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Effects of Different Salt Stress on Physiological Growth and Yield of Drip Irrigation Cotton (*Gossypium hirsutum* L.)

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Abstract: This study adopted the method of barrel planting to artificially set the salt content of six different soils (CK:1.5 g kg^{-1}, T1:3.0 g kg^{-1}, T2:4.0 g kg^{-1}, T3:5.3 g kg^{-1}, T4:6.2 g kg^{-1}, T5:7.3 g kg^{-1}) to study the effects of different degrees of mild salt stress on photosynthetic physiology, growth index and yield of cotton under drip irrigation. The results showed that with the increasing salt stress and the prolongation of stress time, the photosynthetic physiological indexes of cotton showed a downward trend ($P < 0.01$), and the plant height and leaf area were significantly affected by salt stress in the early growth stage. Furthermore, the comprehensive analysis showed that compared with moderate and severe salt stress, stomatal limitation was the cause of photosynthetic rate decline in cotton under mild salt stress at early growth stage, while non-stomatal limitation was at late growth stage. Photosynthetic parameters were closely related to the degree of salt stress, and cotton yield showed a good correlation with photosynthetic indicators. This experiment could provide a theoretical basis for the cultivation and management of cotton in mild saline-alkali land in Xinjiang.

Keywords: Drip irrigation; salt stress; photosynthesis; cotton yield; barrel planting

1 Introduction

Cotton (*Gossypium hirsutum* L.) is a salt-tolerant crop and one of the most important cash crops and it has a large planting area in Xinjiang, China [1]. In recent years, the annual planting area had reached (1.7~2.4) × 106 ha, accounting for about 40% of the total planting area of crops in Xinjiang [2]. As food security has been paid more attention and the contradiction between grain and cotton has become increasingly prominent, it is of great significance to develop cotton planting technology in saline-alkali land to stabilize cotton production in China [3]. According to statistics, the area suitable for agriculture, forestry and animal husbandry in Xinjiang plain area is 2.15 × 107 ha, and the saline-alkali land is about 0.8 × 107 ha, which accounts for 40% of the total reclaimable wasteland area [4]. While the proportion of light saline-alkali land in Shihezi Irrigation Area and Manas Irrigation Area were larger, occupying 753.3 km^2 (73.2%) and 1 249.5 km^2 (91.2%), respectively [5]. Therefore, it is of great significance to study the effects of salt stress on cotton photosynthetic characteristics and yield in irrigation area for improving cotton yield and cotton planting technology in saline-alkali land.

In recent years, the salt tolerance of cotton has been studied by scholars at home and abroad. The results show that when the salinity of irrigation water reaches 4 g L^{-1}, it will inhibit the vegetative growth of cotton, but less affect the reproductive growth (bud and boll stage) [6]. Salt stress reduced cotton leaf area and reduced dry matter content of aboveground part. With the increase of soil salinity, transpiration rate, water content and net photosynthetic rate of cotton functional leaves decreased, but leaf temperature increased [7,8]. Under the conditions of seawater irrigation, stomatal conductance, net photosynthetic rate and intercellular CO_2 volume fraction of cotton reached the highest level [9]. When soil salinity was 0.4%, leaf photosynthesis was inhibited, and the relative photosynthetic rate decreased. With the increase of soil salinity, the dry matter accumulation, boll number per plant, boll weight and lint yield of cotton decreased [10]. The initial salinity of soil was 7.7 dS/m, the yield of cotton began to decrease, and the yield of cotton decreased by 5.2% when salinity increased by 1 dS/m [11]. However, when the salt content was 3.0 g kg^{-1} in the soil, the growth of crop was significantly inhibited, and the yield was reduced [12].

Although predecessors have done some research on cotton planting in saline-alkali soil, most of the studies were carried out on moderate and severe salt stress, and only a few studies were conducted on the physiological growth of cotton under mild salt stress. Moreover, the salt tolerance of cotton is complex and affected by many other factors (hereditary characteristics, environment, and cultivation measures), the results of research were also different and lack of quantitative research. Therefore, to further study the physiological growth characteristics and yield changes of drip irrigation cotton under mild salt stress, clarify the restriction mechanism of light salt stress on photosynthesis and growth index of cotton and ultimately provide theoretical basis for optimizing cotton planting technology, this paper conducted serval experiments using barrel planting method in mild saline-alkali soil in Xinjiang.

2 Materials and Methods

2.1 Experimental Site

The experiment was conducted in the Key Laboratory of Modern Water-Saving Irrigation Production and Construction Corps, Xinjiang, China (44°19'28"N, 85°59'47"E, Altitude 412 m). The time horizon covers from April to October in 2016, with an average annual rainfall of 198 mm and average annual evaporation of 1340 mm, and the average sunshine hours and temperature were 3463 h and 10℃, separately.

