Effects of nitrogen and salt on growth and physiological characteristics of processing tomato under drip irrigation

Jiulong Wang[1,2], Zhenhua Wang[1,2*], Haiqiang Li[1,2], Wenhao Li[1,2], Tianyu Wang[1,2], Mingdong Tan[1,2]

(1. *College of Water Resources and Architectural Engineering, Shihezi University, Shihezi 832000, Xinjiang, China*; 2. *Key Laboratory of Modern Water-Saving Irrigation Corp, Shihezi University, Shihezi 832000, Xinjiang, China*)

Abstract: Xinjiang of China is one of the three largest planting bases of processing tomato in the world, but soil salinization has restricted the production of tomato processing. In order to study the effects of soil nitrogen, salt and their interaction on growth and physiological characteristics of processing tomato under drip irrigation, different amount of nitrogen fertilizer were added to reconcile different salt stress to explore the response mechanisms of growth and yield of processing tomato to soil nitrogen and salt contents with a two-year experiments. The results showed that the effects of soil salinity on the growth and physiological characteristics of processing tomato were significantly greater than that of input of nitrogen fertilizers. The higher soil salt content (≥5.0 g/kg) significantly inhibited the growth of processing tomato. The increase in addition of nitrogen fertilizer could alleviate the salt inhibition and promote the growth of processed tomato with the increase of soil salt content, and the maximum nitrogen application rate was 300 kg/hm^2. The linear plus platform was selected to determine the nitrogen effect models of non-saline-alkali soil and weak saline-alkali soil, but the square root nitrogen effect model of moderate saline-alkali soil was selected to accurately predict the yield of processing tomato. It was suggested that the processing tomatoes should be planted in moderate saline-alkali soil to achieve higher yields due to lower input of nitrogen fertilizer, potentially reducing fertilizer costs and maximizing profits from high processing tomato yields. The results have a strong guiding significance for planting of processing tomato on saline-alkali land and appropriate fertilization to increase the yield of processing tomato.

Keywords: drip irrigation, processing tomato, salinity, photosynthetic fluorescence parameters, nitrogen use efficiency, water use efficiency

DOI: 10.25165/j.ijabe.20211406.6568

Citation: Wang J L, Wang Z H, Li H Q, Li W H, Wang T Y, Tan M D. Effects of nitrogen and salt on growth and physiological characteristics of processing tomato under drip irrigation. Int J Agric & Biol Eng, 2021; 14(6): 115–125.

1 Introduction

Soil salinization is a global issue that causes soil degradation and affects the sustainable development of irrigated agriculture[1]. There are 9.32×10^8 hm^2 of salinized soil all over the world[2], which damages nearly 4×10^8 hm^2 of cultivated land[3]. Saline-alkali land, which the saline-alkali wasteland and part of the cultivated saline-alkali land exceed 3×10^7 hm^2 in China, is an important reserve resource of cultivated land in China. The efficient utilization of saline-alkali land is of great significance to guarantee the national food security. Soil salinization has universally existed in Xinjiang of China due to the arid climate and excessive surface evaporation. One-third of the irrigated land, including 1.1×10^7 hm^2 saline-alkali wasteland and 7.27×10^6 hm^2 over-saline-alkali wasteland[4], is endangered by salinization in Xinjiang[5]. Because the region has the climate characteristics of large solar radiation and long sunshine time and highly effective accumulated temperature, tomato (*Lycopersicon esculentum Mill*) can grow well in Xinjiang. At present, the yield of processing tomato in Xinjiang was largest compared with other provinces of China. However, because of the weak salt tolerance of processing tomato, salt-alkali stress negatively affected the growth and yield of processing tomato and the expansion of its planting area in Xinjiang of China. Although the most plant growth regulators have been adopted to reduce the negative impact of salt on the growth of processing tomato[6-10], the cost of adding regulators was larger and thus the option was not viable. Therefore, understanding the response mechanism of crop growth and yield to soil salt stress would be very helpful to globally increase the productivity of crop for salt-alkali soil.

The higher content of soil salt leads to the deterioration of soil permeability, hydraulic conductivity and infiltration capability, thus affecting the activities of microorganisms and limiting the release and movement of soil nutrients[11,12]. Furthermore, soil salt hinders the availability and uptake of nutrients by crop roots and restricts their metabolism into organic compounds within the plant[13,14]. In addition, soil salinity significantly increased the content of Na^+ in plants, leading to the imbalance of crop nutrient and thus reduction of crop yield by hindering uptake of potassium, calcium, magnesium and other nutrients[15]. For instance, Paul

Received date: 2021-03-04 **Accepted date:** 2021-11-01

Biographies: Jiulong Wang, PhD candidate, Lecture, research interest: water-saving irrigation, Email: wjl2013007@126.com; **Haiqiang Li**, PhD, Associate Professor, research interest: water-saving irrigation, Email: hqli1991@163.com; **Wenhao Li**, PhD candidate, Associate Professor, research interest: water-saving irrigation, Email: lwh8510012@163.com; **Tianyu Wang**, PhD candidate, research interest: water-saving irrigation, Email: 15963100756@163.com; **Mingdong Tan**, MS candidate, research interest: water-saving irrigation, Email: tanmingdong1998@163.com.

***Corresponding author: Zhenhua Wang**, PhD, Professor, research interest: theory and technology of water saving irrigation. Shihezi University, Shihezi 832000, Xinjiang, China. Tel: +86-993-2058979, Email: wzh2002027@163.com.

and Lade[16] found that the non-salted soil was more prone to provide a labile pool of nutrients than the soil with high-salinity when the external fertilization level is constant. Li et al.[17] indicated that the nitrogen use efficiency decreased with the increase of soil salt content. Munns and Tester[18] and Parida and Das[19] demonstrated that high salts resulted in the premature senescence of plant, thereby decreasing the plant metabolism and photosynthetic capacity and hindering the plant protein synthesis and conversion. Previous observations even showed that salt stress could lead to close stomata, decrease intercellular CO_2 concentration and deteriorate photosynthetic capacity, further affecting plant growth and resulting in the decrease in plant productivity[20-22]. However, the response mechanisms of crop growth and yield and soil nutrients to soil salt content remain unclear with the change in crop growth stage under long-term drip irrigation. The understanding of the effects of the change soil salt with crop growth stage on crop growth and soil nutrients could help to increase the crop yield in extreme drought and saline-alkali land.

Soil nutrients was one of the important factors affecting crop growth and yield[23]. Addition of nitrogen fertilizer could effectively compensate the nitrogen limitation due to the limited supply from the soil and ensure the sustainable use of soil and the crop growth[24-25]. Pessarakli[26] indicated that the shortage of nitrogen hindered crop growth, mainly because of that the coupling of nitrogen nutrients to organic compounds (i.e., proteins, hormones and nucleic acids) is essential for crop growth and development. Duan[27] and Wang[28] observed that adding a certain amount of nitrogen was prone to the growth and development of crops under the heat stress and salt stress. Xiao[29] indicated that the suitable nitrogen applications could increase the photosynthetic capacity of crops, weight and length of crop roots, and thus crop yield. However, the redistribution characteristics of soil nitrogen with soil water are still insufficiently understood under the integrated water and fertilizer technology, hindering the understanding of response mechanism of crop growth and yield to soil nitrogen contents.

This paper presented the processing tomato growth and physiological characteristics with changes in soil nitrogen and salt contents under drip irrigation in Xinjiang of China. The nitrogen fertilizer was added to reconcile salt stress to explore the response mechanism of crop growth and yield to soil nitrogen and salt contents[30,31]. At the same time, the quantification of nitrogen application and the maximum yield in tomato processing in Xinjiang is realized by the comparing and selecting the preferable fitted model of nitrogen effect. The main objectives of this study were to address how processing tomato growth and physiological characteristics respond to the addition of chemical nitrogen fertilizers, and to identify whether such characteristics vary with soil salt contents. Such knowledges are essential for the understanding of relationship of the rational application nitrogen to maximize processing tomato yields in extreme arid region affected by higher soil salt contents.

