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Effects of soil potassium levels on dry matter and nutrient accumulation and distribution in cotton

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Abstract

Background Potassium (K) is an essential nutrient for plant growth and development. However, plant fertilization ignoring the soil K level is very likely to cause excessive fertilizer use, and further arouse a series of side effects. This study investigated the response of cotton growth to different soil K levels and the uptake of major nutrients, aiming to evaluate the appropriate K supply level for cotton growth. Using a random block design with 6 soil K levels, we conducted 18 micro-zones field experiments over two continuous years. The soil available K concentration of each treatment was K1 (99.77–100.90 mg·kg^{-1}), K2 (110.90–111.26 mg·kg^{-1}), K3 (123.48–128.88 mg·kg^{-1}), K4 (140.13–145.10 mg·kg^{-1}), K5 (154.43–155.38 mg·kg^{-1}), and K6 (165.77–168.75 mg·kg^{-1}). Cotton nutrient contents, soil nutrient contents, accumulation and distribution of dry matter in cotton were determined, and the relationships between K content in soil and plants and dry matter accumulation were analyzed.

Results The soil K content had a significantly positive relationship with dry matter and K accumulation in cotton plants. There were significant differences in dry matter accumulation, single-plant seed cotton yield, mineral nutrient uptake and the proportion of K accumulation in reproductive organs among different soil K levels. The results showed that there was significant difference between K4 and lower K level treatments (K1 and K2), but no significant difference between K4 and higher K level treatments (K5 and K6) in dry matter, single-plant seed cotton yield, or accumulation, distribution and seed cotton production efficiency of N, P and K.

Conclusion The soil K level of K4 was able to provide sufficient K for cotton growth in our experiment. Therefore, when the soil K level reached 140.13 mg·kg^{-1}, further increasing the soil K concentration no longer had a significant positive effect on cotton growth.

Keywords Cotton, Soil potassium level, Matter accumulation, Uptake and distribution

Introduction

Potassium (K) is an essential mineral nutrition for plant growth and development (Sullivan et al. 2000), and is required in large amounts by plants (Oosterhuis et al. 2013). It affects many fundamental physiological processes in the metabolism, growth and development of plants, especially in the accumulation of dry matter (Oosterhuis et al. 2013; Vyn and Janovicek 2001; Yin and Vyn 2004; Yu et al. 2023). Nutrient uptake and distribution are affected when no sufficient K available in the soil (Hu et al. 2016b). The appropriate soil K level is

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crucial for obtaining high yield (Oosterhuis et al. 2013; Kang et al. 2019).

Cotton is an exhaustive crop and has a high requirement for K (Tariq et al. 2018). Cotton is the most sensitive crop to K deficiency compared with other row crops (Cope 1981). K nutrition is vital to cotton plants because it influences the production of dry matter and the development of bolls (Zhao et al. 2001; Wu et al. 2019). Studies have shown that lower accumulation of biomass and fewer boll numbers are induced when cotton is cultivated in K-deficient soil (Gerardeaux et al. 2010; Lokhande and Reddy 2015), as the dry matter of reproductive organs is significantly reduced (Pettigrew et al. 2005; Makhdum et al. 2007). Adequate K could improve nitrogen (N) fertilizer use efficiency (Pettigrew and Meredith 1997), while K-deficiency has a negative effect on nutrient uptake in cotton plants (Zhang et al. 2009). Over the course of cotton growth and development, maintaining adequate K levels is essential to ensure high yield.

The total amount of K absorbed by crops depends on the total native soil K and extra fertilizer K applied during the growing season (Pettigrew 2008). Reasonable fertilization is an important measure to improve cotton yield (Girma et al. 2007), and the premise of reasonable fertilization is to consider the level of soil available nutrients (Wakeel et al. 2017). Many studies have focused on the appropriate K fertilizer dosage for improving cotton fields, which should be established on native soil K, otherwise it is very likely to cause excessive fertilizer use. The unreasonable implementation of fertilizer would cause a series of negative problems, including a reduction in fertilizer application efficiency and production, an increase in production costs, and ecological environmental pollution (Barton and Colmer 2006; Zhang et al. 2023). In recent years, signs of K deficiency in cotton have become increasingly common, especially in modern high-yield cotton varieties, such as *Bt*-transgenic cotton. Some studies have suggested that *Bt*-transgenic cultivars are more sensitive to K deficiency than conventional cultivars (Zhang et al. 2007; Dong et al. 2010). Soil K deficiency is implicated as the main contributing factor for K deficiency in cotton (Dong et al. 2005). Our previous research showed that a low soil K level (soil available K below 120 $mg \cdot kg^{-1}$) would affect the K content of various organs in cotton plants, net photosynthetic rate, dry matter accumulation, and boll-setting rate of individual plants, resulting in decreased yield (Jin et al. 2021). Based on this research, a micro plot experiment on different soil K levels was carried out, which aimed to investigate the response of dry matter accumulation, nutrient uptake and distribution to different soil K levels. The present research discussed the appropriate K supply level for cotton growth and provided a theoretical basis for K management in cotton fields.

