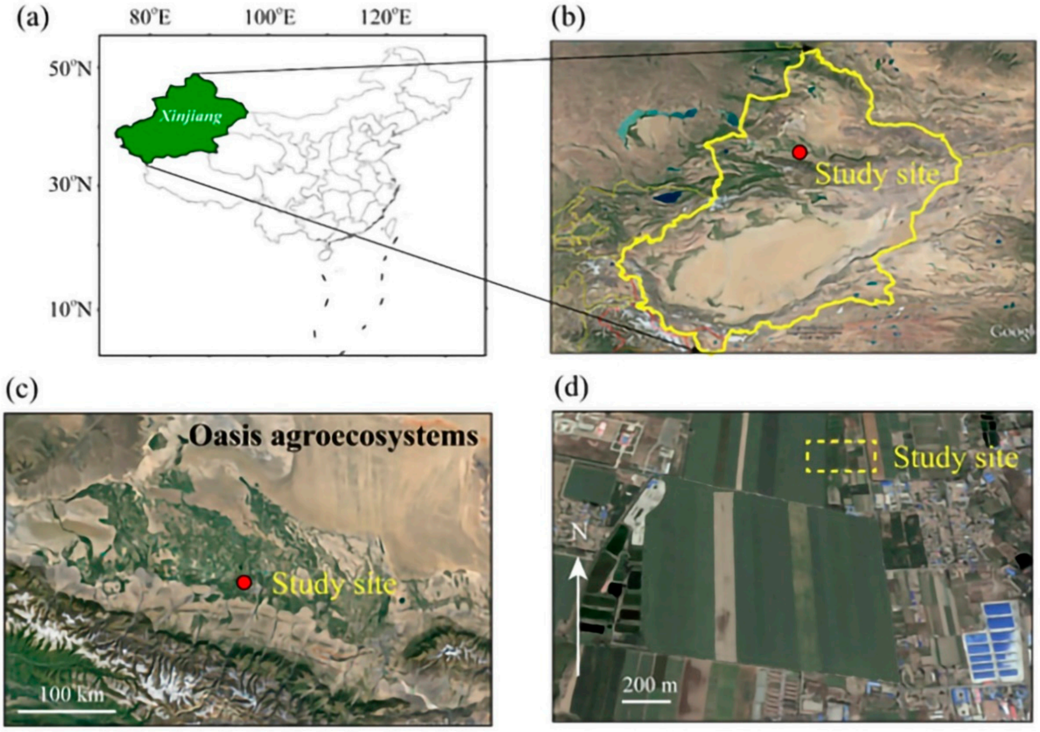

Figure 1. Maps and imagery of the study site. Xinjiang is located in the northwest of China (**a**) and is characterized by an extremely arid desert climate (**b**). Large agricultural irrigation demand is required for the oasis agroecosystems in Xinjiang (**c**). Field experiments were conducted at the Key Laboratory of Modern Water Saving Irrigation of the Xinjiang Production and Construction Corps (85°59′47″ E, 44°19′29″ N) in Shihezi City, Xinjiang (**d**).

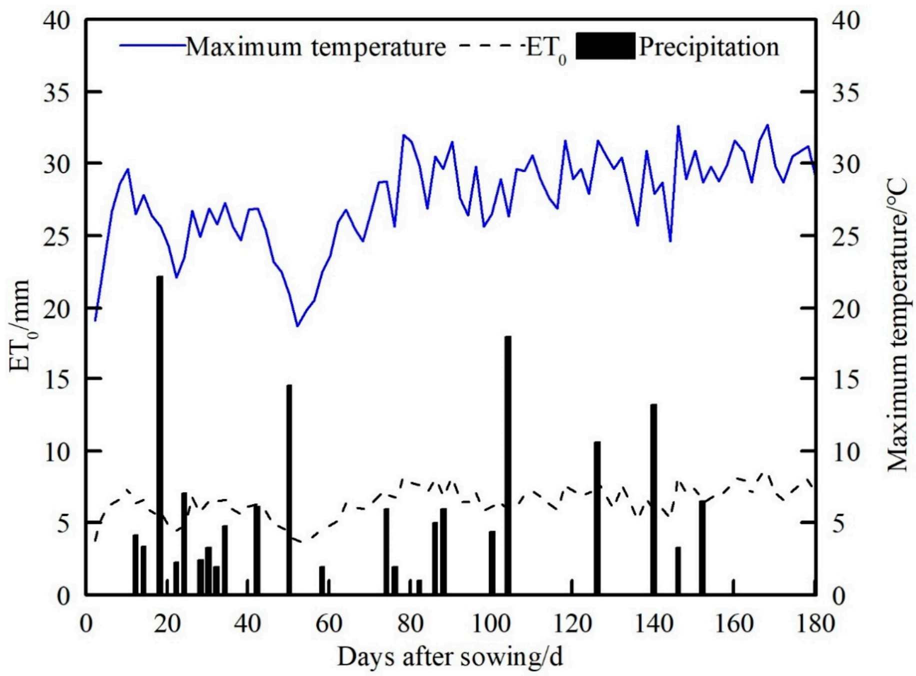

Figure 2. T-max (the maximum air temperature, indicated by the curves), daily precipitation (indicated by the bars) and ET_0 (reference crop evapotranspiration, indicated by the dashed curve) during the cotton growing season at the experimental site in 2018.

Table 1. Composition and physical indexes of soil particles in the experimental area.

Soil Texture	Soil Particle Composition/%			Total Nitrogen (g/kg)	Available Nitrogen (mg/kg)	Available Phosphorus (mg/kg)	Available Potassium (mg/kg)	Organic Matter (g/kg)	Average Bulk Density of 0–100 cm Soil
	<0.002 mm	0.002–0.02 mm	0.02–2 mm						
Clay	28	40	32	0.78	100.43	9.15	188.70	10.45	1.35
Loam	12	43	45	0.56	77.45	16.45	417.50	9.55	1.55
Sand	9	14	77	0.34	59.56	8.42	102	4.52	1.72

2.2. Experimental Design

A split-plot experimental design was adopted, whereby the plots did or did not contain concealed pipe drainage. The main plots included T1 (cotton grown under drip irrigation under plastic film combined with concealed pipe drainage) and T2 (cotton grown under conventional drip irrigation under plastic film). Soils with different textures were applied to the subplots, including clay, loam and sandy soil. Each subplot was about 12 m^2 (3 m × 4 m), and three replications were conducted in each subplot, with a total of 18 plots. The cotton planting model with one film, three drip tapes and six rows (Figure 3) was adopted for each subplot. We used a machine-harvested cotton planting pattern (10-cm plant distance, 66 cm + 10 cm of wide-narrow rows, and a planting density of 260,000 plants ha^{-1}), and a total of 312 plants were included in each plot. The soil particle composition and physical indexes in the test areas are shown in Table 1.