2 Materials and methods

2.1 Experimental site

The study was conducted in the Key Laboratory of Modern Water-Saving Irrigation of Xinjiang Production and Construction Corps which is located on the Shihezi City in Xinjiang of China (86°03′47″E, 44°18′28″N) in 2017 and 2018, respectively. The area is characterized by an arid continental climate. The average annual sunshine duration is 2865 h, and the frost-free period is about 170 d. The average accumulated temperature above 10°C and 15℃ is 3463℃ and 2960℃, respectively. The total rainfall and average temperature during the growing period of processing tomato (from May to August) in 2017 and 2018 were 81.8 mm and 30.9℃, and 137.1 mm and 30.0℃, respectively (Figure 1). The processing tomato was mainly selected crop in the saline-alkali land of the 121st regiment in Shihezi City, Xinjiang of China, due to such climate conditions. The soil in Shihezi City is classified as loam. The average soil salt content was 1.15 g/kg, and soil salinity was normal saline soil.

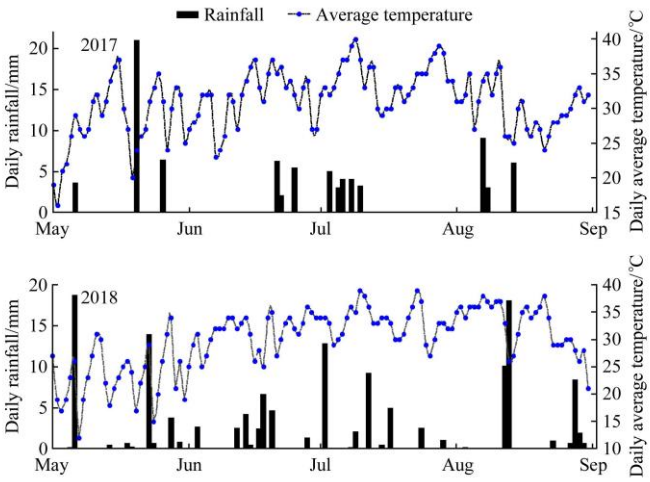


Figure 1 Daily rainfall and daily average temperature from May to August in 2017 and 2018

2.2 Experimental Designs

The experiments were established to address the interacted effects of soil nitrogen and salt contents on processing tomato growth consisted (Figure 2) in 2017 and 2018. Four salt content levels and four nitrogen levels were chosen, and four salt gradients were untreated saline-alkali (CK), light saline-alkali (S1), medium saline-alkali (S2) and severe saline-alkali (S3 and SS3), respectively (Table 1). The original S2 treatment (7 g/kg) and S3 treatment (10 g/kg) were canceled according to the monitoring results in 2017, but SS2 treatment (5 g/kg) and SS3 treatment (7 g/kg) were added to kindly address the effects of soil salt contents in 2018. Four soil nitrogen levels was high nitrogen (N1), moderate nitrogen (N2), low nitrogen (N4) and normal nitrogen (N3), respectively. The amount of nitrogen application varied with each level based on the tomato plant growth stages (at seedling, flowering, expansion and Mature stages) (Table 2). Fertilizer is applied to soils with water under irrigation, which the amount of chemical fertilizer input and irrigation quota and frequency were presented in Table 2. In this study, the effects of irrigation quota and frequency and input of P, K fertilizer were ignored at the same irrigation levels and the same addition levels of P, K fertilizer. Sodium chloride (NaCl) was added to the tested soils as needed to achieve the desired salt treatment levels. The tested soil samples were paced in a test basins and fertilizer treatments levels were randomly assigned to the basins and replicated three times. The size of the test basin was 0.60 m×0.55 m×0.45 m (top height×top inner diameter×bottom inner diameter). The bottom of the basin was perforated, and test basins for each treatment were arranged side by side in a 50 cm deep test pit which had been excavated (Figure 2). The soil basic physical and chemical properties at 0-40 cm soil depth are shown in Table 3, which N, P, K and other nutrient indicators were determined by colorimetric analysis with CleverChem Anna automatic discontinuous chemical analyzer, and dry bulk density and water holding capacity were determined by ring knife method. Soil particles composition was analyzed with the specific gravity method.

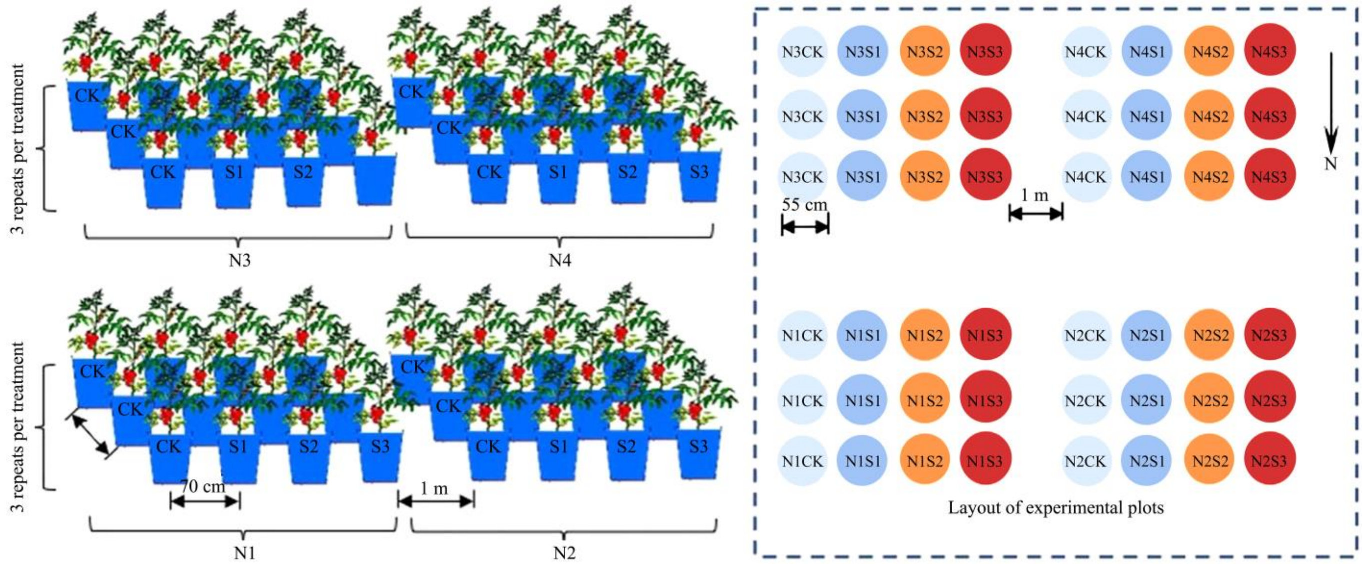


Figure 2 Layout of experimental plots

Table 1 Soil salt content gradient in 2017 and 2018

2017		2018	
Treatments	Soil salinity/$g\cdot kg^{-1}$	Treatments	Soil salinity/$g\cdot kg^{-1}$
CK	1.5	CK	1.5
S1	4.0	S1	4.0
S2	7.0	SS2	5.0
S3	10.0	SS3	7.0

Table 2 Amount of irrigation and fertilizer application in 2017 and 2018

Year	Growth stage	Date	Water treatment		Fertilizer treatment						
			Amount of irrigation/mm	Irrigation frequency	Urea/$kg\cdot hm^{-2}$				Monoammonium phosphate/$kg\cdot hm^{-2}$	Potassium chloride /$kg\cdot hm^{-2}$	Times of fertilization
					N1	N2	N3	N4			
2017					47	38	28	19	28	28	1
			150	3	140	112	84	56	84	84	3
	Expansion stage	Jun.22 to Jul.31	200	4	187	150	113	75	113	113	4
	Mature stage	Aug.1 to 20	50	1	—	—	—	—	—	—	—
	Whole growth stage		450	9	375	300	225	150	225	225	8
2018	Seedling stage	Apr.30 to May.27	50	1	47	38	28	19	28	28	1
	Flowering stage	May.28 to Jun.22	150	3	140	112	84	56	84	84	3
	Expansion stage	Jun.23 to Jul.26	200	4	187	150	113	75	113	113	4
	Mature stage	Jul.27 to Aug.15	50	1	—	—	—	—	—	—	—
	Total growth stage		450	9	375	300	225	150	225	225	8

Table 3 Mean of soil physical and chemical properties at 0-40 cm soil depth in 2017 and 2018

Years	Dry bulk density /$g\cdot cm^{-3}$	Total nitrogen /$g\cdot kg^{-1}$	Total phosphorus /$g\cdot kg^{-1}$	Total potassium /$g\cdot kg^{-1}$	Available phosphorus /$mg\cdot kg^{-1}$	Available potassium /$g\cdot kg^{-1}$	Field water holding capacity/%
2017	1.29	0.58	0.82	7.1	29.24	418.59	30.65
2018	1.32	0.63	0.77	8.0	31.22	415.31	28.43

It was found that soil with 10 g/kg salt content seriously inhibited the growth of processing tomatoes and decreased the yield and the quality of processing tomatoes, which was not conducive to the cultivation of processing tomatoes. To determine the suitable range of soil salt content for processing tomato cultivation, the level of 10 g/kg salt content was removed in the experiments in 2018. According to the agronomic requirements of local seed cultivation institutions, the amount of nitrogen fertilizer input was 225 kg N/hm^2 at the control group (N3). In 2017, it was found that low-nitrogen (N1) significantly affected the growth and yield of processing tomato with soil salt contents. Therefore, the non-nitrogen treatment (N0) was added to further analyze and determine the responses of processing tomatoes to low nitrogen treatment in 2018.