Materials and methods

Experimental site description

The experiment was conducted at the Experimental Station of Institute of Cotton Research, Chinese Academy of Agricultural Sciences (36°13′ N, 114°35′ W) in Anyang city, Henan Province, China. The climate is typical semi-humid, and the daily air temperature and precipitation in 2020 and 2021 are shown in Fig. 1. The total precipitation was 383.9 mm and 851.2 mm in 2020 and 2021, respectively. The soil type is sandy loam.

Experimental design

A total of 18 micro-zones were set in the field experiment in 2017. Each micro-zone has a north–south length of 3.6 m, an east–west width of 4.0 m, and an area of 14.4 m^2. All micro areas are arranged in two rows from east to west, and the areas and boundaries are separated by a cement structure with 10 cm wide and 60 cm deep. Afterward, the random block experiment has been arranged with 6 levels of K applications for three consecutive years from 2017 to 2019.

Before planting in 2020 and 2021, we determined the soil nutrients of the 0–20 cm plow layer in the experimental micro-area. The nutrient status of six K levels is shown in Table 1. The soil available K concentrations of each treatment were K1, K2, K3, K4, K5, and K6. Each treatment was repeated 3 times. Each plot contained five rows (southnorth orientation), with a row spacing of 80 cm and plant spacing of 20 cm. The sowing dates were April 25 in 2020 and 2021, with upland cotton cultivar Ji228 as the tested cultivar and a colonization density of 3 935 plants per 666.67 m^2. Field cultivation management, such as fertilization and irrigation, was the same in each micro-zone. Urea (N, 46%) was used as the nitrogen fertilizer, the fertilizer amount was 15 kg N per 666.67 m^2, and the base top dressing ratio was 4:6. The phosphate fertilizer was triple superphosphate (P_2O_5, 42%), the fertilizer amount was 8 kg P_2O_5 per 666.67 m^2, and all was used as base fertilizer, in a one-time application. No K fertilizer was applied in any micro-zone throughout the cotton growing season.

Dry matter mass

At the bud stage, flowering stage, flowering and boll stage, and boll opening stage of cotton, three plants were randomly selected and dug out from the soil in each plot. Then all the dug-out plants were partitioned into different parts, mainly into vegetative organs (root, stem, and leaves) and reproductive organs (buds, flowers, and bolls). Cotton bolls were divided into boll shells and seed cotton to calculate the single-plant seed cotton yield. After