2.2 Experimental Method

During the experiment, the local cotton variety "Nongfeng 133" was selected for the barrel planting experiment. The height, top inner diameter and bottom inner diameter are 0.55 m, 0.45 m and 0.35 m respectively.

Table 1: Irrigation and fertilization treatment of cotton at different growth stages

Growth period	Time	Irrigation		Fertilization		
		Irrigation amount (mm)	Irrigation times	$CO(NH_2)_2$ /(kg ha^{-1})	KH_2PO_4 /(kg/ha)	Fertilization times
Seeding	04.22-04.30	30	1	—	—	—
Seedling stage	05.01-06.15	25	1	30	15	1
Bud stage	06.16-07.03	70	2	90	45	2
Flowering and boll stage	07.04-08.18	200	5	450	225	5
Boll opening stage	08.19-10.16	60	2	30	15	1
Whole growth period	174 d	385	11	600	300	9

The holes were punched at the bottom of the plastic barrel. The experimental soils were dried and crushed naturally to remove stones and other impurities. The middle loam soil were evenly blended with 0, 20%, 40%, 60%, 80%, 100% saline-alkali soil and each treatment was repeated three times. According to the classification index of soil salinization degree, we designed five treatments of CK with different soil salt contents (CK: 1.5 g kg^{-1}, T1: 3.0 g kg^{-1}, T2: 4.0 g kg^{-1}, T3: 5.3 g kg^{-1}, T4: 6.2 g kg^{-1}, T5: 7.3 g kg^{-1}). On April 22th, 2016, "dry sowing and wet out" method was used to sow seeds. The sowing depth was 3~4 cm, and the seedlings emergence were on April 29th. The plastic hose and the spiral water stop clamp were used to drip irrigation, the irrigation and fertilization amount of each barrel was precisely controlled, and the dripper discharge was 1.8 L h^{-1}. The water and fertilizer management measures adopted in each treatment were the same. The irrigation quota was 385 mm, the irrigation time was 11 times, and the salinity of irrigation water was 0.87 g L^{-1}. The amount of fertilizer applied was 600 kg ha^{-1} for urea (N: 46.4%) and 300 kg ha^{-1} for potassium dihydrogen phosphate (P_2O_5: 51.5%). The detail information is shown in Tab. 1.

2.3 Measurements and Methods Applied

2.3.1 Soil Salinity Determination

The soil samples were air-dried indoors, and the soil was evenly crushed and screened by 1 mm soil sieve. After that, 100 mL distilled water and 20 g soil were put into a triangular bottle to prepare a clarifying liquid with the mass ratio of soil to water of 1:5 [13]. Finally, the conductivity was measured by DDS11-A digital display conductivity meter, and the total amount of water-soluble salt is determined by the drying-residue method.

The equation of fitting conductivity and salt content was as follows:

$$S = 0.0018EC + 0.7795, (R^2 = 0.9805) \quad (1)$$

where S is the soil salt content (g/kg); EC is the conductivity value (S/cm).

2.3.2 Photosynthetic Physiological Indicators

The photosynthetic characteristics of cotton were measured at the bud stage (June 20th), flowering and boll stage (August 15th) and boll opening stage (September 6th) with CI-340 hand-held photosynthetic meter, respectively. The measurement items included photosynthetic active radiation, atmospheric temperature, atmospheric CO_2 concentration, and photosynthetic physiological indexes such as cotton transpiration rate (T_r), net photosynthetic rate (P_n), stomatal conductance (G_s), intercellular CO_2 concentration (C_i) and stomatal limiting value (L_s). In good weather time, the same function cotton leaves were measured at different growth stages from 10:00 to 20:00, and the time interval was 2 hours. Three cotton plants were continuously measured in each treatment, and the average value was obtained.

The water use efficiency (WUE) and Ls of photosynthesis were calculated from these measured data mentioned above. The formulas were listed as follows [14,15]:

$$WUE = Pn/Tr \quad (2)$$

$$Ls = 1–Ci/Ca \quad (3)$$

2.3.3 Growth Index

Measurements of plant height (H) and leaf area index (LAI): In cotton seedling stage (June 15th), bud stage (July 10th), flowering and boll stage (August 5th) and boll opening stage (September 5th), three representative plants were selected for marking each treatment, and cotton plant height and leaf length and width were measured by tape measure, and then leaf area and leaf area index were calculated.

Cotton leaf area per plant (cm^2) = leaf length (cm) × leaf width (cm) × 0.84

LAI = leaf area per plant × number of plants per unit land area/unit land area

2.3.4 Cotton Yield Index

The boll number per plant, boll quality and seed cotton yield per barrel of cotton were determined.

