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Peanut production in saline-alkali land of Yellow River Delta: influence of spatiotemporal changes of meteorological conditions and soil properties

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Abstract

Background This study clarified the synergistic relationship among annual changes to specify the changes in agro-meteorological factors, soil characteristics and peanut growth in saline-alkali land near the estuary of the Yellow River Delta. We aimed to find the key factors affecting peanut production to optimize and regulate peanut planting mode in saline alkali soil.

Results The daily average temperature from early May to late September in Lijin and Kenli was above 24 °C, with 470–600 mm of precipitation. The sunshine duration was 7.9 h/day and 7.3 h/day and the accumulated temperature was 3742 °C and 3809 °C, in Lijin and Kenli, respectively. Agro-meteorological conditions were suitable for peanut growth and development with the consistent main developmental period in the two experiment regions. The best sowing period was when the soil temperature stabilized above 18 °C in early May, and the best harvest was in mid-September. The soil volumetric water content in Lijin concentrated among 25–40%. Salt was mainly distributed in the 40–60 cm soil layers, and increased rapidly to 2.5 g kg^{-1} in 0–20 cm cultivation layer in mid-May due to lack of precipitation. In Kenli experiment region, the soil volumetric water content ranged from 10 to 35%. Soil salinity was mainly distributed in the 20 cm soil layer, and the changes in salinity was little affected by precipitation. From mid-July to mid-August, the effective accumulated temperature of 5 cm soil layer was above 520 °C in both regions, which could ensure the normal pod development. The slow dynamic growth of kernel, high unfilled pod rate (26.99%) and low shelling rate (66.0%) might be the main reasons for low peanut yield in Lijin.

Conclusion Soil salinity was the main factor affecting pod development and yield. It was also a key point in optimizing the peanut planting mode in the saline alkali land of the Yellow River Delta.

Keywords Agro-meteorological condition, Pod development, Peanut yield, Saline-alkali land, Soil salinity

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Background

The Yellow River Delta is located in Dongying City, Shandong Province, China, with rich land resources, favorable natural conditions and strategic ecological location. It has gradually become an important potential resource for alleviating China's food security crisis and expanding the available land area. However, soils in this region have been degraded by the adverse natural environment such as seawater intrusion and strong evaporation for a long time. Excessive exploitation of groundwater in coastal areas has caused a significant drop in groundwater levels in this region. The hydrodynamic balance between seawater and freshwater is disrupted, resulting in the movement of the saltwater boundary towards land, and subsequent seawater intrusion increases the salinity in groundwater. Long term use of high salt groundwater irrigation leads to the accumulation of salt in the soil surface layer. At the same time, soluble salts in high concentration saline water can also accumulate in the tillage layer along capillaries, rising to the surface and causing soil salinization [1, 2]. And the soil salinization and secondary salinization have become increasingly severe. The salinized land area is as high as 180,000 hm^2, accounting for about 63.6% of the total agricultural land area [3–5], which seriously restricts the sustainable development of regional economy and the prospect of agricultural development. Therefore, how to effectively use the saline land in this region is of great significance to realize the sustainable use of land resources.

In the context of climate change, the most suitable peanut planting areas in the Huang-Huai-Hai region are concentrated in the west of the Haihe River Basin and the Huaihe River Basin. The projections from the next 30 years show that both the most suitable and suitable areas have been expanded [6]. In 2013, the "Bohai Granary" project was launched to increase crop production in salt-affected soils across several provinces in north China. The strategic concept for the construction of the 'Bohai Granary' is proposed to address issues such as poor soil fertility, soil salinization, scarcity of freshwater resources in the low plain area around the Bohai Rim region. The 'Bohai Granary' constructions keep 'soil, fertilizer, water, and variety' as the central task, comprehensively adopt the improvement and yield increasing measures, and Transform and utilize the saline alkali wasteland to enhance the production capacity of medium fertile and poor farmland [7]. According to the demand of "Bohai Granary" construction of grain and cotton, to transform the Yellow River Delta saline land into good grain field is the main task of increasing grain production. Peanut is a medium salt-tolerant crop [8], an important oil and cash crop in China, and is a key contributor to the agricultural economy and export sector [9]. While fully tapping the high-yield potential of high-yield fields, planting peanuts in the Yellow River Delta area and improving saline farmland and other low-yielding fields are one of the important measures for rational use of saline land, which is of great significance for expanding peanut planting area, improving planting structure and increasing farmers' income. However, the limited irrigation water from rainfall, and high soil salt content in the Yellow River Delta seriously affected the survival and growth of peanut seedlings, and restricted the peanut production in this region [10, 11]. Maximizing the use of local climate resources, optimize peanut cultivation practices and obtain high and stable yield according to the conditions required for normal growth and development of peanut in non-saline soils has become a new proposition for peanut planting industry in saline soils. In recent years, we have carried out relevant studies on the evaluation of peanut salt tolerance, the influence of planting density and planting regime on peanut quality in saline soils [12–15]. However, the research on the cultivation regime of peanut in saline soils based on meteorological conditions has not been fully carried out. Therefore, based on agro-meteorological factors such as accumulated temperature, precipitation and sunshine, as well as the spatiotemporal changes in soil temperature, humidity, and salinity in the whole year and the whole growth period of peanut in the saline land area of the Yellow River Delta, in this study, we examined whether the meteorological and soil conditions in each growth period were consistent with the growth process of peanut, identified the key factors, adjusted and optimized the moisture and cultivation regime. The aim is to increase peanut yield and improve production technology, and to provide theoretical basis and technical support for peanut cultivation in the Yellow River Delta saline land.

Methods

Experimental site and agro-meteorological data

The experimental sites were selected in Lijin and Kenli located on the north side of the estuary of the Yellow River Delta. The selected areas were saline wasteland, and the soil type belongs to salinized tidal soil and coastal saline soil.

Lijin is located at latitude 37°22'–38°12'N, longitude 118°07'–118°54'E, with an altitude of 10.8 m. The average annual sunshine duration is 2812.6 h, the average temperature is 13.1 °C, and the average annual precipitation is 598.1 mm. Frost-free period is about 230d throughout the year [16].

The geographical coordinates of Kenli are latitude 37°24'–38°10'N, longitude 118°15'–119°19'E, with an altitude of 12.0 m. The average annual sunshine duration of the region is 2415.6 h, the average annual temperature is 13.2 °C, and the average precipitation is 499.34–532.6 mm. The average ground evaporation was

1860.9 mm, and the frost-free period is 196 d throughout the year [5].

The annual agro-meteorological data for 2019 collected in the analysis in Lijin and Kenli, including sunshine duration, average temperature and precipitation, were provided by Dongying Government Meteorological Bureau.

Soil properties monitoring

Soil environment automatic monitoring system (RR-7260, Beijing Yugen Technology Co., Ltd; China) was installed according to installation and operation manual in the experimental sites. The monitoring system consists 5 sets of RR-5TE sensors to record soil moisture, soil conductivity, and soil temperature. Five sets of the RR-5TE sensors were installed inside the soil with installation depth of 5 cm, 10 cm, 20 cm, 40 cm, and 60 cm, respectively. The numbers of the 5 sensors and their corresponding data collector channels were recorded at the same time. The dynamic distribution characteristics and rules of water, salt and temperature of 0–60 cm soil profile were monitored in real time. Data were collected every 10 min using RR-1060 data collector.