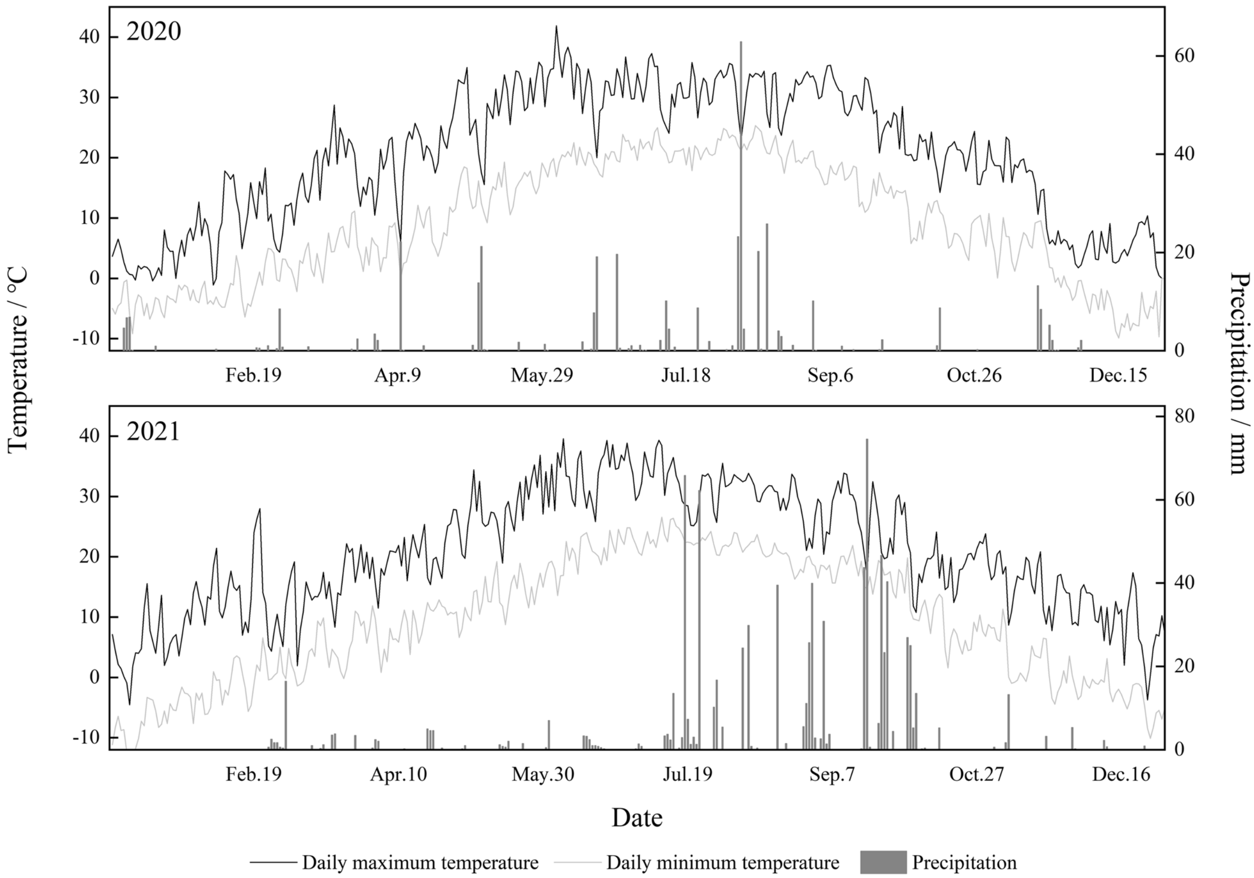

Fig. 1 Daily air temperature and precipitation in 2020 and 2021, respectively

Table 1 The micro area arable layer soil nutrient status

Year	Treatment	Total N content/($g \cdot kg^{-1}$)	Olsen-P content /($mg \cdot kg^{-1}$)	Available K content /($mg \cdot kg^{-1}$)	Organic matter content /($g \cdot kg^{-1}$)
2020	K1	0.57 ± 0.02	18.75 ± 6.76	99.77 ± 3.94	11.20 ± 1.33
	K2	0.58 ± 0.02	23.67 ± 4.99	110.90 ± 6.74	10.72 ± 0.61
	K3	0.57 ± 0.02	14.25 ± 2.28	123.48 ± 13.35	10.81 ± 0.40
	K4	0.58 ± 0.02	15.33 ± 2.87	140.13 ± 6.11	10.53 ± 0.24
	K5	0.57 ± 0.02	17.67 ± 4.92	154.43 ± 19.74	10.28 ± 0.39
	K6	0.57 ± 0.03	17.67 ± 4.50	165.77 ± 13.04	11.62 ± 1.17
2021	K1	0.60 ± 0.01	14.67 ± 0.94	100.90 ± 0.91	10.32 ± 0.23
	K2	0.58 ± 0.01	14.00 ± 3.27	111.26 ± 6.65	9.95 ± 0.85
	K3	0.60 ± 0.01	11.00 ± 1.41	128.88 ± 1.20	10.77 ± 0.10
	K4	0.63 ± 0.03	13.00 ± 4.08	145.10 ± 9.91	9.82 ± 0.09
	K5	0.61 ± 0.01	10.67 ± 0.47	155.38 ± 23.96	10.18 ± 0.28
	K6	0.60 ± 0.03	13.67 ± 3.40	168.75 ± 15.10	10.54 ± 0.78

being heated at 105 °C for 30 min, all the plant samples were dried at 70 °C in an oven to a constant weight, and weighed to determine the dry weight of each cotton organ.

Nutrient accumulation

The plant samples of different organs were ground and sifted through a 0.5 mm sieve for chemical analysis. The total N concentration was determined by the micro-Kjeldahl method. Phosphorus (P) contents were determined colorimetrically using a spectrophotometer. An atomic adsorption spectrophotometer was used to determine the K concentration (Bao 2005). The K uptake by each organ was calculated by multiplying its K content by its dry weight. The K uptake by cotton was the sum of the K uptake by each organ. The partitioning percentage of K to reproductive organs was calculated by dividing the K uptake of reproductive organs by the total K uptake of cotton plants. The methods used for calculating the above indicators of K were consistent with the methods used for calculating the indicators of N and P.

According to the amount of seed cotton and nutrients uptake of selected cotton plants, the seed cotton production efficiency of nutrient in cotton plants was calculated as follows,

Seed cotton production efficiency of K (N or P) = Seed cotton yield / K (N or P) uptake of cotton plants.

Differences in nutrient accumulation

The increase in nutrient accumulation in cotton plants was affected by dry matter weight and nutrient content. The proportion of the increased nutrient accumulation due to the increase of one factor to the total added value is calculated as follows,

$$\text{Increasing rate of nutrient accumulation}(\%) = (C_2W_2 - C_1W_1)$$

$$\text{Increasing rate because of nourishment content}(\%) = (C_2 - C_1) \times W_2$$

$$\text{Increasing rate because of dry matter}(\%) = C_1 \times (W_2 - W_1)$$

C_2, Nourishment content of treatment 2. C_1, Nourishment content of treatment 1. W_2, Dry matter weight of treatment 2. W_1, Dry matter weight of treatment 1.

Statistical analysis

The data were processed by Microsoft Excel 2007, figures were drawn using Origin 2018, and the statistical analysis was performed using SPSS ver. 26. The least significant differences (LSD) test was used for comparing and ranking the treatments.