2.4 Statistical Analysis

Excel 2013 was used to sort out the data, SPSS 17.0 software was used to analyze variance, and OriginLab 8.5 was used to plot.

3 Results and Analysis

3.1 Changes of Main Meteorological Factors in the Growth Period

Atmospheric temperature, light effective radiation and atmospheric CO_2 concentration are the main environmental factors affecting plant photosynthesis. Photosynthetic measurements were carried out at cotton bud stage (June 20th), flowering and boll stage (August 15th) and boll opening stage (September 6th). The variation regularity of these three environmental factors with growth period and their statistical analysis are shown in Tab. 2. With the advancement of the growth process, the three factors all showed the trend of increasing first and then decreasing. Compared with the value of environmental factors in flowering and boll stage, the value of environmental factors in the other two growth stages showed significant differences ($P < 0.05$). The maximum values of the three factors appeared at the flowering and boll stage, which were 1788.25 μmol $(m^2 \cdot s)^{-1}$, 35.49℃ and 490.22 μmol mol^{-1}.

Table 2: Changes of environmental factors in different growth stages

	Light effective radiation /($\mu mol \cdot m^{-2} \cdot s^{-1}$)	Atmospheric temperature /℃	Atmospheric CO_2 concentration /($\mu mol \cdot mol^{-1}$)
Bud period (20th June)	1653.84 a	31.59 a	471.84 b
Flowering and bolling Period (15th August)	1788.25 b	35.49 b	490.22 c
Flowering Period (6th September)	1747.15 bc	31.78 a	425.01 a

3.2 Effects of Soil Salt on Photosynthetic Physiological Indicators of Cotton under Drip Irrigation

3.2.1 Effects of Salt Stress on the Pn and Tr of Cotton under Drip Irrigation

The variation of Net Photosynthetic Rate (P_n) and variance analysis of drip irrigation cotton under different salinity treatments are shown in Tab. 3. Tab. 3 showed that there are significant differences in net photosynthetic rate among different salt treatments ($P < 0.01$). The net photosynthetic rate of all treatments was lower than CK, and with the increasing salt stress, the net photosynthetic rate decreased more. Compared with CK, the net photosynthetic rate of T1 and T2 treatments decreased slightly ($P > 0.05$), while the values of T3 and T5 treatments decreased gradually, and T5 treatments reached the minimum, showing significant difference ($P < 0.05$). This indicated that low salt treatments had less effect on P_n of cotton, and when the net photosynthetic rate exceeded the critical salt tolerance value of cotton, it decreased significantly. The net photosynthetic rate (P_n) of cotton varied in different growth stages under salt stress, and the P_n of each treatment increased first and then decreased with the advance of growth stage. The maximum net photosynthetic rate appeared in the flowering and bolling stage (June 20th), up to 31.31 μmol/$(m^2 \cdot s)$, and the minimum value was 13.20 mol/$(m^2 \cdot s)$ in the bolling stage (September 6th), this is the consequence of the further reduction of stomatal conductance induced by long-term salt stress.

In addition, Tab. 3 showed that the variation of transpiration rate (T_r) of drip irrigation cotton in different growth stages was consistent with the trend of net photosynthetic rate (P_n). With the increasing salt stress, the transpiration rate of cotton in different growth stages showed a downward trend. With the development of growth period, the transpiration rate increased first and then decreased. It reached the largest value in the boll stage, followed by the second value in the bud stage, and achieved the minimum value in the opening stage. However, there are some other characteristics under different salinity levels in different growth stages. For example, there was no significant difference between T1 and T2 treatments and CK treatments ($P > 0.05$), which occurred between T3 and T5 treatments in transpiration rate and CK treatment ($P < 0.05$). Moreover, different degrees of salt stress have different effects on transpiration rate, but all of them make it difficult for cotton roots to absorb water, resulting in water shortage in the plant, and finally reduce the transpiration rate.

Table 3: Effects of different salinity treatments on net photosynthetic rate and transpiration rate of cotton