Experimental design

Field experiment was carried out to study the synergistic interactions among agro-meteorology, soil properties and peanut growth during whole peanut growth period in saline alkali land. The peanut variety was the salinity-tolerant variety Huayu 25 (HY25). The peanut was cultivated using film covered ridge planting, with a ridge spacing of 85 cm, two rows (30 cm distance between rows) on one ridge, plant distance of 17.4 cm. This cultivation method has function of heat preservation, effectively increasing the accumulated soil temperature required for peanut early growth and development. It also plays the roles in weeds control, reducing pest infestations, reducing soil moisture evaporation, and improving soil physicochemical properties and promoting root development. A Random block design with 3 repetitions was adopted. Each plot area was 42.5 m^2 with density of 135,000 plant per ha. Seeds were sown 4 cm deep with two seeds in each hole on May 9 and 10, and plants were harvested on September 6 and 9 in Lijin and Kenli, respectively. Other cultivation operations referred to general field management [17].

Determination of growth stages and plant agronomic traits

Standards for the universal development period of seedling, flowering, pegging, pod setting and maturity of peanut plant were based on the fact that the population with a certain developmental characteristic accounting for more than 50% of the total plant number. Six representative plants of each plot were harvested at each developmental stage. The main stem height was recorded. Samples for root, stem, leaves and pods were dried at 80 °C and used for dry matter. Leaf area was measured using disc method and leaf area index (LAI) was calculated as $LAI = S_2/S$, where S_2 was green leaf area (cm^2) and S was unit land area (10,000 cm^2).

Pod growth and yield parameters

From pod development to harvest, dry mass of 100 kernels was measured every 3 to 7 days. The kernel dynamic growth curve was modeled using a mathematic equation as:

$$G = G_M[1 - G_B(1 - \beta t)][1 + (1 - \beta t)e^{-\alpha(t-\tau)}]^{-1} - GB(1 - \beta t).$$

In the equation, G was kernel dry biomass; G_M was the maximum increment of biomass; G_B was the original biomass at beginning; α was the constant related with the steep part of the curve; β was the constant related with sloping part of the curve before and after the fast growth; τ was the time point when the biomass increment reached half amount of G_M; and t was the pod growth time after flowering [18–21].

The accumulation rate of kernel dry mass (V) was calculated with pod development time (t) and modeled by modified Gaussian function as:

$$V = VMe^{[-\alpha'(t-\tau')^{\wedge 2}]} + VB[1 + \beta'(t - \tau)^2].$$

Parameter V_M was the maximum increment of accumulation rate; V_B was the original rate at beginning; α' was a constant related to the curvature of the curve; $[1+\beta'(t-\tau')^2]$ was to adjust the height of the curve tail; β' can be positive or negative, which indicated an upward or downward trend in the tail of the curve; τ' was the time of maximum accumulation rate [22, 23].

During harvest, ten representative plants were selected from each plot. Variables including number of primary branches, pod number per plant, 100-kernel weight, unfilled pod percentage, shelling rate and fruit yield were recorded.

Statistical analysis

Microsoft Excel 2003 was used to organize and plot the data. Statistical analysis was carried out by the SPSS version 28.0 for windows (SPSS Inc, Chicago, Illinois, USA). All data were the means of three replicates, and were subjected to the one-way analysis of variance (ANOVA) and followed by the SSR (shortest significant ranges) test. Path analysis was conducted for correlation analysis between meteorological variables, soil characteristics, with plant and pod development. The Komogorov-Smirnov test was used to perform normality test on the dependent variables plant biomass, pod biomass. Regression analysis was used finally to describe the relationships between the parameters.

Results

Annual agro-meteorological conditions

The monthly precipitation was mainly concentrated between June to August, and the highest precipitation occurred in August, which was 414.9 mm and 349.9 mm in Lijin and Kenli, respectively (Table 1). The average temperature from May to September exceeded 20 °C, and the highest temperature occurred in July at 27.9 °C and 28.5 °C, respectively, in Lijin and Kenli. In the two experiment sites, the monthly sunshine duration exceeded 200 h from March, and reached the highest in May (298.1 h in Lijin and 269.1 h in Kenli). With the increase of rainfall, the sunshine duration decreased from June, and remained above 200 h until September.

According to the agrometeorological conditions required for the normal development of peanut, seeding and emergence generally require a stable daily average temperature of more than 12 °C, and a stable ground temperature of 15 °C [24]. The 10-day average daily temperature in late April in two experiment sites reached or exceeded 15 °C, with 12–15 mm of precipitation and more than 70 h of sunshine duration (Fig. 1a, b). In early May, although the temperature reached 20 °C and the sunshine duration exceeded 90 h, which met the basic needs for peanut germination, there was a lack of effective rainfall, almost 0 in the whole month in May. From early May to the end of September, when is the main time for peanut growth and development in Shandong Province of China, the average daily temperature was above 24 °C, with the precipitation of 470–600 mm in Lijin and Kenli. The average sunshine duration was above 7 h, and the accumulated temperature was 3742 °C and 3809 °C, respectively (Table 2). Therefore, the agrometeorological conditions in Lijin and Kenli were suitable for the growth and development of peanut. Early May was the suitable time for planting, and mid-September was the best harvest timing.

Spatiotemporal changes of soil characteristics

Soil temperature

In late April to late September, when the growth period of peanut coincides with the agro-meteorological period, was the main monitoring period of soil characteristics. Soil temperature in each soil layer changed basically with the rise and fall of air temperature with the highest in the upper 5 cm layer in both Lijin and Kenli experiment sites (Fig. 2a, b). As the soil depth increased, the difference in soil temperature among different soil layers in Lijin was larger than that in Kenli. In both Lijin and Kenli, as the air temperature in late April exceeded 15 °C, soil temperature in the 5 cm layer was ≥12 °C or even over 20 °C, but fluctuated greatly with the changes of air temperature. Since early May, soil temperature of 0–20 cm layer was gradually stabilized above 18 °C with the increase of air temperature, when was suitable for sowing, and was remained at 25 °C to 30 °C until early September (Fig. 2a, b). From mid-July to mid-August, when is the period from the insertion of fruit needles to pod maturation, the soil effective accumulated temperature in 5 cm layer was 520.5 °C and 551.3 °C in Lijin and Kenli, respectively (Table 3). However, it was decreased greatly to 441.4 °C in 10 cm soil layer and to 419.3 °C (lower than 450 °C) in 20 cm soil layer in Lijin. Peanut pods develop normally, requiring effective accumulated soil temperature to reach 480 °C. The lower effective accumulated soil temperature in 10–20 cm layers in Lijin may become a factor affecting pod normal growth and development.