Results

Dry matter accumulation and distribution

The dry matter mass of cotton plants increased as the bolls developed across all K levels. The soil K level only changed the dry matter accumulation in different growth periods, but the overall trend of dry matter accumulation remained unchanged (Fig. 2). There was no significant difference in the dry matter accumulation of cotton plant at the bud stage, but significant differences were found under different soil K levels from the flowering stage, with extremely significant differences ($P < 0.01$) among different soil K levels during the flowering and boll stage and boll opening stage. Moreover, these differences were consistent in both 2020 and 2021. The results showed that there were no significant differences in dry matter accumulation per plant among K4, K5, and K6, which were significantly improved compared with those in K1 and K2 in the flowering and boll stage and boll opening stage (Fig. 2).

The dry matter distribution percentage of vegetative organs gradually decreased with the advancement of the growing process, while the distribution percentage of reproductive organs continued to increase (Fig. 3). The dry matter distribution percentage of reproductive organs was not significantly different in different soil K levels at the bud stage, flowering stage, flowering and boll stage. The dry matter distribution percentage of reproductive organs in K4 was significantly higher than that in K1 during the flowering and boll stage, and boll opening stage, but not significantly different from that in K2, K3, K5 and K6 (Fig. 3). The results were consistent over the two years. These results indicated that adequate K supply can sufficiently promote the development of cotton bolls.

Single-plant seed cotton yield

In 2020 and 2021, with the increase in the soil K level, the single-plant seed cotton yield showed an increasing trend. The single-plant seed cotton yield reached a significant difference level at different soil K levels, K4, K5, and K6 showed no significant difference, but they were significantly higher than K1 and K2 (Fig. 4). The difference between years was not significant, nor was the difference between years and treatments.

Nutrient accumulation and distribution

The nutrient (N, P, and K) uptake of cotton increased under different soil K levels with the advancement of the growth period (Fig. 5). Neither the N nor P content of cotton plants was significantly affected by different soil K levels during the bud stage. Significant differences were observed in the accumulation of N and P among different

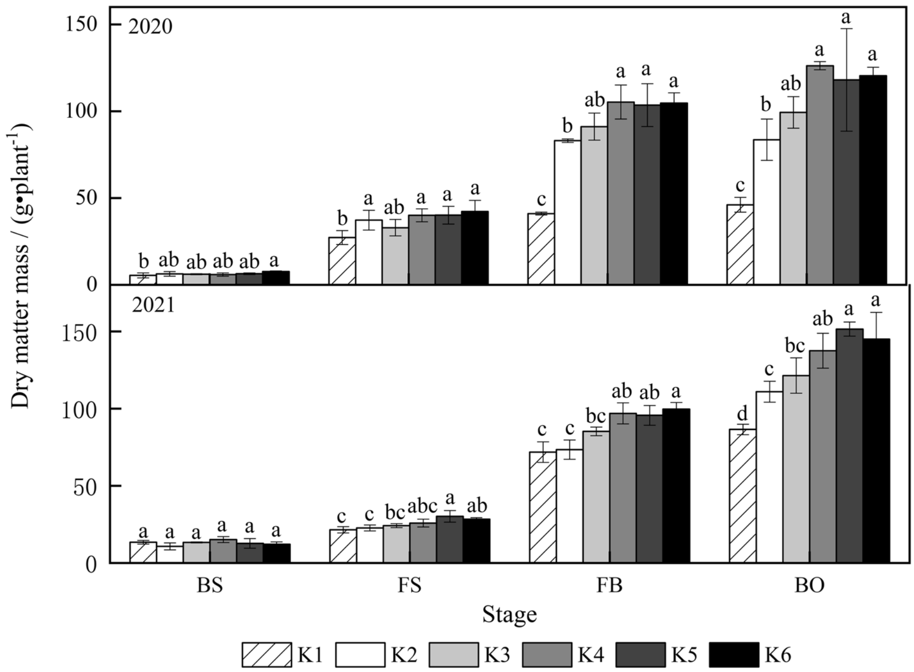

Fig. 2 Effects of different soil K levels on dry matter accumulation in cotton. BS, bud stage. FS, flowering stage. FB, flowering and boll stage. BO, boll opening stage. Different lowercase letters at the same stage indicate significant differences at the 0.05 probability level