Three plants with a 30-cm space of each plant were planted in each basin and surface soil within each basin was covered with plastic film. The applied chemical fertilizers were mainly Urea $CO(NH_2)_2$ (N: 46.4%), Monoammonium phosphate $NH_4H_2PO_4$ (P_2O_5: 60.5%) and Potassium chloride KCl (K_2O: 57%). The amount of chemical fertilizer input were 225 kg NPK/hm^2 of urea in the whole growth period according to the agronomic recommendation of the local seed breeding institution[32]. In addition, the total irrigation amount was 450 mm in all growth periods according to the local production practice of Shihezi City[33]. The medical infusion tube was used to simulate the dripper, and the irrigation volume of each barrel was precisely controlled. The dripper flow rate was 1.8 L/h, and the irrigation water salinity was 0.78 g/L.

2.3 Acquisition of indicator data

Three representative plants, which the middle lobes of the third pinnate compound leaf were counted from top to bottom, were selected in each treatment at the end of each growth stage. The plant height was measured with tape gauge and the stem diameter was determined using vernier caliper.

From May to August in 2017 and 2018, the photosynthesis rate (*Pn*), transpiration rate (*Tr*) and stomatal conductance (*Gs*) of processing tomatoes were measured with Li-6400 photosynthesis measurement system (Li-COR 6400, USA). Photosynthetic indicators such as intercellular CO_2 concentration (*Ci*) and meteorological indicators such as atmospheric CO_2 concentration (*Ca*) and photosynthetically active radiation (*PAR*) were determined. In the sunny and cloudless day of each stage of growth, the labeled single plant leaves and functional leaves of different parts for each test were selected to investigate the physiological indicators of the time period from 14:00 to 16:00. The functional leaves in different parts were selected for 3 repetitions, and the average value of each plant was taken. The average value of the plants was continuously recorded for 3 days (if the weather did not allow, the measurement was postponed), and the three-day average value was taken as the representative value of the growth stage.

The labeled individual functional leaves were selected, and their chlorophyll fluorescence parameters were determined with a PAM-2500 portable chlorophyll fluorescence instrument and a 2030-B leaf clamp (Walz, Germany). Firstly, the leaves were exposed to 1200 μmol/m^2 s (PFD) saturated pulse light for about 0.8 s after dark adaptation for 30 min, and the chlorophyll fluorescence parameters (initial fluorescence (F_0), maximum fluorescence (F_m), etc.) of dark reaction were measured. Before entering the daytime measurement, the corresponding F_m and F_0 of the blade were manually inputted, and then the stable fluorescence (F') and the maximum fluorescence under light were measured under light adaptation conditions. The fluorescence parameters included maximum fluorescence yield (F_m') and minimum fluorescence yield (F_0'), and the PSII maximum photochemical efficiency (F_v/F_m), PSII potential activity (F_v/F_0), photochemical quenching coefficient (*qP*), non-photochemical quenching coefficient (*NPQ*) and other fluorescence parameters (i.e., actual photochemical efficiency (ΦPSII) and non-photochemical quenching quantum yield ($Y(NO)$)). The parameters were calculated using the following equations[34] :

$$F_v/F_m = (F_m - F_0)/F_m \quad (1)$$

$$Fv/F_0 = (F_m - F_0)/F_0 \quad (2)$$

$$qP = (F_m' - F')/(F_m' - F_0') \quad (3)$$

$$NPQ = F_m/F_m' - 1 \quad (4)$$

$$\Phi PS\text{II} = (F_m' - F')/F_m' \quad (5)$$

$$Y(NO) = 1/(NPQ + 1 + qL \times (F_m/F_0 - 1)) \quad (6)$$

$$qL = qP \times F_0'/F' \quad (7)$$

where, in complete dark adaptation, F_0 is the minimum fluorescence yield; F_m is the maximum fluorescence yield; F_v is variable fluorescence yield; In light adaptation; F' is stable fluorescence yield; F_m' is maximum fluorescence yield; F_0' is minimum fluorescence yield; *qP* is photochemical quenching coefficient; *NPQ* is Non photochemical quenching coefficient; ΦPSⅡ is the actual photochemical efficiency; $Y(NO)$ is quantum yield of non-photochemical quenching; *qL* is the photochemical quenching coefficient.

In this study, the equation of irrigation water use efficiency (*i*WUE)[35] and nitrogen partial factor productivity (NPFP)[36] were presented as below:

$$i\text{WUE} = Y/I \quad (8)$$

$$\text{NPFP} = Y/N \quad (9)$$

where, Y is economic output, kg/hm^2; I is amount of irrigation, mm; N is amount of pure fertilization, kg/hm^2.

2.4 Fertilizer effect model

In this study, the single pot yield of processing tomatoes was fitted by univariate fertilizer effect model with linear plus plateau. The model was presented as below:

$$\begin{cases} y = a + bx & (x \le c) \\ y = P & (x > c) \end{cases} \quad (10)$$

where, y is the single pot yield of processing tomatoes, kg/hm^2; x is the amount of fertilizer application, kg/hm^2; a, b and c are the equation intercept, the regression coefficient and the intersection of the platform and the straight line, respectively; P is the platform Production, kg/hm^2.

In addition, the unary quadratic model was also used to fit the single pot yield of processing tomatoes according to the following equation:

$$y = \text{a}_1 + \text{b}_1 x + \text{c}_1 x^2 \quad (11)$$

where, a_1, b_1 and c_1 is the equation intercept, regression coefficient of the first term and regression coefficient of the second term, respectively.

The single pot yield of processing tomatoes was also fitted using square root model as below:

$$y = a_2 + b_2 x^{0.5} + c_2 x \quad (12)$$

where, a_2, b_2 and c_2 is the equation intercept, regression coefficient of the square root term and regression coefficient of the first term, respectively.

2.5 Data analysis

Two-way analysis of variance (ANOVA) and Post hoc multiple comparisons were used to test the main effects of the soil salt contents, soil nitrogen contents, and interaction of soil salt contents with soil nitrogen contents on the growth and physiological characteristics of processing tomato. The two-way analysis of variance was conducted with SPSS 22.0 software (SPSS Inc., Chicago, IL, USA).

3 Results and discussion

3.1 Effects of nitrogen and salt on the growth of processed tomato

The plant height and LAI of processing tomatoes gradually increased with the growth stages in 2017 and 2018 (Figure 3). However, the growth rate significantly decreased from the end of expansion to the end of maturity (Jul 25-Aug 15) compared with the growth stage of the earlier period (May 20-June 16) and even

LAI presented the decrease at the end of maturity (Figure 3). For N3S2 treatment, the plant height in 2017 was higher than that in the earlier period (May 20-June 16). For instance, the growth rate of plant height plant height increased at by 3.62% and 41.56%, and the LAI was –6.69% and 58.41% in the late and early growth stages of processed tomato, respectively, but was constant in the intermediate growth stages of processed tomato. The changes were generally consistent in 2018 and 2017. The plant height and LAI of processing tomatoes were higher in low salt treatment (i.e., CK and S1) than those in high salt treatment (i.e., S2, SS2, SS3 and S3) in 2017 and 2018 (Figure 3), indicating that S1 promoted but S2 and S3 inhibited the growth of processing tomatoes, and the inhibition strengthened with the increase of soil salt content under the same nitrogen level in 2017 and 2018 (Figure 3). Our results were in agreement with previous observations that soil salinity negatively affected the growth of mangrove, tomato, and chile pepper plants and the effects increased with increase in soil salinity[37-39]. Zhang et al.[40] found that tomato growth was not significantly affected by short-term (<21 d) salinity stress regardless of the growth stage of the plant.