Soil water

There were two differences in soil water characteristics between Kenli and Lijin experiment sites. First, the soil

Table 1 Monthly average temperature, precipitation and sunshine duration

Month	Average temperature (°C)		Precipitation (mm)		Sunshine duration (hours)	
	Lijin	Kenli	Lijin	Kenli	Lijin	Kenli
Jan.	-1.0	-0.4	0.0	0.0	176.8	186.6
Feb.	0.8	1.0	2.6	4.1	113.5	129.7
Mar.	9.5	9.8	6.2	5.6	245.6	253.0
Apr.	13.9	14.0	34.7	31.1	223.5	224.0
May	22.2	22.7	0.2	0.7	298.1	269.1
Jun.	26.0	26.1	45.2	40.8	254.1	240.5
Jul.	27.9	28.5	122.0	66.0	214.7	203.9
Aug.	25.8	26.4	414.9	349.9	204.7	186.8
Sep.	23.0	23.5	2.9	4.2	213.2	201.0
Oct.	15.2	15.5	7.5	7.3	194.7	181.4
Nov.	8.3	8.7	15.7	21.4	155.4	154.1
Dec.	0.8	1.5	10.5	11.4	140.8	191.6

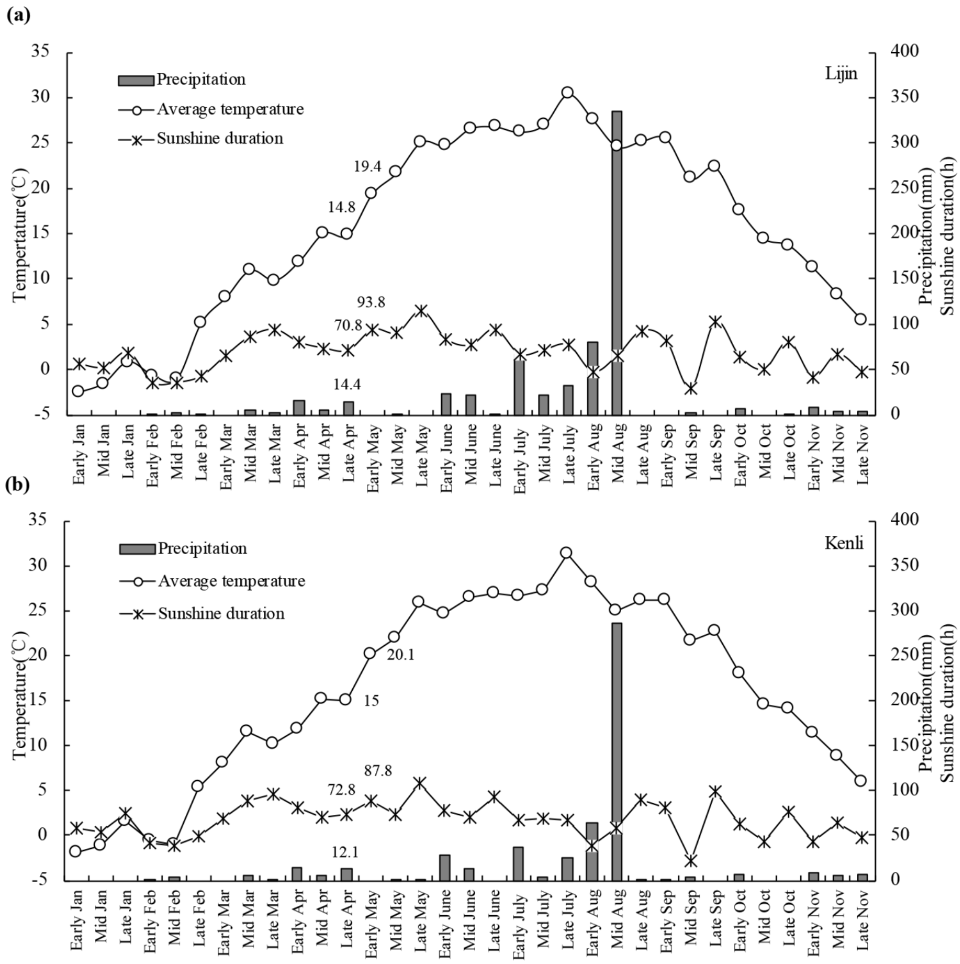

Fig. 1 Changes in monthly (ten-day) precipitation, average temperature, and sunshine duration in Lijin (**a**) and Kenli (**b**) throughout the year

Table 2 Meteorological conditions from early May to late September

	Accumulated temperature (°C)	Average temperature (°C)	Precipitation (mm)	Average sunshine duration (hours)
Lijin	3742	24.9	585.2	7.9
Kenli	3809	24.7	473.7	7.3

moisture and soil volumetric water content were 9–13% and 25–40% respectively in Lijin (Fig. 3a, b), which were higher than those (7–11% of soil moisture, 10–35% of soil volumetric water content) in Kenli (Fig. 3c, d). And the difference in soil water content among different soil layers was small, while it varied greatly under the influence of precipitation in Kenli (Fig. 3c, d). Soil water in the 5 cm layer was increased rapidly due to the increased rainfall in mid-August, with soil volumetric water content exceeding 50%. Secondly, as the increase of soil depth, soil water content was increased, with the highest in 60 cm soil layer in Lijin (Fig. 3a, b), while the largest was in 20 cm soil layer in Kenli (Fig. 3c, d).

Soil salinity

Soil salinization is serious in the Yellow River Delta. High salt content is the most important characteristic of the soil, which is also a restricting factor affecting growth and production of crops in this region. The soil salt content in Lijin experimental site ranged from 0.25 to 2.5 g kg^{-1}, and the EC (Electrical Conductivity) value was fluctuated from 0.1 to 1.4 mS cm^{-1} (Fig. 4a, b). Due to the lack of precipitation in mid-May, the soil salt content and EC value were increased rapidly up to 2.5 g kg^{-1} and 1.4 mS cm^{-1}, respectively, and then were decreased from mid-late June with the increase of precipitation. As the depth of the soil layer increased, the soil salinity gradually increased and was mainly concentrated in the bottom layers (40–60 cm) of the soil. The soil salinity profile should be classified into normal salinity profile type with the largest salt variability in the bottom soil layer.

There were also two differences in the distribution characteristics of salt salinity in soil profile in Kenli compared to that in Lijin. One difference was the lower salt content about 0.8–1.5 g kg^{-1} and the EC value around 0.4–0.8 mS cm^{-1}, which was little affected by

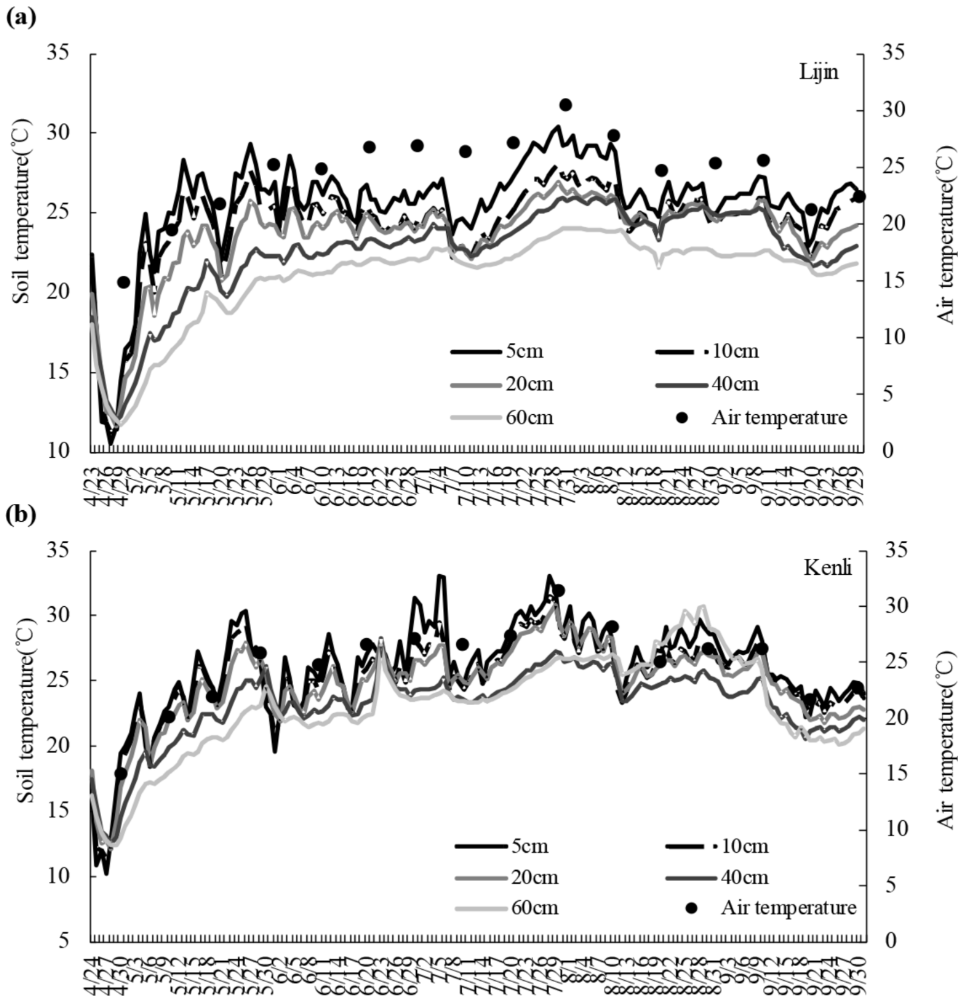

Fig. 2 Spatiotemporal changes of soil temperature from late April to late September in Lijin (**a**) and Kenli (**b**)