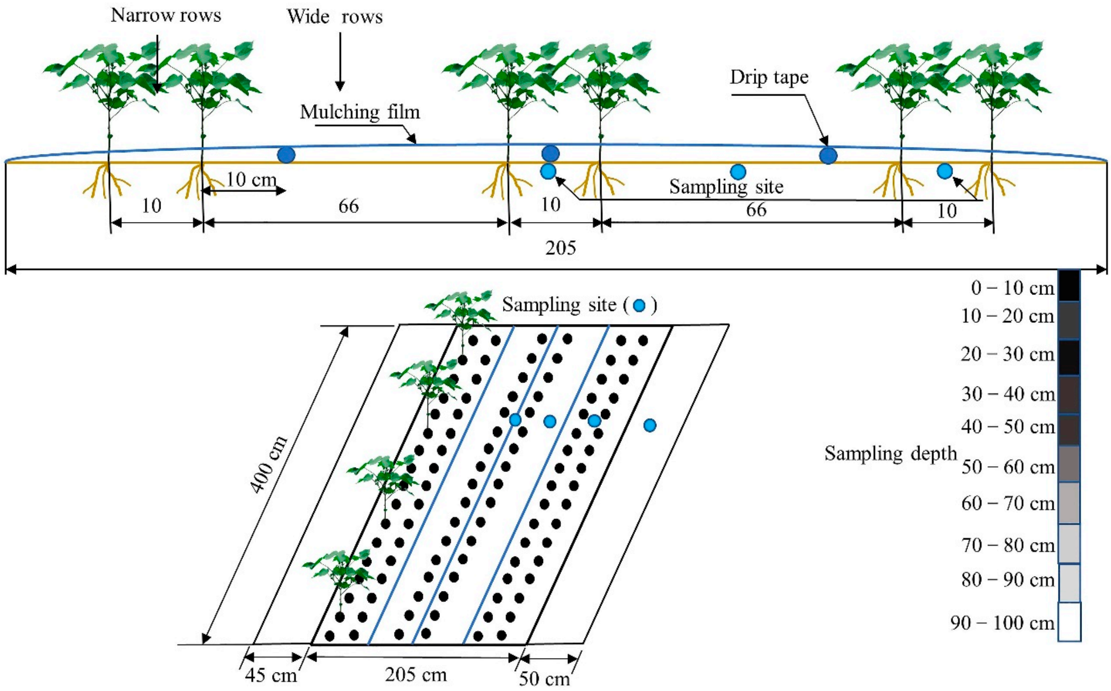

Figure 3. Schematic diagram of cotton planting pattern (unit: cm).

The cotton was sown using the "dry sowing and wet out" method (the water storage and salt drainage technology for drip irrigation under plastic film). The cotton was planted on 22 April 2018. During the growth period, the drip irrigation method under the film was used to provide the necessary water and nutrients for cotton growth. The drip irrigation capillary was a single-wing labyrinth thin-walled drip tape. The emitter flow rate was 2.6 L h^{-1}. The distance between the drippers was 30 cm, and the thickness of the plastic film was (0.008 ± 0.0003) mm. The water supply system in the study area was pressurized mainly by a water pump, and the pressure gauge and regulating valve were installed at the head of the system. The amount of irrigation, irrigation dates and frequencies, and fertigation frequencies for the T1 and T2 treatments were the same throughout the experiment. The cotton was irrigated 13 times during the whole growth period. In total, 450 mm of irrigation were applied; N fertilizer was applied at 225 kg ha^{-1} and P fertilizer at 140 kg ha^{-1} during the whole growth period. Irrigation was carried out by drip irrigation under the mulch. The irrigation interval was 7–10 days: four times during the seedling stage, four times during the flowering period, three times during the bolling period and twice during the mature stage. The fertilizer was dissolved in the water used for irrigation. The details of irrigation and fertilization management during the cotton growth period are shown in Table 2. For each subplot under the T1 treatment, two concealed pipes were buried in each test pit. The concealed pipes were buried in the middle of the wide row of cotton, with a spacing of 1 m, and buried at a depth of 60 cm at a pre-designed slope of 2 %. PVC double walled corrugated pipe 100 mm in diameter was used for the drainage pipe, and eight water inlets were evenly distributed around its circumference. The buried concealed pipe was wrapped with non-woven fabric to prevent soil particles from entering it. The cotton planting mode is shown in Figure 3.

Table 2. Irrigation schedule during the cotton growing season in 2018.

Growth Stage *	Irrigation Date	Irrigation Quota (mm)
Seedling	24 April 2018	20
	9 June 2018	25
	16 June 2018	25
	23 June 2018	25
Flowering	1 July 2018	50
	9 July 2018	50
	16 July 2018	50
	23 July 2018	50
Bolling	30 July 2018	35
	6 August 2018	35
	13 August 2018	35
Maturity	20 August 2018	25
	27 August 2018	25
Total irrigation amount (mm)		450

* Seedling stage indicates the period from emergence to budding of cotton; flowering indicates the beginning of flowering; bolling indicates boll development; and maturity indicates that over 90% of bolls are open. Definitions of cotton phonological stages are from Munger et al. [27].

2.3. Sampling and Field Measurements

2.3.1. Soil Water Content

The soil moisture was measured to a depth of 100 cm at 10 cm intervals during different cotton growth periods. The sampling points were located between the wide and narrow rows of cotton and the bare ground outside the film (Figure 3). Soil was removed directly through the film by drilling a hole, and the hole was backfilled with fine soil. Soil samples were collected using a stainless-steel ring knife (100 cm^3). Three replicate soil samples were taken at each depth. These soil samples were oven-dried to a constant weight to calculate the gravimetric soil moisture. The volumetric soil moisture content was calculated based on the measured gravimetric soil moisture and soil bulk density. Soil water storage was calculated to a depth of 0–100 cm.