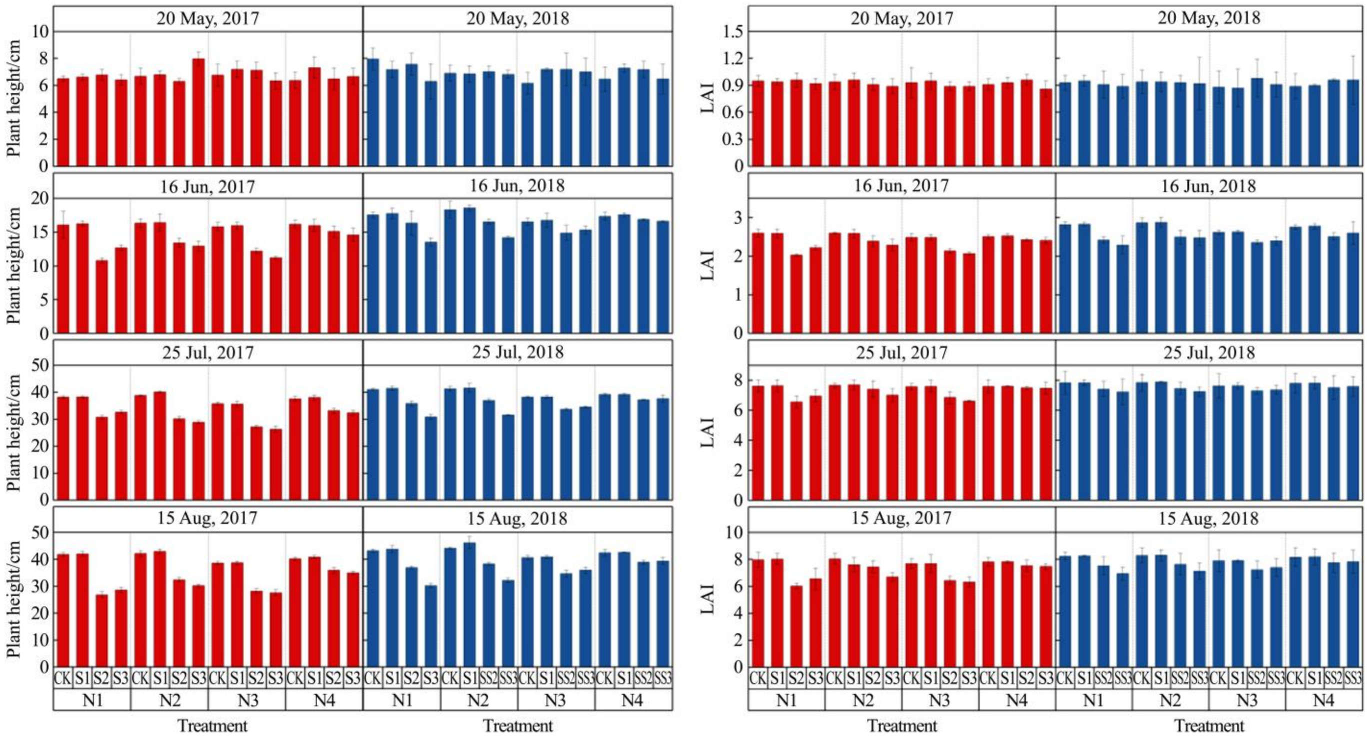


Figure 3 Plant height and LAI of processing tomato in different soil nitrogen and salt contents

Table 4 Two-way analysis of variance (ANOVA) of the effects of nitrogen and salt on plant height and LAI of processing tomato

Years	Treatments	Plant height /(cm)				LAI			
		20 May	16 Jun	25 Jul	15 Aug	20 May	16 Jun	25 Jul	15 Aug
2017	N	65.610**	689.554**	72.196**	4629.192**	18.442**	782.237**	5820.412**	20.491**
	S	83.615**	4059.103**	68.767**	36804.592*	75.509**	3251.361**	17683.942**	87.275**
	N*S	160.642**	285.922**	12.370**	1395.038**	18.155**	311.289**	2518.048**	11.300**
2018	N	55.777**	360.899**	267.247**	40.166**	11.207**	18.365**	232.715**	1063.871**
	S	45.694**	2412.584**	4417.385**	610.760**	7.934**	141.453**	2720.700**	11043.724**
	N*S	40.658**	261.629**	404.810**	42.769**	9.053**	5.244**	109.670**	639.378**

Note: Different letters indicate significant difference between treatments (p<0.05). ** and *. Indicates correlation is significant at $p < 0.01$ and $p < 0.05$ (two-tailed), respectively. N: nitrogen, S: salt content.

In this study, soil salt did not affect the plant height and LAI of processed tomatoes during the seedling and flowering and fruit setting stages but significantly influenced them during the fruit expansion and maturity stages in 2017 and 2018. Soil salt significantly inhibited the plant height and LAI of processed tomatoes as the soil salt content exceeded 5.0 g/kg. This is in accordance with the observation of Chaichi, who found that high salt resulted in a decrease in nitrogen absorption and thus low nitrogen content in tomato plant tissues. The increase of nitrogen fertilizer input significantly increased the plant height and LAI of processed tomatoes under the low soil salt content[41]. However, as soil salt content was too high, adding nitrogen fertilizer not only resulted in the decrease in plant height and LAI of processed tomatoes, but also led to the decrease in nitrogen use efficiency[41].

3.2 Responses of photosynthetic index of processing tomatoes to soil nitrogen and salt content

Figure 3 shows the response of photosynthetic indexes (i.e., Pn, Gs and Ci) of tomato processed by drip irrigation to nitrogen application rate and soil salt content under drip irrigation in 2017 and 2018. The Ci gradually increased with the whole growth stages. However, Pn and Gs significantly increased before fruit expansion stage but generally decreased after fruit expansion stage (Figure 4a, 4b and 4c). When soil salt content exceeded 7 g/kg in 2017 and 5 g/kg in 2018, soil salt negatively affected photosynthetic indexes. Zhu et al.[42] found that the salt stress of 5.3 g/kg resulted in a significant decrease in the Pn, Gs and Ci of cotton leaves, which was consistent with the results of this study. Ke et al.[43] found that low concentration of NaCl (i.e., 1 g/kg) had no significant effect on Pn in mulberry seedling leaves, while high concentration of NaCl (i.e., 3 g/kg, 5 g/kg and 7 g/kg) had significant inhibition on Pn. The effects on photosynthetic index increased with the increase of salt content. In addition, it was found that the maximum nitrogen application rate was 300 kg/hm^2. The nitrogen fertilizer input positively influenced photosynthetic index when soil salt content was lower, but increase of nitrogen fertilizer did not improve the photosynthetic index obviously and aggravated the inhibition of salt at a certain extent as soil salt content was higher. Salt stress inhibits photosynthesis of plants (especially non-halophytes) and reduces the ability of plants to assimilate products[44]. As the salt concentration increases, the degree of inhibition of plant photosynthesis increases[45]. Li et al.[46] found that photosynthetic parameters (i.e., Pn and Gs) significantly decreased as the concentration of NaCl in the soils increased from 0 mmol/L to 400 mmol/L, indicating that the photosynthesis of mangrove leaves is severely affected under salt stress conditions.