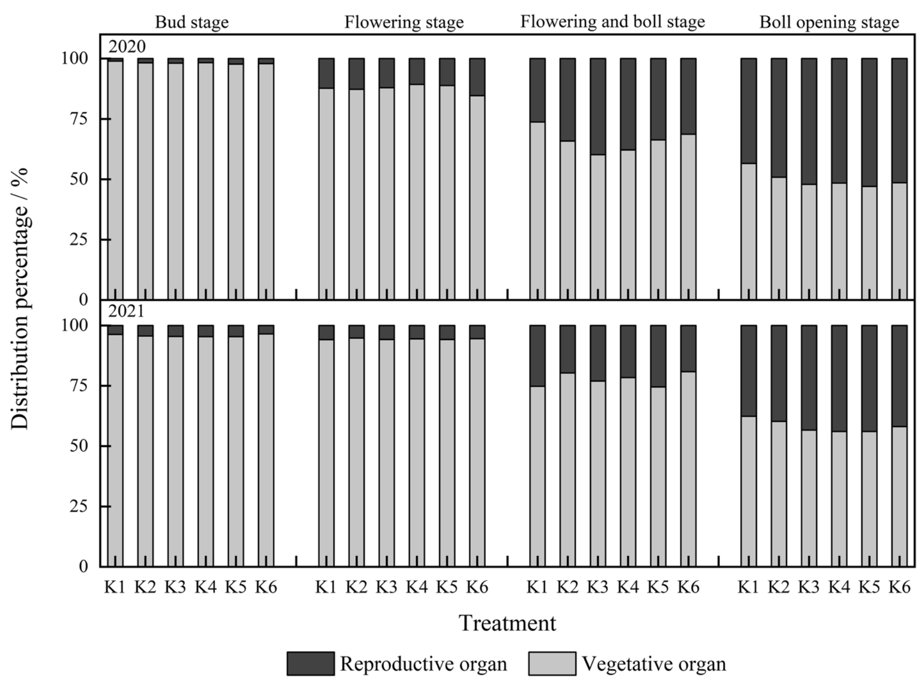

Fig. 3 Dry matter distribution of vegetative organs and reproductive organs under different soil K levels in 2020 and 2021

K levels at the flowering stage, the flowering and boll stage, and the boll opening stage. There were significant differences in the K uptake of cotton plants with different soil K levels during various plant growth periods. The principle of N, P, and K uptake roughly suggests that K4, K5, and K6 had significantly higher uptake than K1 and K2, while there was no significant difference among K4, K5, and K6 at the flowering and boll stage and the boll

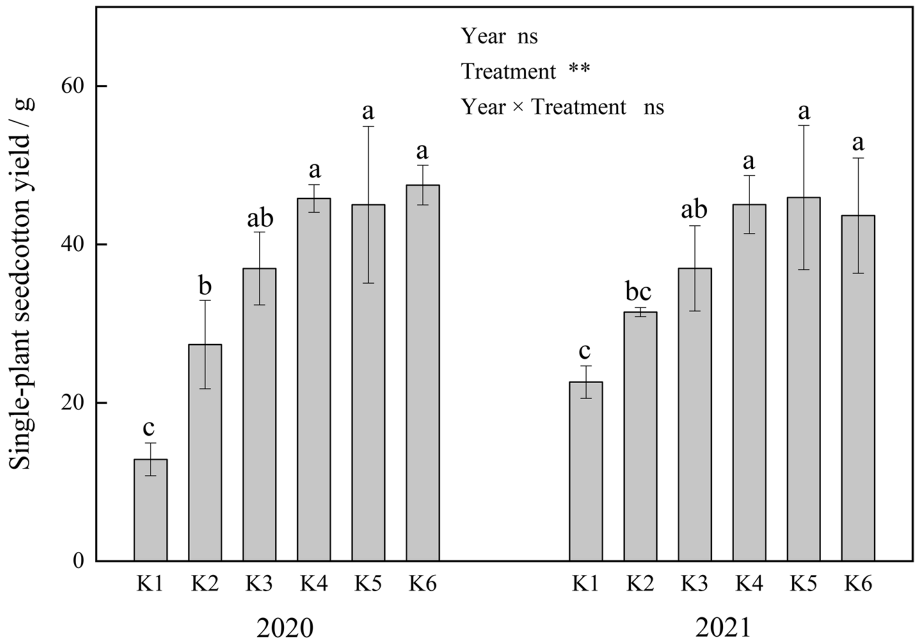

Fig. 4 Single-plant seed cotton yield from the boll opening stage under different soil K levels in 2020 and 2021. Different lowercase letters in the same year indicate significant differences at the 0.05 probability level. * and ** indicate significant differences at the 0.05 and 0.01 probability levels, respectively. ns indicates no significant difference

opening stage. Additionally, the significance of the difference was consistent in both 2020 and 2021.

The distribution percentages of N, P, and K in vegetative organs gradually decreased with the advancement of the growing process, and the distribution percentages in reproductive organs continued to increase (Fig. 6). The distribution percentages of N and P in vegetative organs and reproductive organs under different soil K levels were significantly different only at the boll opening stage. The basic performance was that the distribution percentages of N and P in vegetative organs and reproductive organs among K3, K4, K5, and K6 were not significantly different, but they were all significantly different from K1. The K distribution of both vegetative organs and reproductive organs under different soil K levels was significantly different at each period, and with the increasing of soil K levels, the K allocation ratio of reproductive organs showed an overall decreasing trend. During plant growth, the distribution percentages of K in vegetative organs and reproductive organs between K4, K5, and K6 were almost not significantly different. The results were consistent between 2020 and 2021 (Fig. 6). The results revealed that the K content of cotton bolls did not increase as the soil available K increased when the soil K concentration was above 140 $mg \cdot kg^{-1}$ (K4 level).