2.3.2. Soil Salinity

Soil samples were collected from the wide and narrow rows of cotton under plastic film at different stages of plant growth. To measure soil salinity, the oven-dried soil samples were pulverized and passed through a 1 mm sieve. Then, 20 g of soil powder were taken from each sample and mixed at a ratio of 1:5 with water. After being evenly shaken, the mixture was set aside for 2 h. The electrical conductivities ($EC_{1:5}$) of the mixtures were measured using a portable electrical conductivity meter (DDS11-A, manufactured by

Shanghai Leichi, China). The absolute change (ΔS) and relative change (R) in soil salinity were calculated as:

$$\Delta S = EC_{1:5}{}' - EC_{1:5} \quad (1)$$

$$R = \frac{\Delta S}{EC_{1:5}} \times 100\% \quad (2)$$

where $EC_{1:5}$ and $EC_{1:5}{}'$ (ds m^{-1}) represent soil salinity before sowing and after harvest, respectively.

2.3.3. Soil Permeability Coefficient

The outdoor double ring infiltration method was used to determine the soil permeability coefficient. The K was calculated as:

$$\text{K (soil permeability coefficient)} = \text{QL/F (H + Z + L)} \quad (3)$$

where Q represents the stable infiltration water volume (cm^3/min), F represents the water seepage area of the inner ring of the test pit (cm^2), Z represents the water thickness in the inner ring of the test pit (cm), H represents the capillary pressure (generally equal to half of the capillary rise in the soil) (cm), L represents the penetration depth of water (determined by excavation after test) (cm).

The dimensionless parameter relative permeability coefficient was used to characterize the change in soil permeability. The relative permeability coefficient is the ratio of the measured (0~100 cm) average permeability coefficient K and the initial average permeability coefficient K0 of different soil textures treated with T1 and T2. The relative permeability coefficient was used to reflect the change in the soil permeability coefficient. When K/K0 is greater than 1, the soil permeability coefficient increases, while a smaller K/K0 indicates a decrease in permeability.

2.3.4. Soil pH

To measure soil pH, the oven-dried soil samples were pulverized and passed through a 1 mm sieve. Then, 20 g of soil powder were taken from each sample and mixed at a ratio of 1:1 with water. The mixture was stirred three times at intervals of about 1 h. After stirring, the pH of the mixtures was measured using a pH meter.

2.3.5. Aboveground Dry Matter, Cotton Plant Stem, Plant Height, and Leaf Area

Five cotton plants from each test pit were selected at the cotton seedling stage (25 May), bud stage (25 June), flower and boll stage (25 July) and boll opening stage (1 September). The plant samples were dried to a constant weight to measure the biomass. Moreover, the date the plants entered each phenological stage (e.g., emergence, squaring, flowering, boll opening, and maturity) was recorded for all plots. The definition of each phenological stage was adopted from Munger et al. [27]. Five representative cotton plants were selected from each plot at the emergence stage. The plant height, leaf length, and leaf width were measured every 10–15 days from the beginning of the emergence stage using a tape measure with an accuracy of 1 mm. The leaf area was measured using an empirical coefficient formula (0.75 × leaf length × leaf width) [28] and a handheld leaf area tester (Yaxin-1241 type, Beijing Yaxin Liyi Technology Co., Ltd., Beijing, China). Then, the average value was used for analysis.

2.3.6. Cotton Yield and Water Use Efficiency

Cotton yield was determined by hand harvesting in the crop following each treatment and calculating the yield per unit area (kg ha^{-1}). The water use efficiency (*WUE*, kg ha^{-1} mm^{-1}) was calculated as the ratio between the annual cotton yield (Y) and evapotranspiration (*ET*) over the growing season in each year [29]. Given the limited influence of groundwater on soil water and the lack of surface runoff at the experimental site, the ET could be calculated as:

$$ET = P_0 + I - D + \Delta SWS \quad (4)$$

$$WUE = \frac{Y}{ET} \quad (5)$$

where, P_0 represents rainfall, I represents irrigation, D represents deep percolation (the amount of concealed pipe drainage) and ΔSWS represents the difference in soil water storage in the 0–100 cm depth of soil between sowing and harvest. Y is the annual cotton yield (kg ha^{-1}).

2.3.7. Cotton Fiber Quality

Representative points within an area of 4 m^2 were selected in each test pit prior to harvesting to determine the boll weight and lint percentage. A sub-sample of lint was sent to the Supervision, Inspection and Test Center of Cotton Quality, Ministry of Agriculture and Rural Affairs, Anyang City, Henan Province, China to examine the fiber quality using a high-volume instrument (HVI) [30].

2.4. Statistics and Analysis

The experimental data were graphed and processed using SPSS 20.0 and Origin 9.0. The SAS package (SAS Institute Inc., Cary, NC, USA) was used to conduct the analysis of variance (ANOVA). Differences were considered statistically significant when $p \leq 0.05$.

3. Results

3.1. Soil Water Content

The changes in the moisture content of different soil layers under the T1 and T2 treatments were measured after irrigation at the flowering and bolling stage (15 July) (Figure 4). Under T1 and T2 treatments, the soil moisture levels in clay and loam in different layers were significantly higher than those in sandy soil, and clay and loam showed better water retention than sandy soil. Compared with clay, the distribution of water within various layers loam and sandy soil changed regularly. Under combined irrigation and drainage (T1), the soil moisture content of the 0–40 cm soil layer in loam and sandy soil decreased gradually, that of the 40–60 cm layer increased, while that of the 60–100 cm layer showed little change. Under the conventional drip irrigation under plastic film treatment (T2), the soil moisture content of the 0–60 cm soil layer in loam and sandy soil decreased gradually, while that of the 60~100 cm soil layer increased gradually. In the T1 and T2 treatments, the soil moisture content of each layer in clay exhibited fluctuating changes.