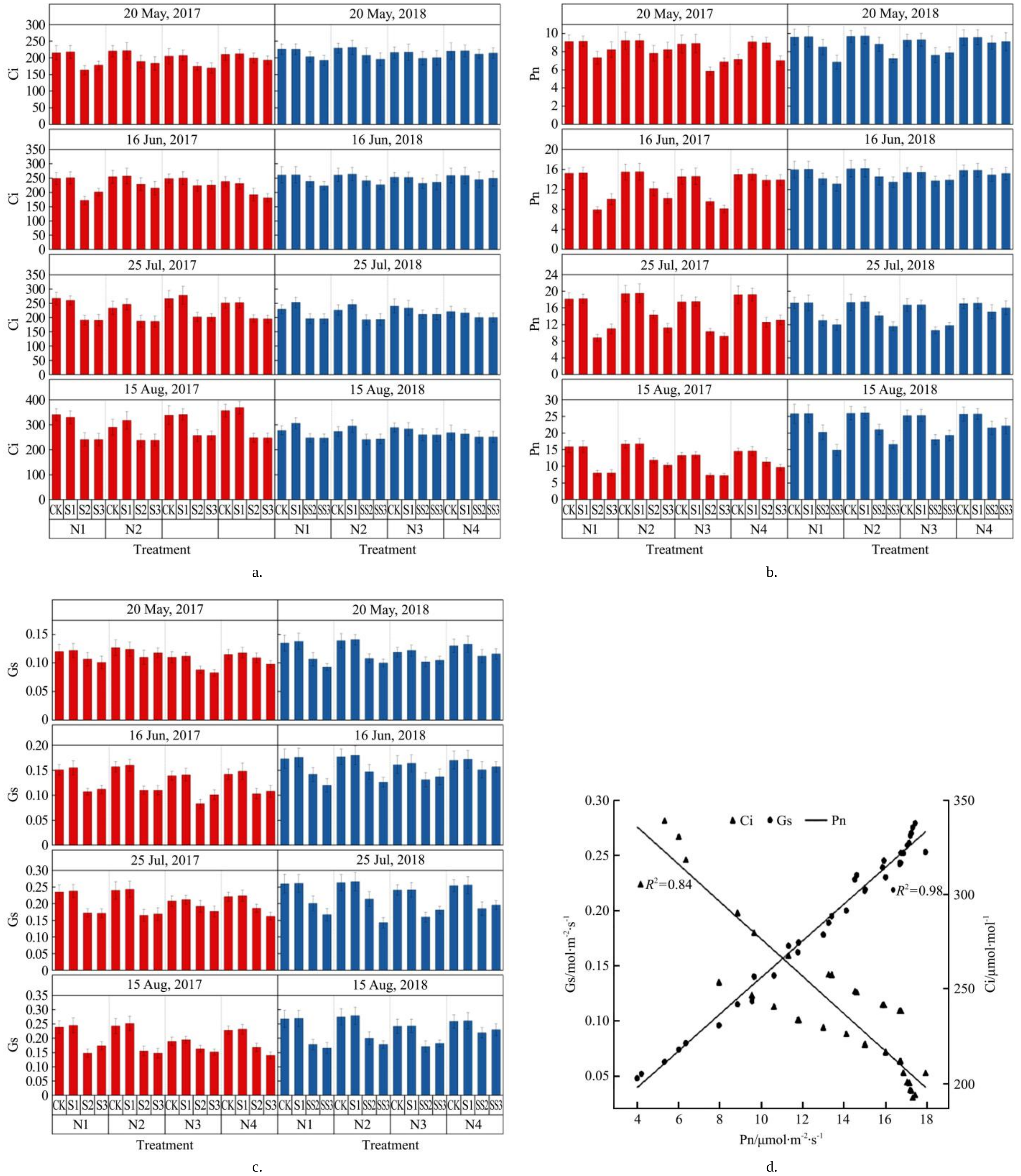
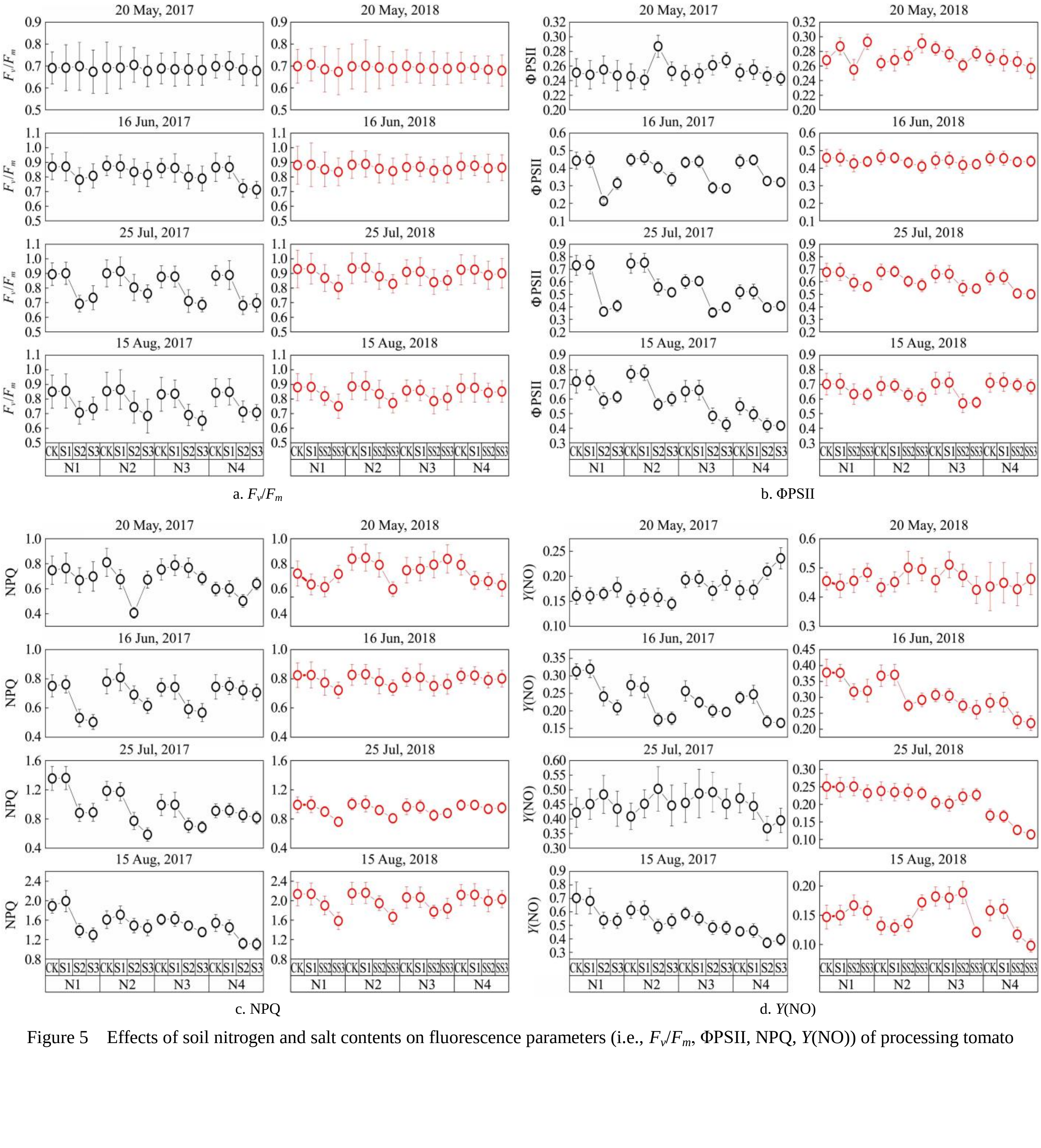


Figure 4 Effects of soil nitrogen and salt contents on photosynthetic indexes (i.e., Ci(a), Pn(b), Gs(c)) of processing tomato and relationships among photosynthetic indexes

3.3 Responses of fluorescence parameters of processing tomatoes to soil nitrogen and salt content

Figure 5 shows the effect of nitrogen and salt on fluorescence index of processing tomato by drip irrigation in 2017 and 2018. The F_v/F_m, ΦPSII and NPQ increased in S1, but decreased in S2 and S3 compared with S0 under all soil nitrogen content in 2017 and 2018, indicating that F_v/F_m, ΦPSⅡ and NPQ increased as soil salt content was lower than 5 g/kg and higher than 7 g/kg but decreased with increase of soil salt contents at the extent of 5-7 g/kg. Salt stress can damage the photosynthetic organs of plant chloroplasts and the ΦPSII reaction center, ultimately leading to a decline in plant photosynthetic capacity[47]. The salt stress on plant chlorophyll fluorescence causes the decreases of F_v/F_m, F_v/F_o, and ΦPSII, but the increase of NPQ[48]. Plants can increase heat dissipation through non-photochemical quenching, consume excessive excitation energy, and thus reduce the damage of the stress environment and protect themselves[49,50]. The stress degree of fluorescence index increased with the increase of salt content. The fluorescence indexes gradually increased with the growth of processed tomato. Increasing soil nitrogen input could improve fluorescence index as soil salt contents was lower (i.e., CK and S1). The medium and high nitrogen application rate was beneficial to the increase of *Fv*/*Fm*, ΦPSII and NPQ when soil salt contents were higher (i.e., S2, S3, SS2 and SS3), thus promoting the photosynthetic capacity of processing tomato. *Y*(NO) gradually decreased with the growth of processing tomato in 2017 and 2018 (Figure 5d). *Y*(NO) decreased with increase of soil salt contents at the extent of 5-7 g/kg during the early growth stages of processing tomato and increased at the extent of 1-7 g/kg during the later growth stages of processing tomato under all soil nitrogen levels. In the middle and high salt area, *Y*(NO) gradually increased with the development of growth period. However, salt stress promoted the increase of *Y*(NO) and *Y*(NO) was highest as soil salinity was highest. When the amount of salt enters plant



a. F_v/F_m

b. ΦPSII

c. NPQ

d. *Y*(NO)

Figure 5 Effects of soil nitrogen and salt contents on fluorescence parameters (i.e., F_v/F_m, ΦPSII, NPQ, *Y*(NO)) of processing tomato cells, the chloroplast function and photosynthetic performance were affected and even damaged[51,52]. Zhao et al.[53] indicated that Fv/Fm and Fo significantly decreased as the salt concentration was 100~200 mmol/L. Additionally, salt stress inhibited the photochemical activity of PSII and electron transfer, and weakened the maximum PSII light energy conversion efficiency.