Salt treatment	P_n/ (μmol·m^{-2}·s^{-1})			T_r/(mmol·m^{-2}·s^{-1})		
	June 20th	August 15th	September 6th	June 20th	August 15th	September 6th
CK	25.22 ± 0.13^a	31.33 ± 0.66^a	23.16 ± 1.58^a	4.78 ± 0.16^a	5.38 ± 0.06^a	4.73 ± 0.11^a
T1	25.12 ± 0.04^a	31.25 ± 0.78^a	22.97 ± 0.20^a	4.64 ± 0.08^a	5.26 ± 0.10^a	4.68 ± 0.03^a
T2	25.17 ± 0.04^a	31.31 ± 0.54^a	23.12 ± 0.17^a	4.56 ± 0.04^a	5.30 ± 0.03^a	4.66 ± 0.01^{ab}
T3	20.74 ± 0.37^b	22.77 ± 0.03^b	18.60 ± 1.65^b	3.93 ± 0.11^b	4.76 ± 0.07^b	3.88 ± 0.08^b
T4	19.47 ± 1.54^{bc}	19.64 ± 0.08^c	14.50 ± 0.78^c	3.78 ± 0.11^{bc}	4.39 ± 0.06^c	3.61 ± 0.02^{bc}
T5	18.59 ± 0.58^c	18.69 ± 0.06^d	13.20 ± 1.00^c	3.64 ± 0.07^c	3.98 ± 0.03^d	3.46 ± 0.01^c
Significance test (F value)						
Salt	40.911**	335.580**	42.218**	45.882**	171.363**	187.156**

Note: * means significant difference (P < 0.05), ** means significant difference (P < 0.01), and different letters mean significant difference (P < 0.05) after the same column value.

3.2.2 Effects of Salt Stress on Gs, Ci and Ls of Cotton under Drip Irrigation

Water and CO_2 in the air enter and exit plants through stomata, which regulate photosynthetic rate and transpiration rate, while stomatal conductance reflects the degree of stomatal opening. That the stomatal conductance (*Gs*) of cotton showed a downward trend under salt stress (seen in Tab. 4). These recorded data in Tab. 4 showed that there were significant differences among different salt treatments (P < 0.01). Nevertheless, there was no significant difference between T1 and T2 treatments in different growth stages compared with CK. With the increase of salt stress, the stomatal conductance of cotton decreased significantly, and reached a prominent difference compared with CK (P < 0.05). The stomatal conductance increased from bud stage to flowering boll stage and then decreased, which was consistent with the changing trend of net photosynthetic rate. However, the salt content of T3, T4 and T5 treatments significantly inhibited stomatal conductance of cotton leaves.

Table 4: Effects of different salinity treatments on stomatal conductance and WUE of cotton

Salt treatment	Stomatal conductance/(mmol·m^{-2}·s^{-1})			WUE/(μmol·mmol^{-1})		
	June 20th	August 15th	September 6th	June 20th	August 15th	September 6th
CK	280.50 ± 2.12^a	412.50 ± 0.71^a	202.17 ± 2.38^a	5.28 ± 0.20^a	5.82 ± 0.18^a	4.89 ± 0.22^a
T1	276.67 ± 0.47^a	403.00 ± 2.83^b	197.20 ± 2.55^{ab}	5.42 ± 0.09^a	5.94 ± 0.26^a	4.91 ± 0.01^a
T2	274.17 ± 1.65^a	408.00 ± 2.83^{ab}	201.30 ± 1.13^{bc}	5.52 ± 0.04^a	5.91 ± 0.13^a	4.96 ± 0.05^a
T3	256.17 ± 4.48^b	367.50 ± 2.12^c	193.17 ± 1.17^c	4.78 ± 0.23^b	4.78 ± 0.07^b	4.79 ± 0.32^a
T4	234.33 ± 2.36^c	347.17 ± 2.59^d	134.14 ± 1.92^d	4.36 ± 0.12^c	4.47 ± 0.04^b	4.02 ± 0.16^b
T5	217.83 ± 3.07^d	331.83 ± 1.65^e	124.50 ± 2.12^e	4.29 ± 0.08^c	4.70 ± 0.02^b	3.81 ± 0.06^b
Significance test (F value)						
Salt	185.121**	465.796**	675.838**	28.477**	45.317**	16.854*

Note: * means significant difference (P < 0.05), ** means significant difference (P < 0.01), and different letters mean significant difference (P < 0.05) after the same column value.

Tab. 5 showed that salt stress had a significant effect on C_i in cotton, showing up a similar change with net photosynthetic rate (P_n). C_i decreased in all treatments compared with the CK, and there was a significant difference (P < 0.01). With the increase of salt stress, C_i decreased more, and T1 and T2 treatments decreased slightly compared with the control (P > 0.05), while T3, T4 and T5 treatments showed a significant downward trend (P < 0.05). Furthermore, C_i in different growth stages of cotton under salt stress had different changing regularities, showing a trend of "rising-falling" over the all treatments. The peak appeared in the flowering and boll stage, and the nadir appeared in the bud stage. Different degrees of salt stress and time of salt stress had different inhibition effects on intercellular CO_2 concentration in cotton leaves.