Under the T1 and T2 treatments, the average water content of clay, loam and sandy soil was 15.97%, 15.36% and 6.41%, and 15.75%, 14.74% and 6.13%, respectively, in the 0–60 cm soil layer, and 16.45%, 16.04% and 5.89%, and 16.06%, 15.91% and 5.67%, respectively, in the 0–100 cm soil layer. Under the same treatment, the soil moisture content of the 0–60 cm layer and 0–100 cm layer in clay was the highest. The soil moisture content of the 0–60 cm layer and 0–100 cm layer in loam was slightly lower than that in clay, but the water distribution in loam was more conducive to cotton root absorption. The soil water content of the same soil textures for T1 was slightly higher than that for T2. The average moisture in the 0–60 cm layer of clay, loam and sandy soil under T2 was 92.37%, 97.96% and 95.63% of that in T1, respectively.

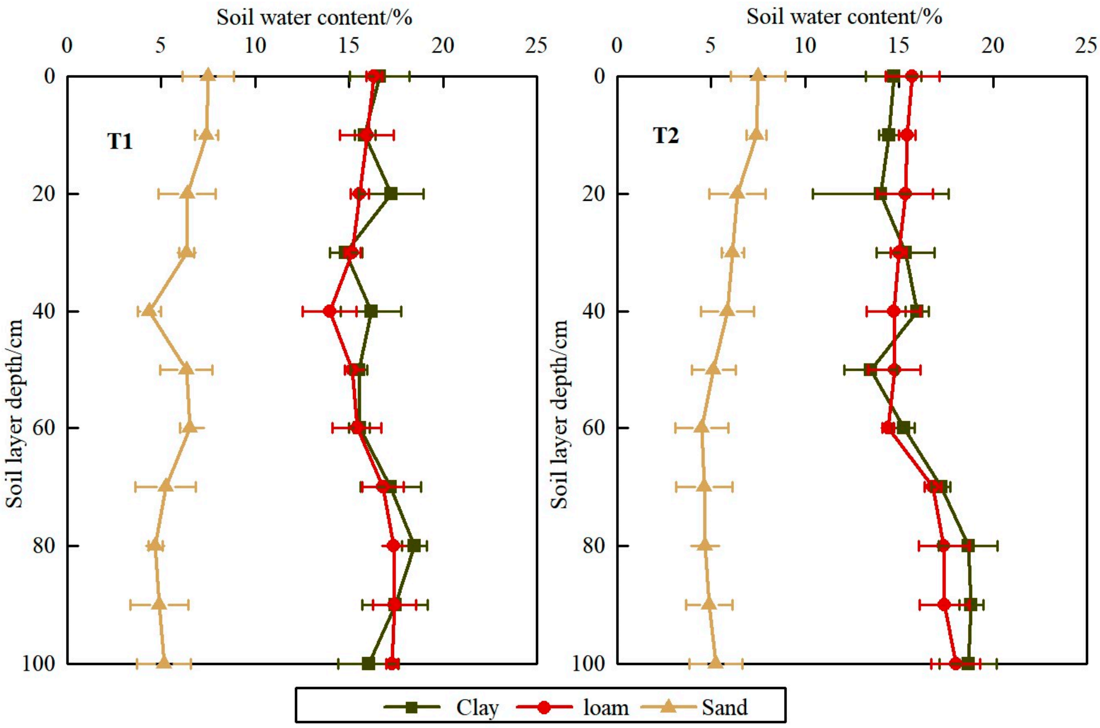

Figure 4. Distribution of moisture in three soil textures at different depths.

3.2. Soil Salinity

Under plastic film drip irrigation combined with concealed pipe drainage (T1), the salt content of the loam and sandy soil in the 0–60 cm soil layer showed a gradually decreasing trend, and the salt content of clay in the 0–60 cm layer also showed a decreasing trend except at 40 cm. The salt content in the 60–100 cm soil layer of different soil textures showed a gradual increase with depth (Figure 5). The T1 treatment was shown to reduce the salt content of shallow soils with different textures. The salt content in the 0–60 cm layer of loam under the T2 treatment gradually increased, while that in the 60–100 cm layer gradually decreased; the salt migrated to the layer of soil at 60 cm with water. The salt content in the 0–60 cm layer of the sandy soil decreased, while that in the 60–100 cm layer increased gradually with depth. Due to the dense structure of clay and a high content of small particles, it retained water well and irrigation water infiltrated slowly. Moreover, with water absorption, clay particles expanded during dripping irrigation, which hindered capillary water movement. There was a significant capillary effect between clay particles and slow permeability, so the distribution of the soil salt content in different soil layers fluctuated and had no obvious structure.

Following analyses of the 0–60 cm layer of soils with different textures under the T1 and T2 treatments, the average salt contents in clay, loam and sandy soil were 1.89 and 1.63 ds/m, 1.42 and 2.20 ds/m, and 1.90 and 1.62 ds/m, respectively. Compared with the T2 experiment, the average salt contents in 0–60 cm soil layer of clay, loam and sandy soil treated with T1 decreased by 14.09%, 14.21% and 12.35%, respectively. The cotton roots were mainly distributed in the 0–60 cm soil layer and we found that the linked irrigation and drainage treatment significantly reduced the salt content of the shallow soil.