3.4 Water and nitrogen use efficiency of processing tomatoes

Figure 6 shows the interaction effects of nitrogen and salt on yield, IWUE and NPFP of processing tomato by drip irrigation in 2017 and 2018. The soil salt contents, soil nitrogen contents and the interaction of soil salt with soil nitrogen significantly affected the Yield, IWUE and NPFP of processing tomato. In general, the Yield, IWUE and NPFP of processing tomato increased in S1 treatment but decreased in S2 and S3 treatment under all soil nitrogen levels compared with CK treatment in 2017 and 2018, indicating that the yield, IWUE and NPFP of processing tomato decreased with increase of soil salt content at the extent of 1-10 g/kg. The surprising results were that the Yield, IWUE and NPFP of processing tomato in N1S3 treatment were higher than those in N1S2 treatment in 2017. The increase of nitrogen fertilizer input could increase the yield of processed tomato and the IWUE in low salt treatment (CK and S1), which were highest in N2S1 treatment. The yield and IWUE significantly decreased in 2017 but were generally constant in 2018 with increasing input of nitrogen fertilizer in high salt treatment. Nitrogen partial productivity decreased significantly with the increase of nitrogen application rate, and the effect of high salt treatment on nitrogen partial productivity was higher than that of low salt treatment. The results were consistent with previous observation that NFP decreased with the increase of fertilizer amount under the same irrigation amount[54,55]. Hou et al.[56] and Gao et al.[57] also found that agronomic efficiency and partial productivity of nitrogen fertilizers significantly reduced with the increase of nitrogen application rate.

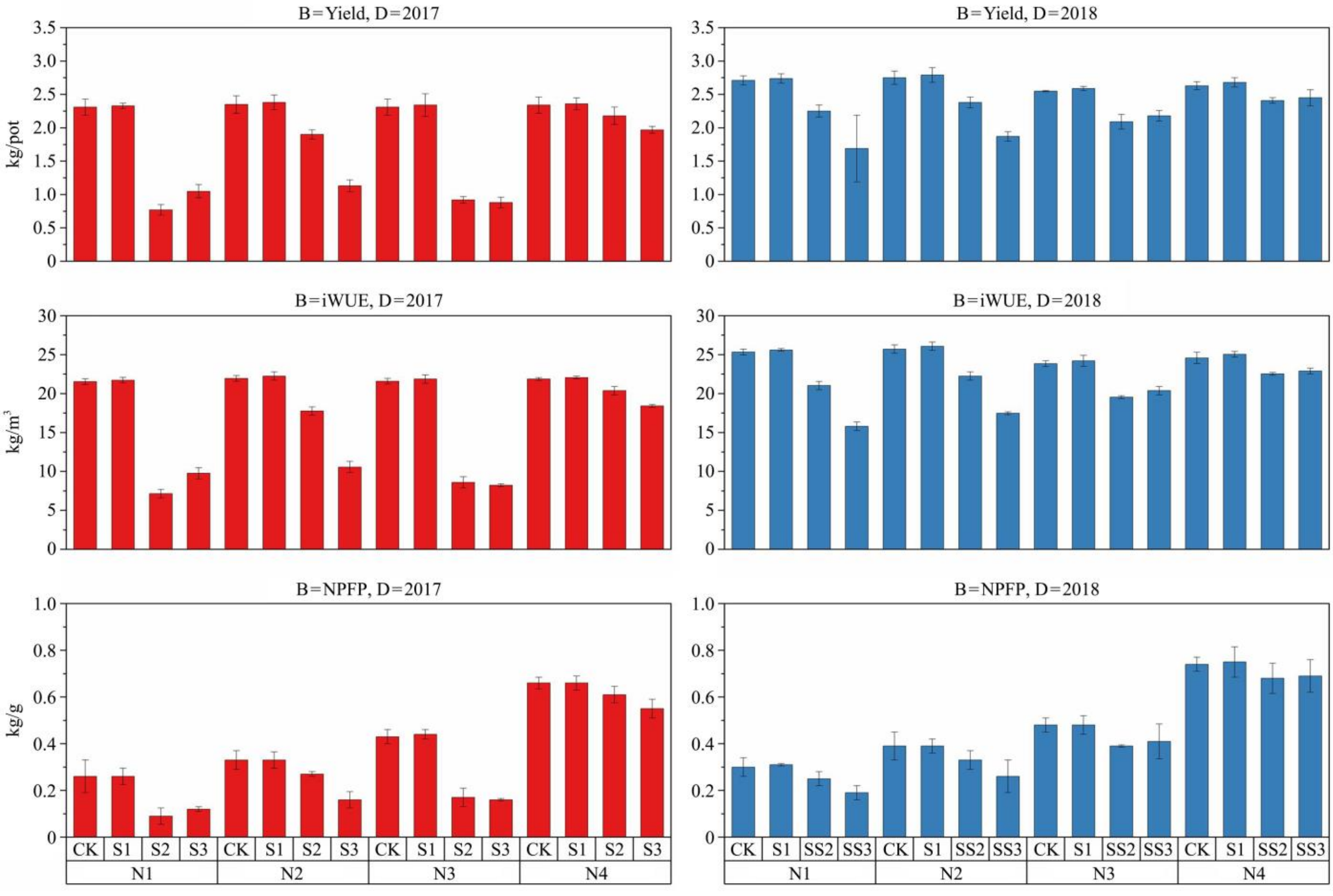


Figure 6 Effects of soil nitrogen and salt contents on the yield and water and nitrogen use efficiency of processing tomato

3.5 Analysis of univariate effect model of nitrogen

Table 5 reflects the corresponding nitrogen effect equation of three saline-alkali soils (non-saline-alkali soil, weak saline-alkali soil and moderate saline-alkali soil). The changing trends in the determinant coefficient R^2 of the nitrogen effect equation was unary quadratic > linear plus plateau > 0.5 > square root for non-saline-alkali soil, linear plus plateau > unitary quadratic > 0.5 > square root for weak saline-alkali soil, and square root > unitary quadratic > linear plus plateau > 0.5 for moderate saline-alkali soil, respectively (Table 5). Therefore, the unitary quadratic and linear plus plateau should be selected to fit the relationship of nitrogen application to yield for non-saline-alkali soil and weak saline-alkali soil, but the square root effects equations was selected to present the relation of nitrogen application with yield of processing tomato for moderate saline-alkali soil.

3.6 Maximum yield and nitrogen application

The fitting results of the maximum yield of the univariate nitrogen effect model for soils with different salinity and alkalinity are shown in Table 6. Although the univariate quadratic and square root effect equations have certain fitting effects for non-saline-alkali soil and weak saline-alkali soil, there is no the amount of nitrogen fertilizer input to fit the maximum yield. Therefore, the linear plus plateau model is selected for the nitrogen effect models of non-saline-alkali soil and weak saline-alkali soil, which the determination coefficients were 0.615 and 0.648, respectively. Three formulas were used to fit the maximum yield and the nitrogen application rate for the moderate saline-alkali soil, but the preferable square root model was selected according to the determinant coefficient. The highest yield was 1.05×10^6 kg/hm^2 with square root equation and the nitrogen application rate was 58.83 kg/hm^2.

Table 5 Unary models of nitrogen fertilizer effects on processing tomato in different saline soil

Fertilizer	Degree of soil salinization	Fertilizer effect model	Model function	R^2
N	Non-salt alkaline soil	Linear plus plateau	$y=2.504+0.019x$ (when x<8.474) $y=2.665$ (when $x\geq8.474$)	0.615
		Unary quadratic	$y=0.0019x^2+0.001x+2.5235$	0.674
		Square root	$y=-0.05809x^{0.5}+0.03799x+2.52369$	0.434
	Weak saline alkaline soil	Linear plus plateau	$y=2.555+0.018x$ (when x<8.625) $y=2.690$ (when $x\geq8.625$)	0.648
		Unary quadratic	$y=0.0009x^2+0.0076x+2.5697$	0.543
		Square root	$y=-0.03076x^{0.5}+0.02608x+2.57057$	0.420
N	Moderate saline-alkaline soil	Linear plus plateau	$y=2.105+0.083x$ (when x<2.867) $y=1.867$ (when $x\geq2.867$)	0.646
		Unary quadratic	$y=-0.0195x^2+0.0076x+2.1359$	0.902
		Square root	$y=0.6601x^{0.5}-0.27816x+2.1086$	0.970

Note: *X* in Linear plus plateau Function is Platform Output.