Table 3 Soil effective accumulated temperature from mid-July to mid-September

Soil layer (cm)	Lijin	Kenli
5	520.5	551.3
10	441.4	516.6
20	419.3	512.3
40	400.2	427.6
60	333.7	446.5

15 °C as biological zero

precipitation (Fig. 4c, d). The second was that the soil salinity was mainly distributed in the 20 cm soil layer. The salt content in other soil layers mainly fluctuated up and down around 0.5 g kg^{-1}. Therefore, the distribution characteristic should belong to surface accumulation type and the salinity in 20 cm soil layer was the main factor affecting peanut production in Kenli.

Plant developmental duration

The development process of peanut plant in saline alkali soil showed almost consistent in Lijin and Kenli (Table 4). Seeds emerged on May 20, and it took 10 to 11 days from sowing to emergence. The plants entered their flowering period on June 10, with 21 days from emergence to flowering. Fruit needles began to penetrate into soil on June 17, indicating plants have entered the flowering-pegging stage. After 30 to 32 days, plants began to develop their pods and entered the pod setting stage on July 17. Pods matured on September 6 and 9 in Lijin and Kenli respectively. The entire growth and development process took 120 to 122 days. These results indicated that the agro-meteorological conditions and soil characteristics could meet the normal growth and development process of peanut in saline alkali soil in Lijin and Kenli.

Plant growth and dry matter distribution

The plant height in Lijin showed significantly higher than that in Kenli at pod setting and maturity stages (Fig. 5a). The leaf area index in Lijin reached to 7 at pod setting

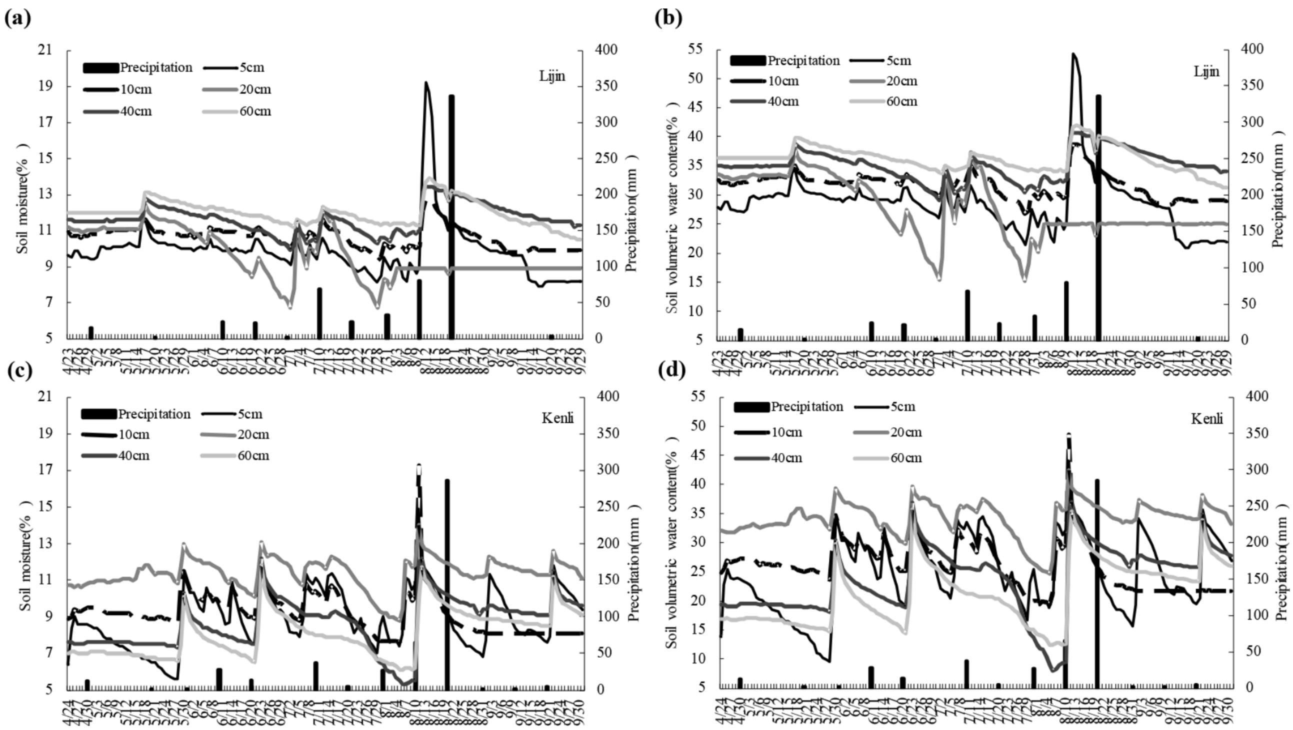

Fig. 3 Spatiotemporal changes of soil water from late April to late September in Lijin and Kenli. (**a**) Soil moisture in Lijin; (**b**) Soil volumetric water content in Lijin; (**c**) Soil moisture in Kenli; (**d**) Soil volumetric water content in Kenli