Differences in nutrient accumulation

The nutrient accumulation of cotton plants showed significant differences among different soil K levels (Fig. 5). There was an increasing trend in the nutrient accumulation of cotton plants with the increasing of soil K levels (Table 2). The results indicated that the significant differences in N and P accumulation by cotton plants under different K levels were the same as dry matter weight (Table 2). The significant difference in K uptake of cotton plants with different K levels was caused by the common difference in dry matter weight and K content at the boll opening stage. However, the roles of dry matter weight and K content were not consistent in 2020 and 2021. In 2020, the difference in K uptake of cotton plants was mainly caused by the effect of dry matter weight, and the difference in K uptake of cotton plants was mainly caused by the effect of K content in 2021 (Table 2).

Nutrient production efficiency

As the soil K level increased, the seed cotton production efficiency of N and P increased significantly. The seed cotton production efficiencies of N and P in K4 were not significantly different from those in K5 and K6. This pattern was consistent between 2020 and 2021 (Table 3). The results indicated that the soil K level had a significant effect on the seed cotton production efficiency of N and P, but the effect could be ignored when the soil K level was sufficient. There was no significant difference in seed cotton production efficiency of K among different soil K levels. In addition, the difference between years was not significant in seed cotton production efficiency of N, P and K. The seed cotton production efficiency of

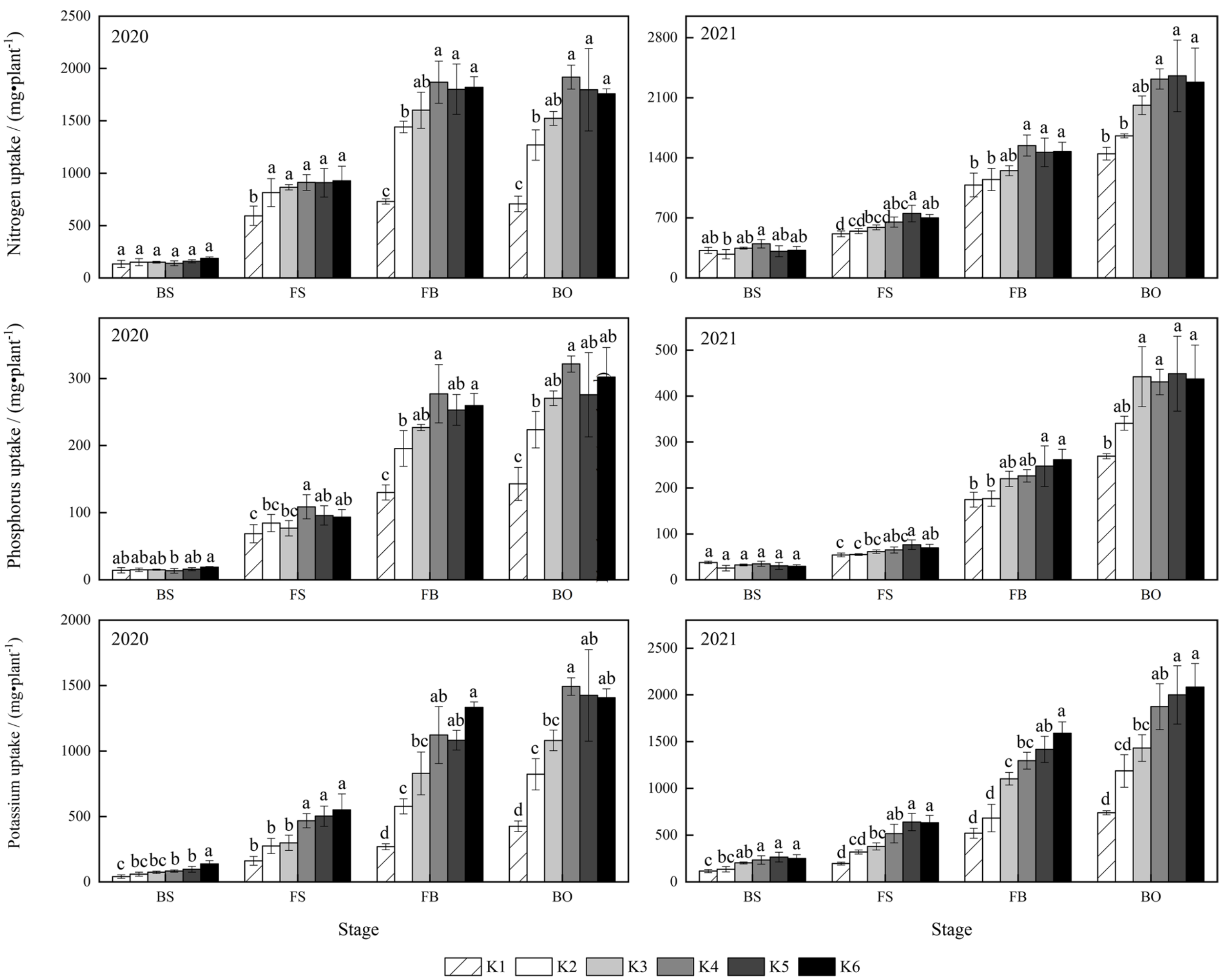

Fig. 5 N, P and K uptake of cotton plants under different soil K levels. BS, bud stage. FS, flowering stage. FB, flowering and boll stage. BO, boll opening stage. Different lowercase letters at the same stage indicate significant differences at the 0.05 probability level

nutrients under different soil K levels in 2020 was higher than that in 2021.