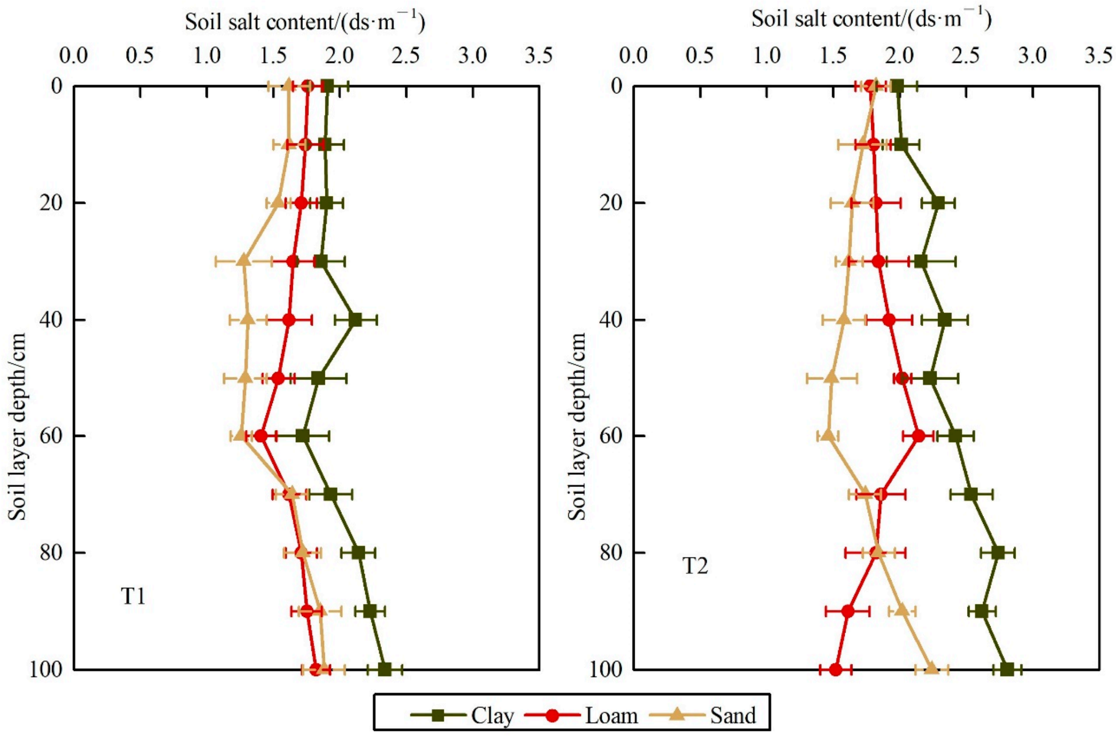

Figure 5. Distribution of salt in various layers of soil under two different treatments.

3.3. Soil Permeability Coefficient

The soil permeability coefficient is one of the main physical parameters used to determine soil permeability. Figure 6 shows the change in the relative permeability coefficient (K/K0) with cotton growth. A K/K0 value > 1 indicates that the soil permeability coefficient has increased. The smaller the K/K0 value, the greater the decrease in permeability. Under T1 and T2 treatments, the K/K0 values of different soil textures at different cotton growth stages were ranked as follows: sandy soil > loam > clay. The relative permeability coefficient of loam and sandy soil increased first and then decreased with the cotton growth stage. The maximum value was obtained at the flowering and bolling stage. The relative permeability coefficient of clay increased slightly, but the increment was lower than that in loam and sandy soil (Figure 6). The K/K0 values of different soil textures at different cotton growth stages under T1 were > 1, indicating that linked irrigation and drainage improved soil permeability.

Compared with the initial permeability coefficient, the relative permeability coefficients of clay, loam and sand under T1 increased by 1.12, 1.40 and 1.52, and 1.08, 1.32 and 1.41 times, at the bolling and maturity stages, respectively. Overall, the permeability coefficients of soils with different textures were higher than the initial values. Under T2, the K/K0 values of different soil textures at cotton seedling stage, bud stage and boll stage were >1, and the K/K0 values at the mature stage were <1, indicating that the soil permeability coefficient at the mature stage was lower than the initial permeability coefficient. Under T2, the permeability coefficients of clay, loam and sandy soil at bolling stage increased to 1.06, 1.14 and 1.21 times those of the initial permeability coefficients, respectively, and the permeability coefficients of clay, loam and sandy soil decreased to 0.88, 0.94 and 0.96 times those of the initial permeability coefficients at the mature stage, respectively. Compared with those seen under T2, the relative permeability coefficients of clay, loam and sandy soil under T1 at the bolling and mature stages increased by 5.66%, 22.81% and 25.62%, and 22.73%, 40.43% and 58.33%, respectively. Overall, the drip irrigation under plastic film technique combined with concealed pipe drainage technology (T1) effectively improved soil permeability and the cotton root soil environment.

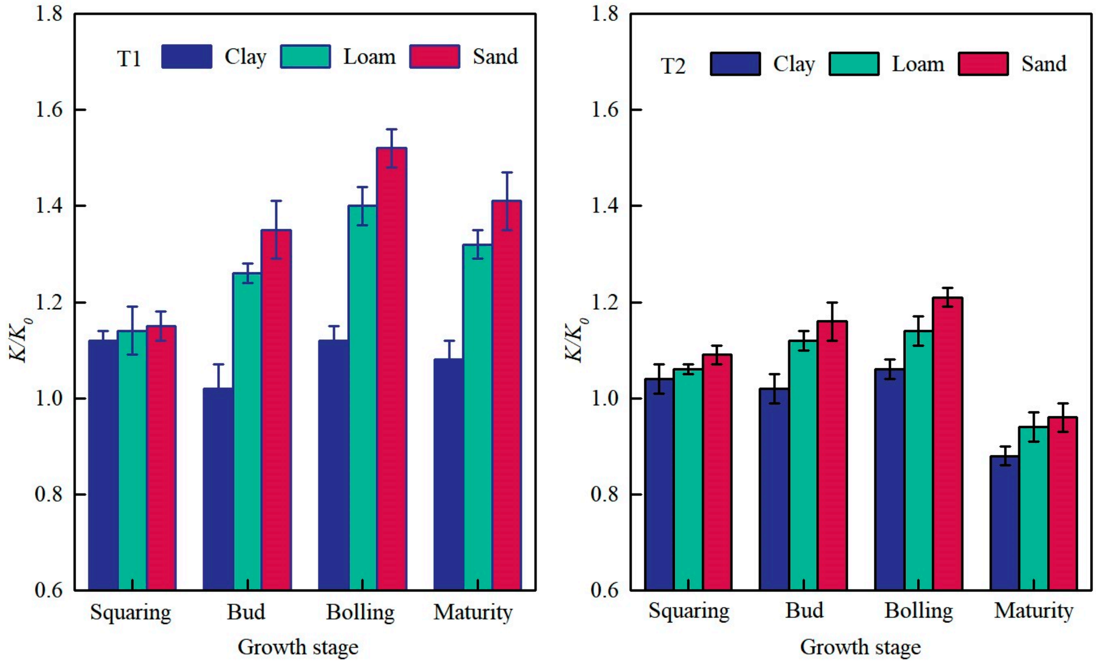

Figure 6. Changes in soil permeability at different growth stages of cotton under T1 and T2 treatments.