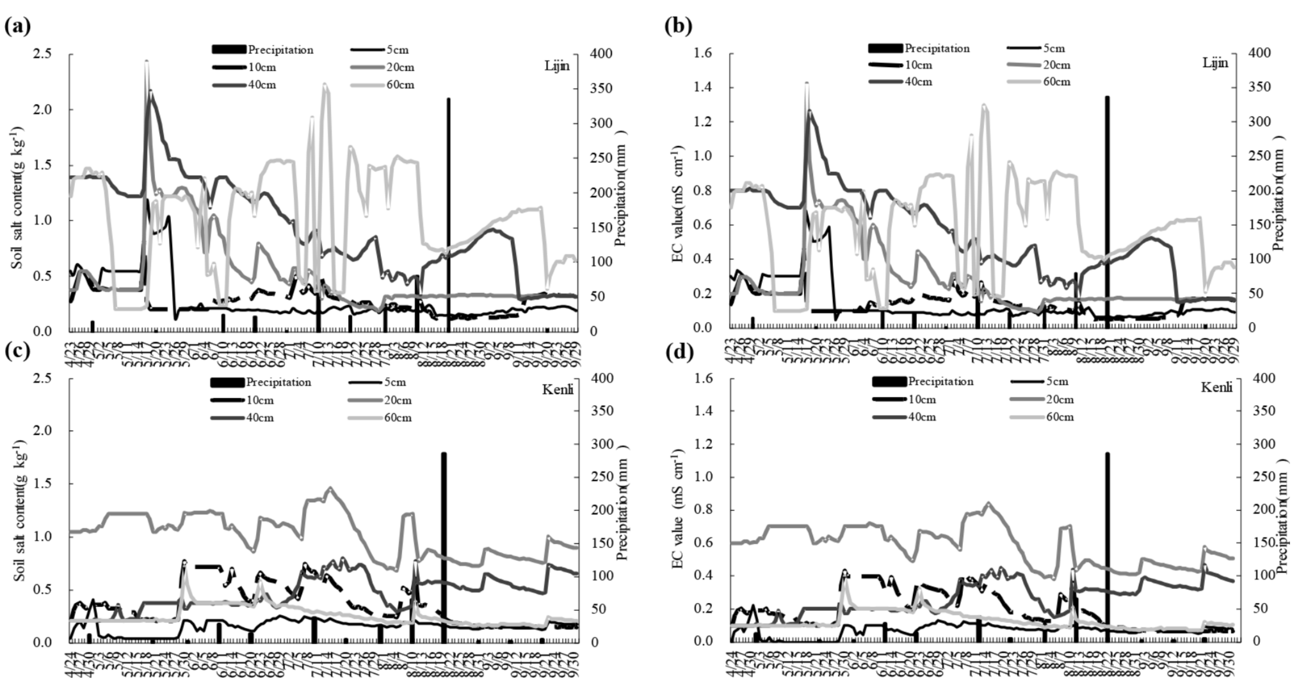

Fig. 4 Spatiotemporal changes of soil salt from late April to late September in Lijin and Kenli. (**a**) Soil salt content in Lijin; (**b**) EC value in Lijin; (**c**) Soil salt content in Kenli; (**d**) EC value in Kenli

stage, significantly higher than that in Kenli and exceeded the normal range (Fig. 5b). This indicated that peanut plant in Lijin may still be in vigorous vegetative growth during the pod setting stage.

As shown in Table 5, the dry matter accumulations (AT) of root, stem and leaf were increased gradually before pod setting stage, and reached the highest at pod setting stage. The dry matter distribution ratio (DR) was

Table 4 Developmental duration of peanut plant in saline alkali soil

Stage	Seedling			Flowering-pegging				Pod setting		Fruit maturity		Develop-ment days (d)
	Sowing date	Emergence date	Duration time	Flowering date	Duration time	Pegging date	Duration time	Pod setting date	Duration time	Maturity date	Duration time	
	(mm-dd)	(mm-dd)	(days)	(mm-dd)	(days)	(mm-dd)	(days)	(mm-dd)	(days)	(mm-dd)	(days)	
Lijin	05–09	05–20	11	06–10	21	06–17	7	07–17	30	09–06	51	120
Kenli	05–10	05–20	10	06–10	21	06–17	7	07–19	32	09–09	52	122

increased from 35 to 55% in leaf and from 38 to 43% in stem from seedling stage to flowering-pegging stage. At this period, leaves grew rapidly, and the photosynthetic products produced by leaf photosynthesis laid a foundation for strong seedling. Vegetative growth and reproductive growth occurred simultaneously at pod setting stage, when the stem and pods grew fast, and DR in leaf was decreased to 29%. DR in pod reached above 50% at fruit maturity stage. Comparing the two experimental sites, DR in leaf in Kenli were 46.97% and 55.20% at the seedling and flowering-pegging stages, respectively, significantly higher than those in Lijin. There was no significant difference in AT and DR in root, stem, leave, and pod at pod setting stage. At fruit maturity stage, no significant difference in DR in pod was found in Lijin and Kenli, while AT in pod was 34.165 g plant$-^{1}$ in Kenli, significantly higher than that in Lijin.

Pod development, yield and the related traits

The dynamic model curves of kernel dry mass and accumulation rate during pod growth showed clear difference between Lijin and Kenli (Fig. 6a, b). The variables from the mathematical analysis were presented in Table 6. The parameter G_M showed the maximum increment of dry mass per 100 kernel during pod growth period. It was significant higher in Kenli (91.3 g) than in Lijin (88.4 g), suggesting the high biomass of peanut pods in Kenli. G_B was dry mass at the beginning of kernel and theoretically should not be different between treatments. The higher value of τ in Kenli indicated that peanut kernels needed shorter time (29.5 days) for their growth to reach half of the maximum dry mass increment, while it cost 35.5 days in Lijin. The coefficients α and β, which were proportional to the slope of the deep and the sloping parts of the growth curve respectively, were higher in Kenli than those in Lijin, indicating the faster pod growth rate in the exponential manner in Kenli.

Parameter V_M, the maximum increment of kernel dry mass accumulation rate, was 2.76 g d$-^{1}$ in Kenli, significant higher compared to V_M (2.10 g d$-^{1}$) in Lijin. The time of maximum accumulation rate (shown by parameter τ') occurred on 30.1 d and on 36.8 d in Kenli and Lijin, respectively. The larger was the value of α', the higher was curvature of the curve, indicating that the accumulation rate of kernel dry matter was faster in Kenli. In overall, the rapid dry matter accumulation of kernels during the pod setting stage in Kenli might be the decisive factor for superior pod development compared to that in Lijin.

There were no significant differences in number of primary branches, pod number per plant, and 100-kernel weight between Lijin and Kenli. The high unfilled pod rate (26.99%) and low shelling out rate (66.0%) might be the main reason for lower fruit yield in Lijin (Table 7).

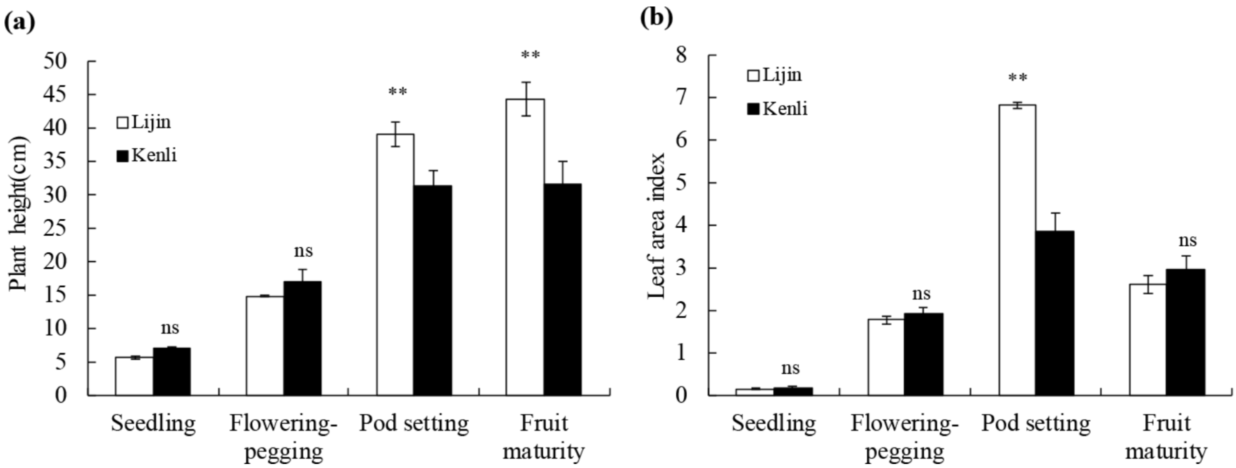

Fig. 5 Plant height (**a**) and Leaf area index (**b**) at different growth and development stages of peanut plant in saline alkali soil. Data were expressed as mean ± SD ($n = 3$); ^{ns} indicates non-significance; ** indicates significant differences at $p \le 0.01$

Table 5 Dry matter distribution ratio (DR), dry matter accumulation (AT) in root, stem, leaf and pod at different development stages in saline alkali soil