Table 5: Effects of different salt treatment on intercellular CO_2 concentration and stomatal limitation value in cotton

Salt treatment	Intercellular CO_2 concentration/($\mu mol \cdot mol^{-1}$)			Stomatal limit value		
	June 20th	August 15th	September 6th	June 20th	August 15th	September 6th
CK	367.84 ± 4.87^{a}	402.84 ± 3.19^{a}	369.84 ± 5.38^{a}	0.22 ± 0.04^{a}	0.18 ± 0.03^{a}	0.13 ± 0.03^{a}
T1	360.67 ± 4.39^{ab}	398.83 ± 5.37^{a}	363.17 ± 5.49^{a}	0.24 ± 0.03^{ab}	0.19 ± 0.04^{a}	0.15 ± 0.03^{a}
T2	356.84 ± 4.70^{b}	396.31 ± 2.07^{a}	358.34 ± 4.58^{ab}	0.24 ± 0.02^{b}	0.19 ± 0.02^{a}	0.16 ± 0.03^{ab}
T3	316.67 ± 1.66^{c}	354.66 ± 2.33^{b}	316 ± 1.71^{c}	0.33 ± 0.02^{c}	0.28 ± 0.01^{b}	0.26 ± 0.01^{c}
T4	291.34 ± 2.03^{d}	329.67 ± 1.59^{c}	299.17 ± 1.32^{d}	0.38 ± 0.01^{d}	0.33 ± 0.01^{c}	0.30 ± 0.02^{d}
T5	265.33 ± 2.23^{e}	302.18 ± 1.72^{d}	274.84 ± 1.77^{e}	0.44 ± 0.01^{e}	0.38 ± 0.01^{d}	0.35 ± 0.02^{e}
Significance test (*F* value)						
Salt	276.550^{**}	150.378^{**}	209.628^{**}	276.589^{**}	150.486^{**}	209.674^{**}

Note: * means significant difference ($P < 0.05$), ** means significant difference ($P < 0.01$), and different letters mean significant difference ($P < 0.05$) after the same column value.

The stomatal limit values (*Ls*) of drip irrigation cotton under different salinity stresses were represented in Table 5. Compared with CK, L_s increased significantly in all salt treatments ($P < 0.01$). With the increase of salt stress, *Ls* increased significantly, and T1 and T2 increased slightly ($P > 0.05$), while T3, T4 and T5 increased evidently ($P < 0.05$), indicating that salt content under T3 treatment had a greater impact on stomatal limit value of cotton. However, L_s showed a downward trend with the growth stage, and the largest value was in bud stage and the smallest was in boll opening stage, which may be related to the decrease of photosynthetic activity of mesophyll cells in cotton under long-term salt stress. The P_n, G_s and C_i of functional leaves of cotton decreased significantly at the early growth stage, while the L_s increased significantly. This was resulted from the difficulty of absorbing water caused by salt stress. In order to reduce the loss of water, some stomata were forced to close, resulting in the decrease of CO_2 concentration entering cells, so the L_s increased. P_n, G_s and L_s in boll opening stage were less than bud stage, while C_i was larger than bud stage. It could be explained that long salt stress inhibited the activity of Calvin circulating enzymes (such as Rubisco, PECP, etc.), which led to the decrease of P_n.

3.2.3 Effects of Different Salt Stresses on WUE of Cotton Leaves under Drip Irrigation

Tab. 4 showed that compared with CK, the WUE of cotton leaves in T1 and T2 treatments increased slightly ($P > 0.05$) and decreased from T3 treatment. There was significant difference between T3, T4 and T5 treatment and CK treatment ($P < 0.05$). With the increase of salt stress, the WUE of cotton leaves in T1 and T2 treatments showed an increase-decrease trend, and the WUE of T5 treatment was the lowest in all growth stages, which indicated that cotton had a certain salt tolerance. When the salt stress was low, it had little effect on photosynthesis, and when it exceeded the salt tolerance threshold, it would inhibit photosynthesis. WUE in different growth stages of cotton showed a trend of "increase-decrease", with the highest in flowering and boll stage and the lowest in boll opening stage. This was caused by the active physiological activities of cotton in flowering and boll stage, which has a certain resistance to salt stress.

3.3 Effect of Soil Salinity on Cotton Growth under Drip Irrigation

Fig. 1 showed the effect of different salinity treatments on cotton plant height. As the soil salinity increased, the plant height showed a remarkable downward trend. In seedling stage, except for T1 treatment, plant height of each treatment was significantly different from CK treatment ($P < 0.05$); in flowering and bolling stage, plant height of T1, T2 and T3 treatment had little change compared with CK treatment ($P > 0.05$), but plant height of T4 and T5 treatment had significant difference compared with CK treatment ($P < 0.05$). In the early growth stage (seedling bud stage), there were conspicuous effects on plant height under T2 treatment. In the late growth stage (boll stage, boll opening stage), only T4 and T5 treatment had significant inhibition on plant height, while the inhibition of T2 and T3 treatment was weakened, indicating that different salt stress had different effects on plant height at different growth stages.