3.4. Soil pH

Under the T1 and T2 treatments, the pH values measured in the same soil layer of different soil textures were ranked as follows: clay > loam > sandy soil (Figure 7). The pH of the 0–60 cm layer in loam and sandy soil under T1 decreased gradually, while the pH value of the 60–100 cm layer increased. The combined irrigation and drainage treatment thus reduced the pH value of shallow soil. The soil pH value of the 0–60 cm layer in clay fluctuated without an obvious structure, and the soil pH value of the 60–100 cm layer increased gradually. Under T2, the pH value of the 0–60 cm layer in loam gradually increased, while that in the 60–100 cm layer gradually decreased. The change of soil pH value was consistent with the change in soil moisture. The pH value of the 0–60 cm layer in sandy soil gradually decreased, while the pH value of the 60–100 cm layer gradually increased with depth.

The average pH values for clay, loam and sandy soil in the 0–60 cm layer under T1 and T2 were 8.33, 8.05 and 7.99, and 8.77, 8.55 and 8.26, respectively. The average pH in the 0–60 cm layer of the clay, loam and sandy soil under T1 decreased by 5.02%, 5.85% and 3.27%, respectively, compared with the T2 treatment. Cotton roots were mainly distributed in 0–60 cm soil layer, and the linked irrigation and drainage treatment reduced the pH of the shallow soil and effectively improved the root growth environment for cotton, which will be of great significance to cotton growth and yield improvement.

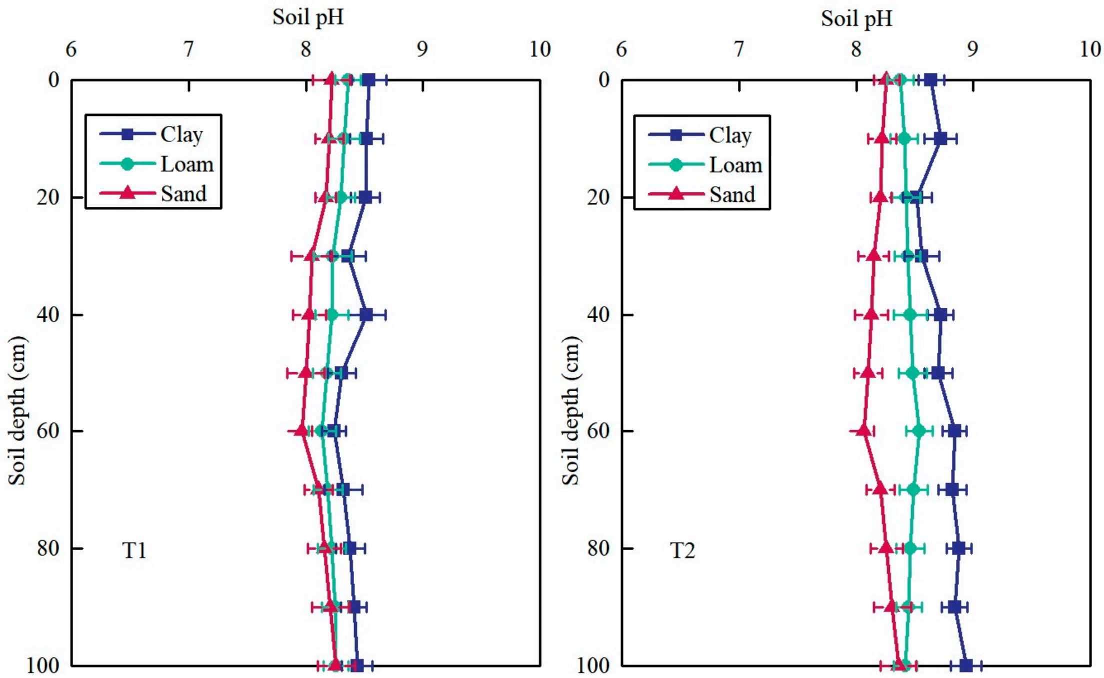

Figure 7. Soil pH values in various layers of soil with different textures.

3.5. Growth Characteristics and Quality of Cotton

The cotton growth indexes at the flowering and boll stage (25 July) and cotton quality at the mature stage (25 September) under T1 and T2 are shown in Table 3. The plant height, stem diameter, leaf area index and dry matter mass of cotton grown in soils of different texture under T1 and T2 were ranked as follows: loam > clay > sandy soil; the differences in these values seen between the soil textures under the same treatment were significant. Among the different treatments on soil with the same texture, the growth index of cotton in loam and clay under T1 was significantly higher than that under T2, but there was no significant difference in the cotton growth index in sandy soil. The plant height, stem diameter, leaf area index and dry matter mass of cotton treated with T2 in loamy soil were 97.26%, 95.16%, 89.47% and 98.74% of those in T1, respectively.

Table 3. Analysis of the agronomic characters of growth and quality in cotton using different soil textures under T1 and T2.

		Cotton Growth Characteristics				Cotton Quality					
	Soil Texture	Plant Height (cm)	Plant Stem (mm)	Leaf Area Index	Dry Matter (g)	Upper Half Mean Length (m)	Length Uniformity Index (%)	Micro-Naire	Breaking Strength (Cn/ Tex)	Elongation (%)	Lint (%)
T1	Clay	69.3 b	10.9 b	3.2 b	69.8 b	27.9 c	84.4 b	4.8 c	26.5 c	6.8 a	40.4 a
	Loam	72.9 a	12.4 a	3.8 a	71.6 a	33.1 a	88.8 a	5.3 a	32.6 a	7.2 a	41.8 a
	Sand	54.2 d	9.4 d	2.3 d	61.4 d	28.4 d	75.5 c	3.9 d	21.2 d	5.9 b	36.8 b
T2	Clay	64.1 c	10.5 c	2.8 c	68.7 c	28.4 c	83.3 b	4.7 c	25.3 c	6.7 a	39.4 a
	Loam	70.9 b	11.8 b	3.4 b	70.7 b	32.2 b	87.3 a	5.0 b	30.1 b	7.0 a	41.5 a
	Sand	53.6 d	8.6 d	2.1 d	54.4 d	28.5 d	72.7 c	3.7 d	20.4 d	5.6 b	36.3 b

Note: the lower case letters within columns indicate significant differences at the 0.05 level.