Growth stage		Root		Stem		Leaf		Pod		
		AT (g plant^{-1})	DR (%)	AT (g plant^{-1})	DR (%)	AT (g plant^{-1})	DR (%)	AT (g plant^{-1})	DR (%)	Total AT (g plant^{-1})
Seedling	Lijin	0.315**	26.27**	0.451*	38.07	0.424	35.66	--	--	1.190*
	Kenli	0.124	13.27	0.375	39.76^{ns}	0.448^{ns}	46.97*	--	--	0.947
Flowering-pegging	Lijin	0.756**	6.26**	5.294*	43.15	6.178	50.59	--	--	12.228
	Kenli	0.422	3.67	4.907	41.13^{ns}	6.728^{ns}	55.20*	--	--	12.057^{ns}
Pod setting	Lijin	1.420	1.96	26.737*	36.78	21.615	29.76	22.913	31.50	72.685*
	Kenli	1.608^{ns}	2.42*	24.518	35.66^{ns}	20.178	29.44^{ns}	22.452^{ns}	32.48^{ns}	68.757
Fruit maturity	Lijin	0.687	1.34	13.188	25.67*	8.227	16.03	29.248	56.97	51.350
	Kenli	0.935*	1.59^{ns}	14.205^{ns}	23.83	10.305*	17.29^{ns}	34.165*	57.31^{ns}	59.610*

^{ns} indicates non-significance; * indicates significant differences at $p < 0.05$; ** indicates significant differences at $p < 0.01$

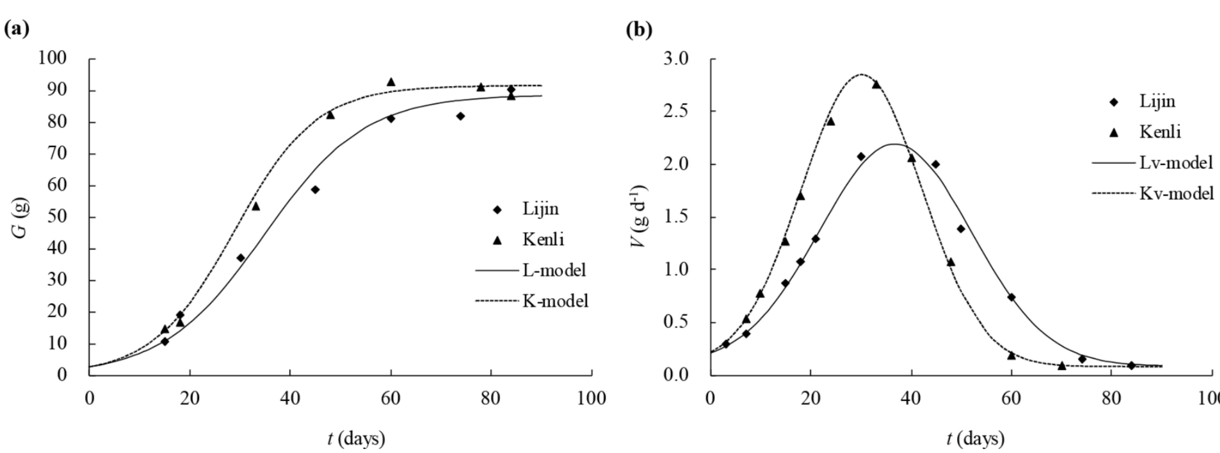

Fig. 6 Peanut kernel dynamic growth curves in saline alkali soil. (**a**) kernel dynamic growth curves; (**b**) dynamic curves of kernel dry mass accumulation rate; L-model and K-model, kernel dynamic growth curves in Lijin and Kenli, respectively, modeled by a mathematic equation $G = G_M[1\text{-}G_B(1\text{-}\beta t)][1+(1\text{-}\beta t)e^{-\alpha(t-\tau)}]^{-1}\text{-}G_B(1\text{-}\beta t)$; Lv-model and Kv-model, the accumulation rate of kernel dry mass (V) was calculated with pod development time (t) and modeled by modified Gaussian function $V = V_M e^{[-\alpha'(t-\tau')\wedge 2]} + V_B[1+\beta'(t\text{-}\tau')^2]$

Table 6 Parameters from $G = G_M[1\text{-}G_B(1\text{-}\beta t)][1+(1\text{-}\beta t)e^{-\alpha(t-\tau)}]^{-1}\text{-}G_B(1\text{-}\beta t)$ and $V = V_M e^{[-\alpha'(t-\tau')^{\wedge}2]} + V_B[1+\beta'(t\text{-}\tau')^2]$

	G_M (g)	G_B (g)	τ (d)	α	β
Lijin	88.4	0.0001	35.5	0.09780	0.00189
Kenli	91.3*	0.0001ns	29.5*	0.12108*	0.00206*
	V_M (g d^{-1})	V_B (g d^{-1})	τ′ (d)	α′	β′
Lijin	2.10	0.10	36.8	0.00219	-0.00158
Kenli	2.76*	0.10 ns	30.1*	0.00345*	-0.00198*

ns indicated non-significance; * indicated significant differences at $p<0.05$

The synergistic relationship of meteorological and soil variables and peanut growth.

Results from path analysis showed that air temperature had significantly positive correlation on soil temperature in both Lijin and Kenli (Table 8, $p<0.01$). However, it was also a major factor that negatively affected soil water content in Lijin ($p<0.05$). Only the variable sunshine duration was the significant positive correlation factor for soil salinity in Lijin ($p<0.05$), which might be a main cause for soil salinity changes. Moreover, plant biomass was significantly negatively correlated with these two factors in Lijin (Table 9, $p<0.05$ and $p<0.01$). Both plant biomass and pod biomass showed significantly negatively correlated with soil salinity in each soil layer in Lijin (Table 10, $p<0.05$ and $p<0.01$), indicating that soil salinity was the main environmental factor causing harm to plant growth and pod development. This implied that air temperature and sunshine duration were the decisive meteorological variables affecting soil water and salt transport in Lijin experimental site. The two variables increased soil temperature, at the same time, also increased soil evaporation, leading to the movement of soil salt from deep layers to the surface layers of the soil. High soil salinity conversely negatively impacted the plant growth of peanut. Unlike Lijin, there was no significant correlation between soil characteristics and agro-meteorological variables in Kenli experimental region (Table 8). Plant biomass showed significantly positively correlated with air temperature ($p<0.05$) and soil temperature ($p<0.01$) (Table 9). Soil salinity did not affect plant biomass in Kenli (Table 9), but showed significantly negative effect to pod biomass (Table 10, $p<0.01$).

Overall, agro-meteorological conditions were suitable for growth and development process of peanut in Lijin and Kenli. The high soil salinity in Lijin was the main reason affecting the vegetative growth of peanut plant, which might not be conducive to transfer nutrients and dry matter from plant to pods. And it could lead to slow development of pods in the later growth stage which in turn affected fruit yield. Relatively speaking, the environmental conditions such as air temperature and soil salinity in Kenli were more suitable to peanut growth and development.