The correlations with soil K level

The soil K content had a certain effect on dry matter mass and K accumulation in cotton plants (Fig. 7). Correlation analysis showed that the soil K level was significantly correlated with dry matter mass in 2020 ($P=0.003\ 9$) and 2021 ($P=0.008\ 5$). There was a significantly positive correlation between the soil K level and plant K accumulation in both 2020 ($P=0.001\ 9$) and 2021 ($P=0.002\ 1$). The soil K level was significantly and positively correlated with the single-plant seed cotton yield in 2020 ($P=0.001\ 3$) and 2021 ($P=0.003\ 3$). The extent of the relationship varied with a stronger relationship in 2020 than in 2021. When the soil K level was higher than that of K4, the dry matter mass, plant K accumulation and seed cotton yield of 2020 and the seed cotton yield per plant of 2021 did not increase, indicating that the soil K concentration of K4 was a suitable concentration of soil K nutrients (Fig. 7).

Discussion

Dry matter accumulation under different soil K levels

The formation process of crop yield is the process of dry matter production, translocation and distribution. Although K does not participate in the composition of plant tissue or structure, it plays an important role in the growth and development of plants. It is the most abundant inorganic ion in plants, and its content can even reach 10% of plant dry weight (White and Karley 2010). Compared with other crops, cotton is more sensitive to K. When the plant K content (in dry matter weight) is less than 20 $mg \cdot g^{-1}$, cotton growth is restricted (Bednarz and Oosterhuis 1999; Reddy et al. 2000). K application affects the growth of cotton, promotes an increase in dry

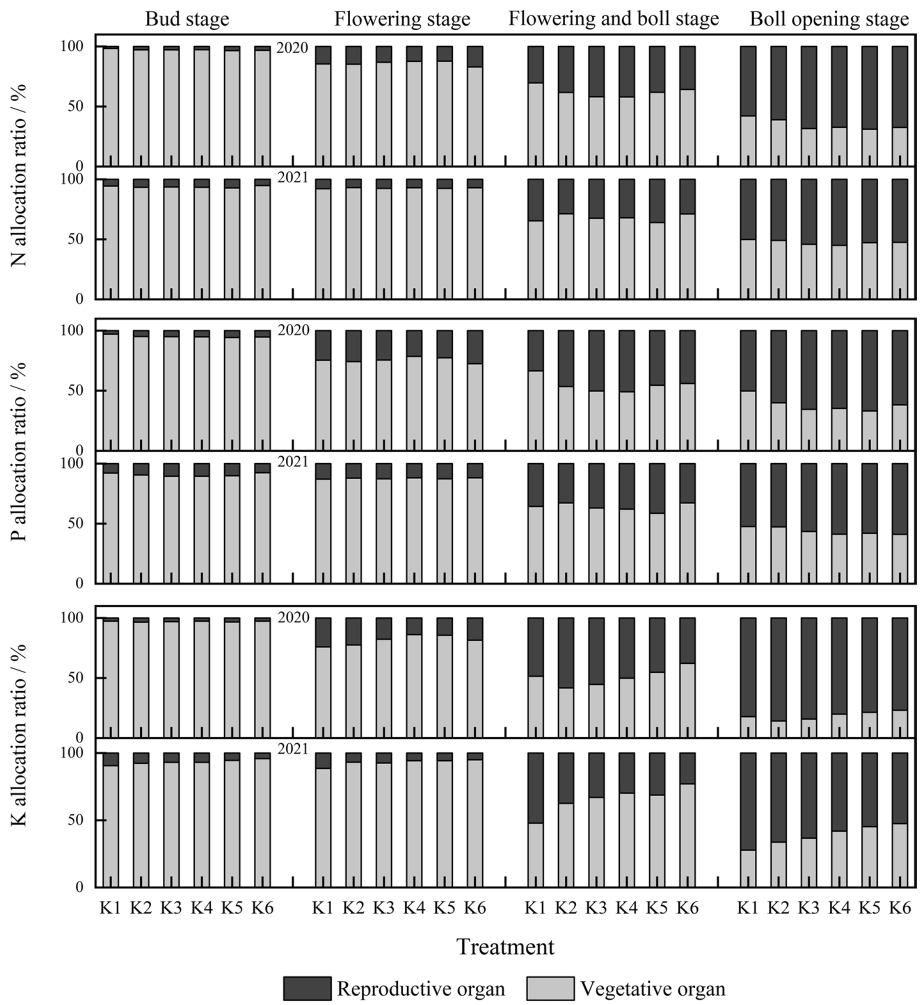

Fig. 6 N, P, and K distribution of cotton under different soil K levels

matter weight (Gerardeaux et al. 2010; Hu et al. 2015), and affects the dry matter distribution ratio of various organs (Pettigrew et al. 2005; Hu et al. 2016b).