Except for elongation and lint percentage, the other indexes of cotton quality under T1 and T2 with different soil textures were ranked as follows: loam > clay > sandy soil. There was no significant difference between loam and clay in elongation and lint percentage, but both values were significantly larger than those in sandy soil. The cotton quality under T1 and T2 using the same soil texture showed no significant difference between clay and sandy soil, but the values for the average length of the upper half, micronaire value and fracture-specific strength under T1 in loamy soil were higher by 2.80%, 6.00% and 8.31%, respectively, than those under T2. In general, the combination of irrigation and drainage greatly impacted the growth and quality of cotton in the loam and clay soil. Compared with clay and sandy soil, the growth and quality of cotton in loam was higher, indicating that soil texture has an important impact on the growth of this crop.

3.6. Cotton Yield and Water Use Efficiency

The yields of seed cotton under T1 and T2 in different soil textures showed that loam > clay > sandy soil, and there were significant differences among the different soil textures (Figure 8). Under T1 and T2, the yield of seed cotton in clay and sandy soil was 87.50% and 80.97%, and 92.25% and 84.49%, of that in loam, respectively. Moreover, using the same soil texture, the yield of seed cotton in loam under T1 was 6.37% higher than that under T2, and this difference was significant. There was no significant difference in the cotton yield between T1 and T2 in clay and sandy soil.

The water use efficiency of different soil textures under T1 and T2 was ranked as follows: loam > clay > sand soil, and there were significant differences between different soil textures (Figure 8). Under T1 and T2, the water use efficiency of the clay and sandy soil was 79.57% and 67.44%, and 87.42% and 74.24%, of that in loam, respectively. The water use efficiency under T1 in loam was significantly (13.70%) higher than that under T2. There was no significant difference, however, in the water use efficiency of clay and sand between T1 and T2. Cotton yield and water use efficiency under T1 and T2 in soils of different texture were ranked as follows: loam > clay > sandy soil. In all, linking irrigation and drainage had a significant impact on cotton yield and water use efficiency. The drip irrigation under plastic film technique combined with concealed pipe drainage technology was able to improve soil water, nutrient and gas conditions, with consequent increases in cotton growth.

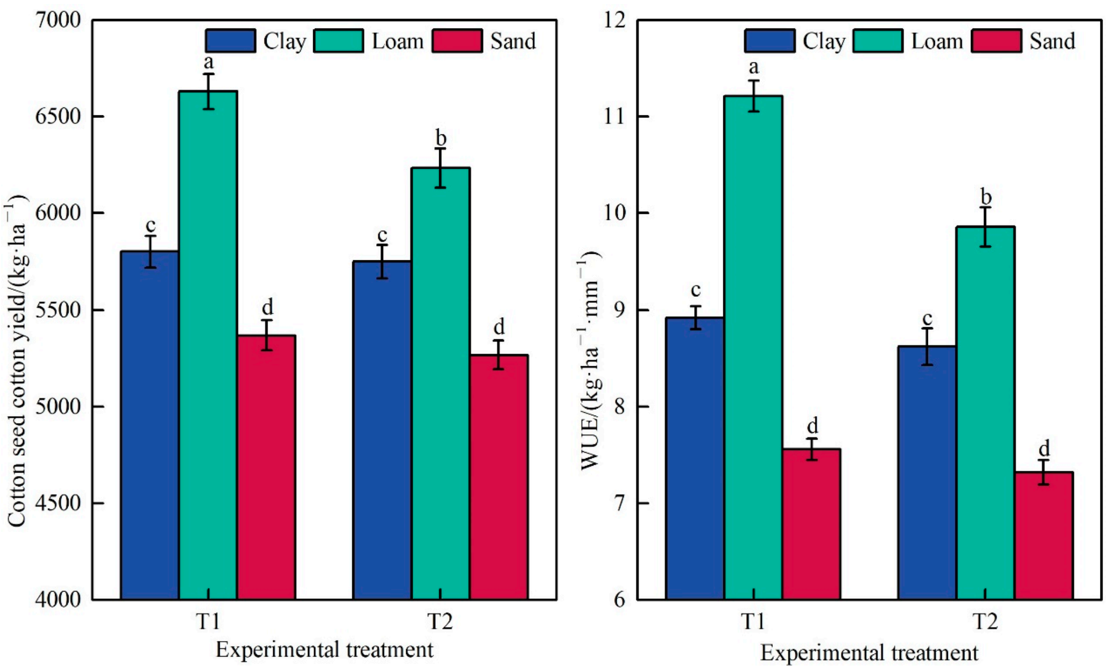

Figure 8. Effects of T1 and T2 treatments on cotton seed cotton yield and water use efficiency. Note: Different superscript letters (a, b, c and d) indicate significant differences between treatments in a year ($p \leq 0.05$).