Discussion

In peanut life cycle, there are five stages: sowing, seedling, flowering, pegging, podding and harvesting. The duration of one cycle is about 140–150 days. The stages in the life cycle require different weather conditions to meet peanut growth, but the changing weather condition often influence the peanut yield. The suitable planting date should be combined with climate resources. The average daily temperature exceeds 12 °C, and stabilizing at 15–20 °C is the best temperature required for peanut seeding [25]. Our previous study has shown that the suitable sowing date of peanut in saline alkali land of Yellow River Delta throughout the year is generally from April 26 to May 9, and the best sowing date is from May 2 to 5. During this sowing period, the development process of peanut is more adapted to the local climate resources, which could effectively play the high-yield potential of peanut in saline alkali soil [26]. The meteorological monitoring data of this study showed that the average

Table 7 Peanut yield and its related characters in saline alkali soil

	No. of primary branches	Pod number per plant	Unfilled pod rate (%)	100-kernel weigh (g)	Shelling out rate (%)	Yield (kg hm^{-2})
Lijin	5.4 ± 0.1	26.93 ± 1.22	26.99 ± 1.38*	90.29 ± 0.80	66.0 ± 0.51	6309.0 ± 51.4
Kenli	5.6 ± 0.1ns	26.35 ± 1.47ns	21.02 ± 1.46	88.13 ± 0.86ns	69.9 ± 0.66*	6941.6 ± 40.4*

ns indicated non-significance; * indicated significant differences at $p<0.05$

Table 8 Analysis of relationship between agro-meteorological variables and soil characteristics

	Air temperature (°C)		Precipitation (mm)		Sunshine duration (hours)	
	Lijin	Kenli	Lijin	Kenli	Lijin	Kenli
Soil temperature (°C)	0.8617**	0.8876**	0.2001	0.1353	-0.4634	-0.2860
Soil water content (%)	-0.6734*	-0.0153	0.3797	0.5065	0.3206	0.0893
Soil salinity (mS cm^{-1})	-0.2956	0.2273	-0.5056	-0.0646	0.6564*	-0.0373
Critical value of correlation coefficient	R0.05 = 0.5529		R0.01 = 0.6835			

Data were recorded from sowing date to harvest. *, indicated significant differences at $p<0.05$; **, indicated significant differences at $p<0.01$

Table 9 Analysis of relationship of agro-meteorological variables and soil characteristics affecting plant biomass during the entire developmental period of peanut

	Air temperature (°C)	Precipitation (mm)	Sunshine duration (hours)	Soil temperature (°C)	Soil water content (%)	Soil salinity (mS cm^{-1})
Lijin	0.6380*	0.3831	-0.6475*	0.6596*	-0.3572	-0.8224**
Kenli	0.6499*	0.3614	-0.5301	0.7788**	0.2149	-0.0880
Critical value of correlation coefficient	R0.05 = 0.5529		R0.01 = 0.6835			

Data were recorded from sowing date to harvest. *, indicated significant differences at $p<0.05$; **, indicated significant differences at $p<0.01$

temperature in Lijin and Kenli in the Yellow River Delta reached 12 °C in early April and 15 °C in the middle and late April, and the average temperature stabilized at 20 °C in early May, meeting the requirements of peanut sowing and seedling growth. This study selected an appropriate sowing date (early May) in both regions. At this time, seedlings can avoid the frequent occurrence of late frost and freezing. Stable temperature conditions were more conducive to uniform, complete, and fast emergence. Moreover, seedlings could be timely released and broken out from the film, avoiding burning due to excessive temperature under the film. The demand range for daily average temperature from the flowering and pegging stage to pod development of peanut is between 23 and 28 °C [27]. If it is below 22 °C, the number of flowers decreases or flowers are irregular [25]. And the daily light demand should reach 8–10 h, no less than 6.7 h. Insufficient light is not conducive to pollen germination and affects peanut yield [28]. Studies have shown that highest impact to peanut growth in Shandong province of China is seen on sunshine (7.7 h/day of sunshine duration) in April and on temperature in August. The weather factor indicates a highly negative effect to yield [29]. The growing of peanut during the whole growth period requires a certain amount of accumulated temperature in May, June, and July to get enough time to accumulate nutrients [27]. In this study, the average temperature in Lijin and Kenli from mid-May to late July was 22–31 °C, with 7.3–7.9 h/day of average sunshine duration and 3742 °C (Lijin) and 3809 °C (Kenli) of accumulated temperature during the entire growth period, which could fully meet the requirements for peanut flowering and pod development.

Peanut seed germination and seedling emergence require precipitation exceeding 5 mm. In Lijin and Kenli, the precipitation in May was almost 0, which could not meet the water requirement for seed germination and seedling growth, and artificial irrigation measures must be taken. The rainfall of 50–150 mm is conducive to the flowering of peanut plant [25], which is a critical period of water demand. Although there is about 20 mm of rainfall in the early and middle June in Lijin and Kenli, the precipitation in the latter half of June was 0, which cannot meet the requirements of water demand for flowering and pegging. At this time, artificial irrigation must be adopted again to ensure the normal flowering and reduce the harm caused by soil salinity. The appropriate precipitation for pod maturation is 200–400 mm [25]. In this study, rainfall in Lijin and Kenli was concentrated from late July to mid-August, with precipitation exceeding 300 mm, which is favorable to the development of peanut pod. Based on comprehensive meteorological conditions, the growth and development stages of peanuts in Lijin and Kenli in this study were basically consistent with other regions in Shandong Province of China. And the growth and development period can be divided as followings: seedling stage in early and mid-May (5.9–5.20), branching stage from late May to early June (5.21–6.10), flowering and pegging stage in mid-June (6.11–6.17), pod setting stage from late June to mid-July (6.18–7.18), pod filling stage from late July to early September (7.19–9.9), and fruit maturity stage in mid-September.

The period from pegging to pod maturation is very sensitive to soil accumulated temperature. The minimum soil temperature for pod development is 15 °C, and

Table 10 Analysis of relationship between soil salinity (mS cm^{-1}) in each soil layer with plant biomass and pod biomass

	Soil layer	5 cm	10 cm	20 cm	40 cm	60 cm
Plant biomass (g $plant^{-1}$)						
	Lijin	-0.6512*	-0.4243	-0.7742**	-0.9630**	-0.4257
	Kenli	0.5536*	-0.3055	-0.5286	0.7859**	-0.4698
	Critical value of correlation coefficient	R0.05 = 0.5529		R0.01 = 0.6835		
Pod biomass (g)						
	Lijin	-0.2717*	-0.9034**	-0.6776**	-0.6037**	-0.2902**
	Kenli	-0.4965**	-0.7700**	-0.6054**	0.1644	-0.8763**
	Critical value of correlation coefficient	R0.05 = 0.2133		R0.01 = 0.2780		

Data for plant biomass were recorded from sowing date to harvest. Data for pod biomass were recorded from June 17 (Lijin) or 18 (Kenli), when peanut pod began to develop, to harvest. *, indicated significant differences at $p<0.05$; **, indicated significant differences at $p<0.01$

an upper limit is 33–35 °C, within which, the higher the soil temperature, the faster the pods develop. And the effective accumulated soil temperature in 5 cm soil layer must be 480–570 °C to ensure the smooth reproductive growth of peanut. When it is lower than 450 °C, peanut pods can still form unripe fruits, but when it drops below 300 °C, pods can only develop into young fruits [30]. In this study, the average effective accumulated temperature in the upper 5 cm soil in Lijin and Kenli from late July to late September was >500 °C, which could meet the requirement of soil temperature for peanut reproductive growth. However, the effective accumulated soil temperature in cultivation (10–20 cm) layers in Lijin was less than 450 °C. This indicated that it might be a potential factor leading to empty and immature pods, resulting in high unfilled pod rate and low shelling out, and finally causing low fruit yield in Lijin. The germination of peanut requires soil moisture, and 60–70% of field water capacity is appropriate. If the field water capacity is lower than 40%, the seedlings will not emerge evenly. The soil moisture content of 0–30 cm layers at flowering and pegging, pod setting and fruit maturity stages should not be less than 50%, 40% and 30% respectively [25]. In this study, air temperature, light and soil temperature in Lijin and Kenli in early May, could meet the needs for peanut sowing, but the high soil salt content and low effective precipitation were the main factors affecting the germination and emergence of seeds.