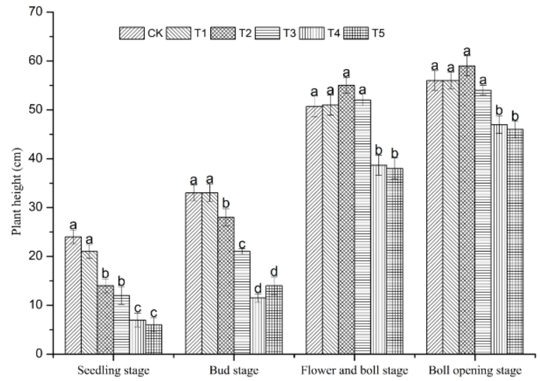

Figure 1: Effects of different salt treatments on cotton plant height

Fig. 2 showed the changes of cotton leaf area index under different salinity treatments. With the development of growth period, the leaf area index of all treatments increased first and then decreased and reached the peak value at blossing and boll-forming stage. In the early stage of cotton growth (seedling bud stage), except for T1 and T2 treatments, the leaf area index of each treatment was significantly different from CK treatment. In the late growth stage, T4 and T5 treatments had significant effects on leaf area. The results showed that soil salinity inhibited the growth of cotton significantly in the early growth stage, while low salinity inhibited the growth of cotton leaves in the late growth stage and alleviated the restrictive effect of high salinity on the growth of cotton leaves to a certain extent.

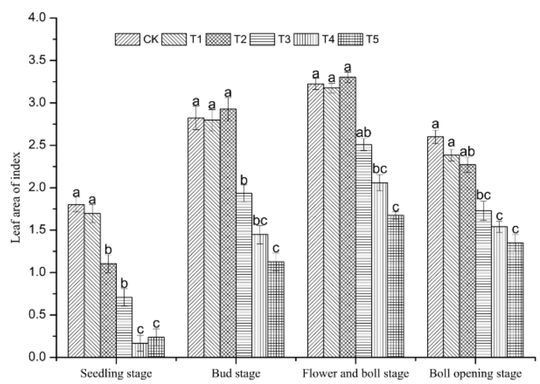

Figure 2: Effects of different salt treatments on LAI of Cotton

3.4 Effect of Soil Salt on Cotton Yield under Drip Irrigation

Tab. 6 showed that the effect of salt stress on boll number per plant and seed cotton yield had statistical significance at 0.01 level and the effect on the quality of cotton boll had statistical significance at 0.05 level. Compared with CK, when soil salinity was less than that in T2 treatment, there was no significant difference in boll number per plant and boll quality ($P < 0.05$). From the beginning of T3 treatment, the gap increased significantly and reached the maximum in T5 treatment. The minimum boll number per plant and boll mass of T5 treatment were 5.67 and 4.95, respectively, which were 4.57 and 0.66 lower than that of the CK. There was no significant difference in seed cotton yield between T1 and T2 treatment, but the yield of T3 treatment began to decrease significantly.

Compared with CK, the seed cotton yield of T3, T4 and T5 treatment decreased by 11.63%, 18.47% and 28.37%, respectively. Soil salinity was negatively correlated with cotton yield and its components. However, when the soil salinity was low, it had little effect on cotton yield, and when the soil salinity exceeded a certain amount, the yield of cotton will be seriously inhibited. It showed that there is a critical value of salt tolerance in cotton, and higher yield can be obtained by controlling soil salinity below the critical value in actual production.

Table 6: Changes in yield and its components under different salt treatments

Salt treatment	Number of bells per plant	Single bell mass /g	Seed cotton yield /(g/plant)	Relative production (%)
CK	10.24 ± 0.84^{a}	5.61 ± 0.16^{a}	57.45 ± 3.72^{a}	100
T1	9.64 ± 0.51^{b}	5.81 ± 0.25^{a}	56.01 ± 2.41^{a}	97.49
T2	9.67 ± 0.58^{ab}	5.75 ± 0.23^{a}	55.60 ± 1.25^{a}	96.78
T3	8.22 ± 0.19^{c}	4.96 ± 0.10^{b}	50.77 ± 0.70^{b}	88.37
T4	6.56 ± 0.20^{d}	4.96 ± 0.07^{c}	46.84 ± 0.52^{c}	81.53
T5	5.67 ± 0.33^{e}	4.95 ± 0.03^{d}	41.15 ± 1.32^{d}	71.63
Significance test (*F* value)				
Salt	43.14**	50.582*	88.419**	—

Note: * means significant difference ($P < 0.05$), ** means significant difference ($P < 0.01$), and different letters mean significant difference ($P < 0.05$) after the same column value.