4. Discussion

Combined irrigation and drainage treatment in different soil textures had an obvious impact on the soil environment. As the main area for crop root growth and nutrient absorption, changes in soil water, nutrient levels, permeability and pH have various effects on crop growth. Soil texture influences the characteristic soil water curve due to differences in the particle composition. The higher the soil clay content, the slower the water infiltration and the smaller the scope of the wetting body, which in turn increases the soil water content and soil water retention [31]. By studying the effect of soil texture on the soil moisture status, it was concluded that evidence of rapid and deep infiltration in 'dry' texture-contrast soils has implications for water and solute management [32]. Our research showed that the soil moisture content of clay and loam in different soil layers under T1 and T2 was significantly higher than that in sandy soil; thus, compared with sandy soil, clay and loam have better water retention. The moisture content of different soil textures under T1 was slightly higher than that under T2, mainly because the sand content of the sandy soil was high, which was conducive to water penetration, whereas the clay has fine soil particles, producing a large surface area and large water absorption capacity; these findings were similar to previous research results [8]. Under combined irrigation and drainage, the amount of salt discharged by the concealed pipe accounts for 28.90% of the salt content of soil at a depth of 0–80 cm [33]. Using linked irrigation and drainage, the total salt content in the root layer was previously found to decrease by 50.34% at a depth of 0–200 cm [34]. Soil texture controls salinity by regulating the composition of the soil microbial community [35]. Our study showed that the average salt content of clay, loam and sandy soil in the 0–60 cm layer under T1 treatment decreased by 14.09%, 14.21% and 12.35%, respectively, compared with T2. The combined irrigation and drainage treatment therefore reduced the salt content of the shallow soil. Using the combined irrigation and drainage treatment, the soil salt content at the end of the cotton growth period decreased by 16–43% compared with that before sowing [36]. There was a positive correlation between sand content and soil permeability. The higher the sand content, the faster the water infiltration rate and the deeper the infiltration depth, with the clay content and its characteristics leading to the opposite [37]. Our research showed that the K/K0 of different soil textures at different growth stages of cotton under T1 and T2 was ranked as follows: sandy soil > loam > clay. Under T1, the K/K0 of different soil textures at different cotton growth stages was >1. Hence, linked irrigation and drainage improved both soil permeability and the cotton root soil environment.

Soil texture has a great impact on soil pH due to compositions of particles. The proportion of silt particles in soil has a very significant negative correlation with soil pH [38]. Our study showed that the pH value of the same soil layer under different soil textures under T1 and T2 was ranked as follows: clay > loam > sandy soil. Under T1, the average pH value of clay, loam and sandy soil in the 0–60 cm soil layer was reduced by 5.02%, 5.85% and 3.27%, respectively, compared with T2. Cotton roots were mainly distributed in the 0–60 cm soil layer. The combined irrigation and drainage treatment reduced the pH value of this shallow soil and effectively improved the root growth environment. Sandy soil has many large pores, few small pores, a weak capillary effect, strong infiltration capacity and poor water retention. Salt infiltrates rapidly with water, increasing the pH value of deep soil. Clay soil has high content of fine particles, slow infiltration of irrigation water, high water absorption and shows expansion of the clay particles, which hinders capillary water movement. At the same time, there is a significant capillary effect between the clay particles, although water permeability is slow, and the pH value of the 0–100 cm soil fluctuates [39]. A similar situation was found in our study. The pH value of the 0–60 cm soil layer in clay fluctuated subtly, while the soil pH value of the 60–100 cm layer increased gradually.

Good soil water and fertilizer holding capacity and aeration performance are beneficial to crop root growth and water, and nutrient absorption levels, which improve crop yield. The water holding capacity, permeability and aeration of soil are important factors that affect drainage under unsaturated conditions Eliminating the hysteresis effect and capillary barrier around the drainage pipe and adjusting the water holding capacity, permeability and aeration of the soil structure using a new subsurface drainage structure may enhance the drainage efficiency of subsurface drainage pipes in saturated-unsaturated zones [40]. Compared with clay and sandy soil, cotton in loamy soil produces the largest single bolls, has a high lint percentage, forms more bolls, and has the highest yield of seed cotton and lint [41]. The yield of seed cotton and irrigation water productivity in loam soil were significantly higher than those in clay and sandy soil [42,43]. The comprehensive growth index of cotton planted in loam with different soil texture is better [28]. When fertilizer rates were the same, soil $NO^{-}{}_{3}$-N was distributed more uniformly in the loam soil than in the sandy soil [44]. Our study showed that the plant height, stem diameter, leaf area index and dry matter mass of cotton in different soil textures under T1 and T2 were ranked as follows: loam > clay > sandy soil. The growth indexes of loam and clay cotton under T1 were significantly higher than those under T2, and there was no significant difference in the cotton growth indexes in the sandy soil. The cotton yield and water use efficiency under T1 and T2 in soils of different texture was ranked as follows: loam > clay > sandy soil, and there were significant differences among different treatments. The cotton yield and water use efficiency under T1 in loam were significantly higher than those under T2, and the research results were similar to those of previous scholars in different regions [45]. With respect to water saving and yield, the proportion of cotton planting in loamy soil should be increased under the same irrigation treatment, and the water and salt of different soil textures should be adjusted through by combining irrigation and drainage, so as to effectively improve the root growth environment of crops. This will play a positive role in increasing crop yield, improving water and fertilizer utilization efficiency and promoting agricultural production. Compared with previous studies, our research systematically explains the effects of combined irrigation and drainage technology on soil moisture, salinity, permeability, soil pH and cotton growth, which provides a new idea for promoting agricultural water saving and saline alkali land improvement.

5. Conclusions

This study evaluated the effects of soil texture on soil water and salt distribution, permeability, pH, cotton growth and water use efficiency using a combined irrigation and drainage technique in the Xinjiang oasis agroecosystem. We came to the following conclusions.

- The water retention of clay and loam was better than that of sandy soil. Combined irrigation and drainage increased the soil water holding capacity and reduced the shallow soil salt content. Combined irrigation and drainage reduced the pH value of the shallow soil and effectively improved the root growth environment of cotton.
- Under the combined irrigation and drainage and conventional drip irrigation treatment, the K/K0 values for different soil textures at the different growth stages of cotton were sand > loam > clay, and the K/K0 values under the combined irrigation and drainage treatment were >1. Combined irrigation and drainage improved soil permeability.
- The growth index, seed cotton yield and water use efficiency of cotton under the combined irrigation and drainage and conventional drip irrigation treatments in different soil textures were loam > clay > sandy soil. The cotton growth indexes of loam and clay under the combined irrigation and drainage treatment were significantly higher than those under the conventional drip irrigation treatment.
- In loamy soil, the cotton yield and water use efficiency of the combined irrigation and drainage treatment were significantly higher than that using the conventional drip irrigation treatment. The cotton yield and water use efficiency of the combined irrigation and drainage treatment were 6.37% and 13.70% higher than those under the conventional drip irrigation treatment, respectively.

The combination of irrigation and drainage effectively improved the root growth environment of cotton in different soil textures, improved the yield and quality of cotton and provided a new idea to use in promoting agricultural water saving and saline alkali land management.

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