Soil salinization is a dynamic phenomenon and process, which depends on the content of water and salt in the soil and their dynamic changes [31–33]. In a certain ecological environment, water and soil soluble salt in the soil will change in different periods with environmental conditions, which may involve certain characteristics and evolution law [34]. Therefore, regulating soil water and salt movement is the key to peanut planting in saline alkali soil. The salt content in Lijin was mainly concentrated in the 40–60 cm soil layers. The salinity characteristics of soil profile showed a bottom-accumulation type. And the salt may move significantly between different soil layers under the influence of sunshine duration. The soil salinity in Kenli was mainly concentrated in the 20 cm soil layer, and was not affected by precipitation. The total precipitation of 10 mm in late April in both Lijin and Kenli could not ensure the moisture content in 0–20 cm soil layer to reach 45–60%, nor could it achieve the purpose of reducing soil salinity. And the overall annual soil volumetric water content was less than 40%. As air temperature rises, the water evaporation of in the soil brings underground salt back to the soil surface. Therefore, the most traditional and effective saline soil improvement measures follow the basic law of water and salt transport of "salt comes with water, salt leaves with water", and should adopt fresh water irrigation [35]. The main measures are removing salt by heavy irrigation and undersurface pipe discharge [5, 35, 36]. The irrigation practice in the early sowing period should be based on "removing salt by heavy irrigation" to ensure the normal germination and emergence of peanut seeds. Therefore, timely supplement irrigation should be done in mid and late May and from late June to late July when the soil moisture content is low, to increase soil moisture and reduce soil salinity.

How to utilize meteorological conditions to adjust planting patterns is essential for peanut growth. Studies have shown that yield can be predicted based on meteorological yield coefficients. And Irrigation or film-covering can also be used in cultivation techniques to change climate conditions and to increase peanut yield [29]. The film covered ridge planting used in this study could fully play the role of heat and moisture preservation as well as improving microclimate conditions. According to the weight coefficient of the three climatic factors in different growth stage of peanut, a meteorological suitability model for different growth stage was established to realize the peanut sowing date suitability determination, providing the quantitative basis for the daily agricultural guidance [37]. Our previous studies have found that, AMF (Arbuscular Mycorrhizal Fungi) coating or applied AMF primarily altered the root structure during the pod setting stage, improved the diversity of the microbial community's structure and enzyme activity in peanut rhizosphere soil in saline-alkali soil, especially increasing the abundance of *Proteobacteria* and *Firmicutes*. At the same time, it was found that AMF also accumulated soil organic matter and nutrient ions, reduced electrical conductivity, and improved the soil microenvironment of saline alkali soil [38–41]. These findings indicated that AMF played important roles in reducing the toxicity of saline-alkali soil on peanut growth, and finally promoted peanut production in the Yellow River Delta. In addition to the original film cover cultivation technology and heavy irrigation practice, AMF seed coating would also be an important cultivation practice to improve peanut production in saline alkali soil.

This study for the first time conducted synchronous analysis on the growth and development patterns of peanut, as well as spatiotemporal changes of ecological environmental factors in saline alkali land of Yellow River Delta. According to the synergistic effects of "meteorology-peanut-soil" throughout peanut entire growth period, the limiting factor for increasing peanut production was identified as soil salinity in this region. Soil salinity mainly affects plant reproductive growth. In addition, alkaline salts had a higher impact on the grain yield compared with neutral salts. Study has found that salinity decreased the seed set rate, effective panicle number, grain number per panicle, head rice rate, and increased the chalky rice rate in rice, adversely affecting the grain yield and quality [34]. In this study, the differences in agricultural meteorological factors and soil characteristics in Lijin and Kenli experimental sites did not have a differential impact on the growth and development process of peanut. However, the difference in growth and development of peanut has started since pod setting stage between Lijin and Kenli.

Excessive leaf area index, high soil salt content, as well as slow accumulation of kernel dry matter caused an increase in unfilled pods and a decrease in shelling rate in Lijin. Analyzing the relationship among peanut, agrometeorological and soil environmental factors, high soil salinity during peanut growth period was the main reason for the poor pod development. In addition, the reproductive growth of peanut is extremely sensitive to soil accumulated temperature. Low soil effective accumulated temperature may also be one of the reasons affecting pod development in Lijin. It is difficult to achieve appreciable yield in the Yellow River Delta region using the general peanut planting mode. Based on these findings, we proposed optimization planting pattern with root zone micro-topography. The goal of future research will focus on salt suppression and yield increase to reveal the cultivation mechanism of optimization planting pattern. Future research will use this as a basis to further adjust and optimize planting mode on the basis of traditional ridge and film covering cultivation mode, in order to reduce the harm of soil salinity to peanut production and improve the rhizosphere microenvironment. This study provides a theoretical basis and technical support for further exploring the potential for increasing peanut production and large scale application in saline alkali soil of Yellow River Delta. The local farmers' belief that peanut cannot be grown on saline alkali land was changed and more farmers are willing to try planting peanut using optimization planting pattern.

Conclusions

This study suggested that agro-meteorological conditions could meet the growth and development of peanut throughout its entire growth period. The restricting factor affecting peanut production in saline alkali soil of the Yellow River Delta was the harm of soil salinity to plant growth, especially to pod development. The differences in the characteristics of soil water and salt transport between Lijin and Kenli were as follows: the soil moisture in Lijin was relatively higher. Soil salinity was mainly distributed in the soil layer below 40 cm, and easily affected by sunshine duration and air temperature moving to the soil surface. In the future, the planting mode in this region should focus on finding sustainable cultivation measures to control deep soil salinity inversion. And the other key point was to adjust or optimize cultivation technique to raise soil accumulated temperature to promote pod growth. The salt salinity in Kenli was mainly distributed in the 20 cm soil layer, and less affected by meteorological changes. The planting technique should be to reduce salt salinity in the cultivation soil layer in the early sowing stage.

Abbreviations

AMF	Arbuscular mycorrhizal fungi
AT	Dry matter accumulation
DR	Dry matter distribution ratio
EC	Electrical Conductivity
LAI	Leaf area index
G	Kernel dry biomass
G_M	Maximum increment of kernel dry biomass
G_B	Original kernel dry biomass at beginning
V	Accumulation rate of kernel dry mass
V_M	Maximum increment of accumulation rate
V_B	Original accumulation rate at beginning

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Author contributions
DC and FQ conceived and designed the experiments; DC, ZX, JW, JY, ZT and FG performed the experiments; FQ and DC analyzed the data and made the figures; JY, ZT and FG provided suggestions; FQ contributed to the writing of the manuscript and DC performed the final editing of the manuscript. All authors received and approved the final manuscript.

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Data availability
No datasets were generated or analysed during the current study.

Declarations

Ethics approval and consent to participate
The collection and experimental research of peanut material involved in this study was approved by Shandong Peanut research Institute in China and comply with the guidelines and legislation in Shandong Peanut research Institute. The experiment sites of Lijin and Kenli, Dongying, China is affiliated to Dongying experiment station of Shandong Academy of Agricultural Sciences. The peanut research involved in this study was permitted by Shandong Peanut research Institute and Shandong Academy of Agricultural Sciences.

Consent for publication
Not applicable.

Competing interests
The authors declare no competing interests.

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