Crop salt tolerance function referred to the relationship between crop yield in different salinity soils and crop yield in non-saline-alkali soils under the same conditions. Based on the yield data of barrel experiment and the soil salt content of 0–40 cm depth in the whole growth period, the salt tolerance index of drip irrigation cotton in the whole growth period was preliminarily determined. The piecewise linear salt production function is as follow:

$$Y_r = \frac{Y}{Y_m} = \begin{Bmatrix} 1, & S \leq S_t \\ 1 - C(S - S_t), & S_t < S \leq S_0 \\ 0, & S > S_0 \end{Bmatrix} \tag{4}$$

where Y_r is the relative yield; Y is the crop yield in the inhibited area (g); Y_m is the crop yield in the control group (g); C is the decreasing coefficient of increasing the yield per unit salt content; S is the soil salt content (g/kg); S_t is the threshold of soil salt content (g/kg) that begins to inhibit crop growth; S_0 is the soil salt content (g/kg) with zero yield.

According to Tab. 6 and Eq. (4), regression analysis was carried out by SPSS 17.0, and salt tolerance function parameters and salt tolerance equation of cotton were obtained. Under this experimental condition, the critical salt tolerance value (S_t) of cotton was 5.441.9 g/kg. When the soil salt content exceeded 5.441 9 g/kg, the yield of cotton began to decrease, The salt tolerance limit value S_0 was 44.2016 g/kg, when the soil salt content exceeded this value, the yield of cotton was zero, The crop yield decline coefficient C was 0.0258. The salt tolerance equation of cotton was finally obtained, $Y_r = 1 - 0.0258(S - 5.4419)$, with a determinant coefficient of 0.850.

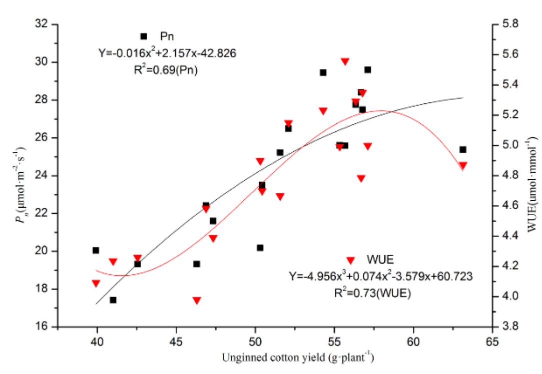

Figure 3: Correlation between cotton yield, P_n and WUE

Fig. 3 was the correlation between cottonseed cotton yield, leaf net photosynthetic rate and WUE. Fig. 4 was the correlation between yield, plant height and leaf area. Fig. 3 showed that cottonseed cotton yield and net photosynthetic rate (P_n) exhibit a quadratic function relationship, $R^2 = 0.69$, cottonseed cotton yield and WUE showed a cubic function relationship, $R^2 = 0.73$. Fig. 4 showed that cottonseed yield and plant height showed a linear relationship, $R^2 = 0.50$, cotton yield and leaf area showed a cubic function relationship, $R^2 = 0.72$. There was an excellent correlation between yield and P_n, WUE and leaf area, but not very close to plant height, which indicated that P_n, WUE and leaf area could reflect cotton yield to some extent.

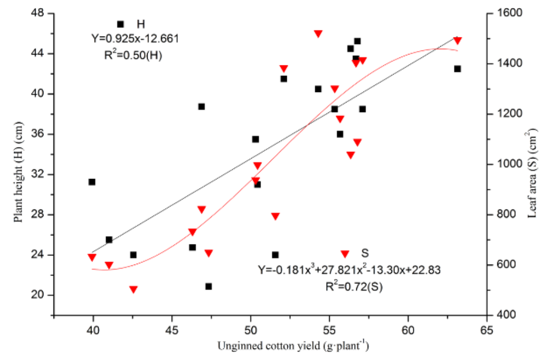

Figure 4: Correlation between cotton yield, plant height (*H*) and leaf area (*S*)

4 Discussion

Cotton photosynthesis is an important physiological activity index in the growth process of cotton and is the main method to analyze the physiological metabolism of cotton under salt stress. Under the background of large-scale mild saline-alkali land in Xinjiang, it is of practical significance to study the characteristics and mechanism of light salt stress on cotton photosynthetic physiological index and growth index and to improve mild saline-alkali land in Xinjiang.