Table 6 Predicted maximum yield with each model of nitrogen fertilizer effects on processing tomato in different saline soil

Fertilizer	Degree of soil salinization	Fertilizer effect model	Nitrogen application rate/kg ·hm^{-2}	The highest yield of fresh fruit/kg ·hm^{-2}
N	Non-salt alkaline soil	Linear plus plateau	355.61	111834.82
		Unary quadratic	—	—
		Square root	—	—
	Weak saline alkaline soil	Linear plus plateau	361.94	112883.93
		Unary quadratic	—	—
		Square root	—	—
	Moderate saline-alkaline soil	Linear plus plateau	120.31	78347.32
		Unary quadratic	8.18	89593.75
		Square root	58.83	104910.71

The larger amount of nitrogen fertilizers is added to achieve the maximum yield for non-salt alkaline soil (355.43 kg/hm^2) and weakly saline alkaline soil (362.15 kg/hm^2), and the yields did not differ between non-salt alkaline soil and weakly saline alkaline soil 1.12×10^6 kg/hm^2 vs 1.13×10^6 kg/hm^2, respectively). However, the lower amount of nitrogen fertilizers (58.75 kg/hm^2) reaches the highest yield of 1.15×10^6 kg/hm^2 for moderate saline-alkali soil. The results indicated that the amount of nitrogen fertilizers in moderate saline-alkali soil was 83.46% and 83.74% lower than that in non-salt alkaline soil and weak saline-alkali soil, respectively. Therefore, the processing tomatoes should be planted in moderate saline-alkali soil to achieve higher yields due to lower input of nitrogen fertilizer. The fitting results are consistent with the experimental results.

4 Conclusions

In this study, we presented the processing tomato growth and physiological characteristics with changes in soil nitrogen and salt contents under drip irrigation in Xinjiang of China. The nitrogen fertilizer was added to reconcile salt stress to explore the response mechanism of crop growth and yield to soil nitrogen and salt contents. At the same time, the quantification of nitrogen application and the maximum yield in tomato processing in Xinjiang is realized by the comparing and selecting the preferable fitted model of nitrogen effect. Conventional nitrogen application (225 kg/hm^2) had the least effect on the growth of processing tomato among all soil salinity treatments. The optimal amount of nitrogen fertilizer input was 300 kg/hm^2 for processing tomato as soil salt content was lower than 4.0 g/kg. The nitrogen application rate of 150 kg/hm^2 is the most effective for processing tomato when salt content was higher than 5.0 g/kg. For practical application, the processing tomatoes should be planted in moderate saline-alkali soil to achieve higher yields due to lower input of nitrogen fertilizer, potentially reducing fertilizer costs and maximizing profits from high processing tomato yields. In addition, the linear plus platform was selected to determine the nitrogen effect models of non-saline-alkali soil and weak saline-alkali soil, but the square root nitrogen effect model of moderate saline-alkali soil was selected to accurately predict the yield of processing tomato.

Acknowledgements

The authors gratefully acknowledge the financial supports by National Key R&D Program “Research and Application of Economic Crop Water and Fertilizer Integration Technology Model” of China (2017YFD0201506), and Shihezi University International Science and Technology Cooperation Promotion Plan Project (GJHZ201803).

[References]

[1] Feng B Q, Cui J, Wu D, Guan X Y, Wang S L. Causes and countermeasures of cultivated land salinization in northwest irrigation area. China Water Resources, 2019; 9: 43–46. (in Chinese)

[2] Da L I N, Tanis I K, Koutroulis A, Koutroulis N N, Varouchakis A E, Karatzasg P. The threat of soil salinity: A European scale review. Science of the Total Environment, 2016; 573: 727–739.

[3] Luca Salvati, Carlotta Ferrara. The local-scale impact of soil salinization on the socioeconomic context: An exploratory analysis in Italy. Catena, 2015; 127: 312–322.

[4] Chen W, Hou Z, Wu L, Liang Y, Wei C. Evaluating salinity distribution in soil irrigated with saline water in arid regions of northwest China. Agr Water Manage, 2010; 97: 2001–2008.(in Chinese)

[5] Xi J B, Zhang F S, Mao D R, Tian C Y, Song Y M, Liu D X. Saline-soil distribution and halophyte resources in Xinjiang. Chinese Journal of Soil Science, 2005; 3: 299–303. (in Chinese)

[6] Akhtar S S, Andersen M N, Naveed M, Zahir Z A, Liu F. Interactive effect of biochar and plant growth-promoting bacterial endophytes on ameliorating salinity stress in maize. Functional Plant Biology, 2015; 42:

770–781.
[7] Ashraf M, Athar H R, Harris P J C, Kwon T R. Some prospective strategies for improving crop salt tolerance. Advances in Agronomy, 2008; 97: 45–110.
[8] Ashraf M. Improving salinity tolerance in cereals. Critical Reviews in Plant Sciences, 2013; 32: 237–249.
[9] Hanay A, Kiziloglu F M, Canbolat M Y. Reclamation of saline-sodic soils with gypsum and MSW compost. Compost Science & Utilization, 2004; 12: 175–179.
[10] Zahir Z A, Akhtar S S, Ahmad M, Nadeem S M. Comparative effectiveness of Enterobacter aerogenes and Pseudomonas fluorescens for mitigating the depressing effect of brackish water on maize. International Journal of Agriculture & Biology, 2012; 14: 337–344.
[11] Reddy N, Crohn D M. Effects of soil salinity and carbon availability from organic amendments on nitrous oxide emissions. Geoderma, 2014; 235-236: 363–371.
[12] Shu S. Effects of exogenous spermidine on photosynthesis, xanthophyll cycle and endogenous polyamines in cucumber seedlings exposed to salinity. African Journal of Biotechnology, 2012; 11: 6064–6074.
[13] Meloni D A, Oliva M A, Martinez C A, Cambraia J. Photosynthesis and activity of superoxide dismutase, peroxidase and glutathione reductase in cotton under salt stress. Environmental & Experimental Botany, 2003; 49: 69–76.
[14] Staff U S S L. Diagnosis and Improvement of Saline and Alkali Soils, Agriculture Handbook No. 60, Rev. ed. United States Department of Agriculture, Washington DC, 1969.
[15] Grattan S R, Grieve C M. Salinity–mineral nutrient relations in horticultural crops. Scientia Horticulturae, 1998; 78: 127–157.
[16] Paul D, Lade H. Plant-growth-promoting rhizobacteria to improve crop growth in saline soils: a review. Agronomy for Sustainable Development, 2014; 34: 737–752.
[17] Li J B, Huang, G H. Pilot study of salinity (NaCl) affecting nitrogen transformation in silt loam soil. Research of Environmental Sciences, 2008, 98–103.(in Chinese)
[18] Munns R, Tester M. Mechanisms Salinity Tolerance. Annual Review of Plant Biology, 2008; 59: 651–681.
[19] Parida A K, Das A B. Salt tolerance and salinity effects on plants: a review. Ecotoxicol Environ Saf, 2005; 60: 324–349.
[20] Misra A N, Sahu S M, Misra M, Singh P, Meera I, Das N, et al. Sodium chloride induced changes in leaf growth, and pigment and protein contents in two rice cultivars. Biologia Plantarum, 1997; 39: 257–262.
[21] Mehta P, Jajoo A, Mathur S, Bharti S. Chlorophyll fluorescence study revealing effects of high salt stress on Photosystem II in wheat leaves. Plant Physiol Biochem, 2010; 48: 16–20.
[22] Burman U, Garg, B K, Kathju S. Water relations, photosynthesis and nitrogen metabolism of Indian mustard (Brassica juncea Czern & Coss) grown under salt and water stress. Journal of Plant Biology-New Delhi, 2003; 30: 55–60.
[23] Strasserf R J S A. Polyphasic chlorophyll a fluorescence transient in plants and cyanobacteria. Photochemistry & Photobiology, 2010; 61: 32–42.
[24] Schansker G, Srivastava A, Strasser R J. Characterization of the 820 nm transmission signal paralleling the chlorophyll a fluorescence rise (OJIP) in pea leaves. Functional Plant Biology, 2003; 30: 785–796.
[25] Percival G C, Fraser G A. Measurement of the salinity and freezing tolerance of Crataegus genotypes using chlorophyll fluorescence. Journal of Arboriculture, 2001; 27(5): 233–245.
[26] Pessarakli M. Handbook of plant and crop physiology. Phytochemistry, 2002; 63: 631–631.
[27] Duan H, Fu L, Ju J C, Liu L J, Yang J C. Effects of application of nitrogen as panicle-promoting fertilizer on seed setting and grain quality of rice under high temperature stress. Chinese Journal of Rice Science, 2013; 27: 591–602. (in Chinese)
[28] Wang Y, Tang X Q, Shi S L, Wang K C. Effects of different nitrogen application levels on physiological characteristics and content of (R, S) -Gaitun in roots of Isatis indigotica at seedling stage under salt stress. Journal of Nuclear Agricultural Sciences, 2017; 31(2): 394–401. (in Chinese)
[29] Xiao Y H, Zhao X L, Wang K C, Shi X M, Tang X Q. Effect of different nitrogen forms and concentrations on biomass and alkaloids of Isatidis Folium. China Journal of Chinese Materia Medica, 2013; 38: 2755–2760. (in Chinese)
[30] Cleland E E, Harpole W S, Ostfeld R S, Schlesinger W H. Nitrogen enrichment and plant communities. Ann N Y Acad Sci, 2010; 1195: 46–61.
[31] Sala O E, Chapin F S, Armesto J J, Berlow E, Bloomfield J, Dirzo R, Huber-Sanwald E, Huenneke L F, Jackson R B, Kinzig A. Global biodiversity scenarios for the year 2100. Science, 2000; 287: 1770–1774.
[32] Zhang T Q, Tan C S, Liu K, Drury C F, Papadopoulos A P, Warner J. Yield and economic assessments of fertilizer nitrogen and phosphorus for processing tomato with drip fertigation. Agron J, 2010; 102: 774–780. (in Chinese)
[33] Hanson B, May D. Effect of subsurface drip irrigation on processing tomato yield, water table depth, soil salinity, and profitability. Agr Water Manage, 2007; 68: 1–17.
[34] Roháček K. Chlorophyll Fluorescence Parameters: The Definitions, Photosynthetic Meaning, and Mutual Relationships. Photosynthetica, 2002; 40: 13–29.
[35] Yang X Z, Zhang X, Ma J X, Zhang Y, Zhang N, Wang Y Q, et al. Effects of drip fertigation on growth, yield and quality of watermelon in plastic greenhouse. Transactions of the CSAE, 2014; 30: 109–118. (in Chinese)
[36] Li Y, Wang F, Sun J S, Liu H, Yang J Q, Xian F, Su H. Coupling effect of water and nitrogen on mechanically harvested cotton with drip irrigation under plastic film in arid area of western Inner Mongolia, China. Chinese Journal of Applied Ecology, 2016; 27: 845–854. (in Chinese)
[37] Shiau Y J, Lee S C, Chen T H, Tian G, Chiu C Y. Water salinity effects on growth and nitrogen assimilation rate of mangrove (Kandelia candel) seedlings. Aquatic Botany, 2017; 137: 50–55. (in Chinese)
[38] Singh M, Singh V P, Prasad S M. Responses of photosynthesis, nitrogen and proline metabolism to salinity stress in Solanum lycopersicum under different levels of nitrogen supplementation. Plant Physiology and Biochemistry, 2016; 109: 72–83.
[39] Villa-Castorena M, Ulery A L, Catalán-Valencia E A, Remmenga M D. Salinity and nitrogen rate effects on the growth and yield of chile pepper plants. Soil Science Society of America Journal, 2003; 67(6): 1781–1789.
[40] Zhang P, Senge M, Dai Y. Effects of salinity stress at different growth stages on tomato growth, yield, and water-use efficiency. Communications in Soil Science and Plant Analysis, 2017; 48(6): 624–634.
[41] Chaichi M R, Keshavarz-Afshar R, Lu B, Rostamza M. Growth and nutrient uptake of tomato in response to application of saline water, biological fertilizer, and surfactant. Journal of Plant Nutrition, 2017; 40(4): 457–466.
[42] Zhu Y K, Wang Z H, Li W H. Effects of different salt stress on physiological growth and yield of cotton under drip irrigation. Journal of Soil and Water Conservation, 2018; 32(2): 298–305. (in Chinese)
[43] Ke Y Z, Zhou J X, Lu N, Zhang X D, Sun Q X. Effects of salt stress on photosynthetic physiology and chlorophyll fluorescence characteristics of Mulberry seedlings. Forest Research, 2009; 22(2): 200–206. (in Chinese)
[44] Chaves M M, Flexas J, Pinheiro C. Photosynthesis under drought and salt stress: regulation mechanisms from whole plant to cell. Annals of Botany, 2009; 103(4): 551–560.
[45] Stepien P, Ktbus G. Water relations and photosynthesis in *Cucumis sativus* L. leaves under salt stress. Biologia Plantarum, 2006; 50(4): 610–616.
[46] Li N Y, Chen S L, Zhou X Y, Li C Y, Shao J, Wang R G, et al. Effect of NaCl on photosynthesis, salt accumulation and ion compaitmentation in two mangrove species, Kandelia candel and Bruguiera gymnorhiza. Aquatic Botany, 2008; 88(4): 303–310. (in Chinese)
[47] Yang S P, Wei C Z, Liang Y C. Effects of salt stress on photosynthesis and fluorescence characteristics of different genotypes of sea island cotton. Scientia Agricultura Sinica, 2010; 43(8): 1585–1593. (in Chinese)
[48] Shi Q H, Zhu Z J, Khalida A, Qian Q Q. Effects of Isoosmotic $Ca(NO_3)_2$ and Na (Cl) stress on photosynthesis of Tomato. Plant Nutrition and Fertilizer Science, 2004; 2: 188–191. (in Chinese)
[49] Qin H Y, Ai J, Xu P L, Wang Z X, Zhao Y, Yang M Y et al. Effects of salt stress on chlorophyll fluorescence parameters and ultrastructure of Grape. Acta Botanica Boreali-Occidentalia Sinica, 2013; 33(6): 1159-1164. (in Chinese)
[50] Tang L, Li Q Z, Rong L P, Li S S. Effects of salt stress on seedling growth and chlorophyll fluorescence parameters of acer chinensis. Acta Botanica Boreali-Occidentalia Sinica, 2015; 35(10): 2050–2055. (in Chinese)
[51] Wang W L, Wan Y J, Liu B, Wang G X, Tang X Y, Chen X, et al. Influence of soil gradual drought stress on Acorus calamus growth and photosynthetic fluorescence characteristics. Acta Ecologica Sinica, 2013; 33(13): 3933–3940. (in Chinese)

[52] Li Y H, Liu J H, Zhao B P, Tian L, Wang Q, Zhu S S, et al. Regulatory effect of humic acid on chlorophyll fluorescence characteristics of oat under drought stress. Journal of Irrigation and Drainage, 2020; 39(4): 26–33. (in Chinese)

[53] Zhao Y F, Ren X X, Chen K. Effects of salt stress on seed germination, photosynthetic index and chlorophyll fluorescence parameters of eggplant. Tianjin Agricultural Sciences, 2018; 24(8): 4–6, 10. (in Chinese)

[54] Di Paolo E D, Rinaldi M. Yield response of corn to irrigation and nitrogen fertilization in a Mediterranean environment. Field Crops Research, 2007; 105(3): 202–210.

[55] Zhou H M, Zhang F C, Wu L F, Fam J L, Xiang Y Z. Effect of water-fertilizer coupling on yield, quality and utilization of water and fertilizer in young apple trees. Transactions of the CSAM, 2015; 46(12): 173–183. (in Chinese)

[56] Yin C X, Li Q, Kong L L, Qin Y B, Wang M, Yu L, et al. Effects of reduced application of controlled release nitrogen fertilizer on yield, nitrogen uptake and transport of spring maize. Scientia Agricultura Sinica, 2018; 51(20): 3941–3950. (in Chinese)

[57] Gao H J, Peng C, Dou S, Zhang X Q, Li Q, Li S Q, et al. Effects of straw returning combined with nitrogen application on nitrogen utilization and soil nitrogen balance in spring maize. Journal of Maize Science, 2020; 28(6): 134–141. (in Chinese)