Photosynthesis is an important metabolic process in plants, and its intensity has an important influence on plant growth, yield and stress resistance [16]. Salt stress may inhibit the normal photosynthesis of plants through ion toxicity, osmotic stress and sugar accumulation [17,18]. The results showed that low salinity had little effect on photosynthetic performance of cotton, when salt stress reached 5.3 g/kg, net photosynthetic rate, transpiration rate, stomatal conductance, intercellular CO_2 concentration and WUE of cotton leaves were significantly reduced, but stomatal limitation value increased. Previous studies on the photosynthetic mechanism of cotton under salt stress have been carried out extensively. However, due to the complexity of photosynthesis, no unified conclusion has yet been reached. Some studies have shown that the decrease of photosynthesis under low salinity conditions is due to stomatal restriction factors, while the decrease of photosynthesis under high salinity stress is due to non-stomatal restriction factors [19]. Salt stress can affect photosynthesis during the crop growth period and indirectly affect growth by inhibiting photosynthesis.

Salt stress can significantly inhibit the normal growth and development of crops, and ultimately reduce crop yield [20–22]). The results showed that the growth of plant height and leaf area was not significantly affected by low salt stress, but only inhibited by high salt stress, which was consistent with the results of [23]. The increase of salt content increased the boll falling rate of cotton, which resulted in the decrease of boll number per plant [24]. There was a close correlation between the Photosynthetic Physiological Indexes of cotton under salt stress. For example, the net photosynthetic rate is closely related to transpiration rate, stomatal conductance, intercellular CO_2 concentration and stomatal limitation. Cotton photosynthesis is a comprehensive process, and the soil salinity affects net photosynthetic rate by controlling cotton transpiration rate, intercellular CO_2 concentration and stomatal conductance. The correlation coefficients between cotton yield and P_n, WUE and leaf area were 0.69, 0.73 and 0.72 respectively, which indicated that cotton yield was closely related to the three indexes, and it was consistent with [25].

5 Conclusions

Salt stress had significant effects on the net photosynthetic rate (P_n), transpiration rate (T_r), stomatal conductance (G_s), intercellular CO_2 concentration (C_i), stomatal limiting value (L_s) and leaf water use efficiency (WUE) of cotton. Under 3.0 and 4.0 g/kg salt treatments, there was no significant difference between physiological indexes such as P_n and 1.5 g/kg salt treatments ($P > 0.05$); under 5.3, 6.2 and 7.3 g/kg salt treatments, there was a significant difference between physiological indexes of cotton leaves and 1.5 g/kg salt treatments ($P < 0.05$). P_n and T_r, G_s and C_i all decreased under salt stress in the early growth stage of cotton, while L_s value increased with salt stress, showing obvious stomatal restriction on photosynthesis; P_n, G_s and L_s in boll opening stage were smaller than that in the bud stage, while C_i was larger than bud stage, probably because long salt stress inhibited the activity of Calvin circulating enzymes (such as Rubisco, PECP, etc.), which led to the induction of photosynthesis, so the P_n decreased. The reason for the decline of photosynthetic rate of cotton under mild salt stress was stomatal restriction factor in the early growth stage and non-stomatal restriction factor in the late growth stage.

In the early stage of cotton growth, salt stress significantly inhibited plant height and leaf area index. In the late growth stage of cotton, due to the self-regulation mechanism of plants, the inhibition effect of 6.2, 7.3 g/kg salt treatment on plant height and leaf area was obvious, while that of 4.0, 5.3 g/kg salt treatment was weakened. The yield, boll number per plant and boll quality of cottonseed and cotton under 3.0 and 4.0 g/kg salt treatments were not different from those under 1.5 g/kg salt treatments. When the salt content was larger than 5.3 g/kg, the yield, boll number per plant and boll quality of cotton began to decrease significantly. Similarly, the difference between 7.3 g/kg salt treatment and 1.5 g/kg salt treatment was significant ($P < 0.05$). Cotton has a critical value of salt tolerance, beyond which the yield will be significantly reduced. Taking yield as a dependent variable and salt function as a independent variable, the critical salt tolerance value and salt tolerance limit value of cotton in this experiment were 5.4419 g/kg (S_t) and 44.2016 g/kg (S_0) by segmented salt tolerance function fitting.

Cotton yield was closely related to the net photosynthetic rate, water use efficiency and leaf area, and the correlation coefficients R^2 were 0.69, 0.73 and 0.72, respectively, indicating that net photosynthetic rate, water use efficiency and leaf area can be used as indicators to identify cotton yield. Meanwhile, the fitting degree between yield and plant height was not high ($R^2 = 0.50$), indicating that plant height cannot be used as a criterion to judge cotton yield.

Abbreviations: P_n, net photosynthetic rate; G_s, stomatal conductance; C_i, intercellular CO_2 concentration; T_r, transpiration rate; L_S, limit stomatal value; S_t, salt tolerance threshold; S_0, salt tolerance limit.

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