The results showed that there was a difference among the dry matter mass under different soil K levels during different growth periods. The dry matter at earlier growing stages was not significantly different, until the flowering stage. The difference was extremely significant at the flowering and boll stage, boll opening stage, and dry matter mass of cotton plants in K4 was significantly higher than that of K1 and K2, which was not significantly different from K5 and K6. The main reason was that the dry matter of cotton plants accumulated as an S-shape curve during the whole growth period, the dry matter had higher accumulation in the late growth period, and the flowering and boll stage was the rapid growth period of dry matter (Yang et al. 2013). The proportion of dry matter distributed to cotton bolls was significantly increased during the flowering and boll stage and the boll opening stage. The proportion occupied by dry matter of cotton bolls was 19%~38% at the flowering and boll stage, which reached 38%~53% at the boll opening stage. Previous studies have shown that appropriate K fertilizer input could help to coordinate the relationship between plant vegetative and reproductive growth, and with the changes in K fertilizer application, the dry matter partitioning in plant vegetative and reproductive organs was altered (Hu et al. 2015; Makhdum et al. 2007; Shukla et al. 2009). The massive transfer of dry matter to economic organs was a precondition for achieving high quality and high yield (Watta et al. 2003), and sufficient K supply is beneficial to high yield (Oosterhuis et al. 2013; Tsialtas et al. 2016; Zhang et al. 2011). In this research, the proportion of dry matter mass in reproductive organs and single-plant seed cotton yield under different soil K levels were significantly different at the boll opening stage. There was no significant difference in the reproductive organs dry weight and

Table 2 Difference analysis of N, P and K accumulation in cotton plants under different soil K levels in 2020 and 2021

Nutrient	Treatment	Increasing rate of nutrient accumulation/%		Increasing factors			
				Increasing rate because of nourishment content/%		Increasing rate because of dry matter/%	
		2020	2021	2020	2021	2020	2021
N	K1						
	K2	79.36	14.36	-1.13	-11.50	101.13	111.50
	K3	115.35	39.08	1.16	-66.11	98.84	166.11
	K4	171.06	60.16	-1.24	5.45	101.24	94.55
	K5	153.96	62.70	0.39	3.62	99.61	96.38
	K6	148.52	57.60	-8.12	-15.77	108.12	115.77
P	K1						
	K2	56.55	26.64	-22.20	-10.27	122.20	110.27
	K3	89.29	64.32	-13.59	4.13	113.59	95.87
	K4	125.04	60.09	-25.42	-0.16	125.42	100.16
	K5	93.02	66.78	-46.88	5.18	146.88	94.82
	K6	111.60	62.51	-28.74	-11.55	128.74	111.55
K	K1						
	K2	93.33	60.49	12.74	55.12	87.26	44.88
	K3	154.12	93.70	25.26	58.25	74.74	41.75
	K4	251.01	153.47	30.68	60.76	69.32	39.24
	K5	235.08	170.52	33.62	60.77	66.38	39.23
	K6	231.01	181.95	30.08	60.79	69.92	39.21

These were calculated on the basis of data from the boll opening stage. The increasing rate was calculated based on the treatment of K1

Table 3 Seed cotton production efficiency of N, P and K in cotton plants in 2020 and 2021

Treatment	Seed cotton production efficiency of N/($g \cdot g^{-1}$)		Seed cotton production efficiency of P/($g \cdot g^{-1}$)		Seed cotton production efficiency of K/($g \cdot g^{-1}$)	
	2020	2021	2020	2021	2020	2021
K1	18.08 c	15.49 c	90.50 c	78.77 c	30.23 a	27.94 a
K2	21.35 bc	17.2 bc	121.19 bc	84.69 bc	33.00 a	25.38 ab
K3	24.20 ab	20.97a	136.3 ab	98.35 ab	34.08 a	24.03 ab
K4	23.98 ab	19.47 ab	142.51 ab	104.44 a	30.70 a	24.32 ab
K5	25.05 ab	19.42 ab	163.57 a	102.28 a	31.78 a	22.84 b
K6	27.02 a	19.18 ab	161.18 a	100.31 a	33.73 a	20.83 b
Year	**		**		**	
Treatment	**		**		ns	
Year × Treatment	ns		ns		*	

Values followed by different letters within the same column are significantly different at the 0.05 probability level

* and ** means the significant differences at 0.05 and 0.01 probability levels, respectively. ns means no significant difference

single-plant seed cotton yield of K4 with K5 and K6. The results revealed that K4 could efficiently promote the development of cotton bolls and is conducive to the formation of high yields. In other words, the proportion of cotton bolls dry weight and seed cotton yield was not affected when the soil available K content reacheed the level of treatment K4 in this study.

Nutrient accumulation under different soil K levels

Nutrient absorption is the basis of biomass accumulation and crop yield formation. Adequate nutrient supply is the key to high yield of cotton during whole plant growth stages. However, the absorption of nutrients does not distinguish their source, soil or fertilizer (Dong et al. 2010). To ensure the production of cotton, fertilizer is

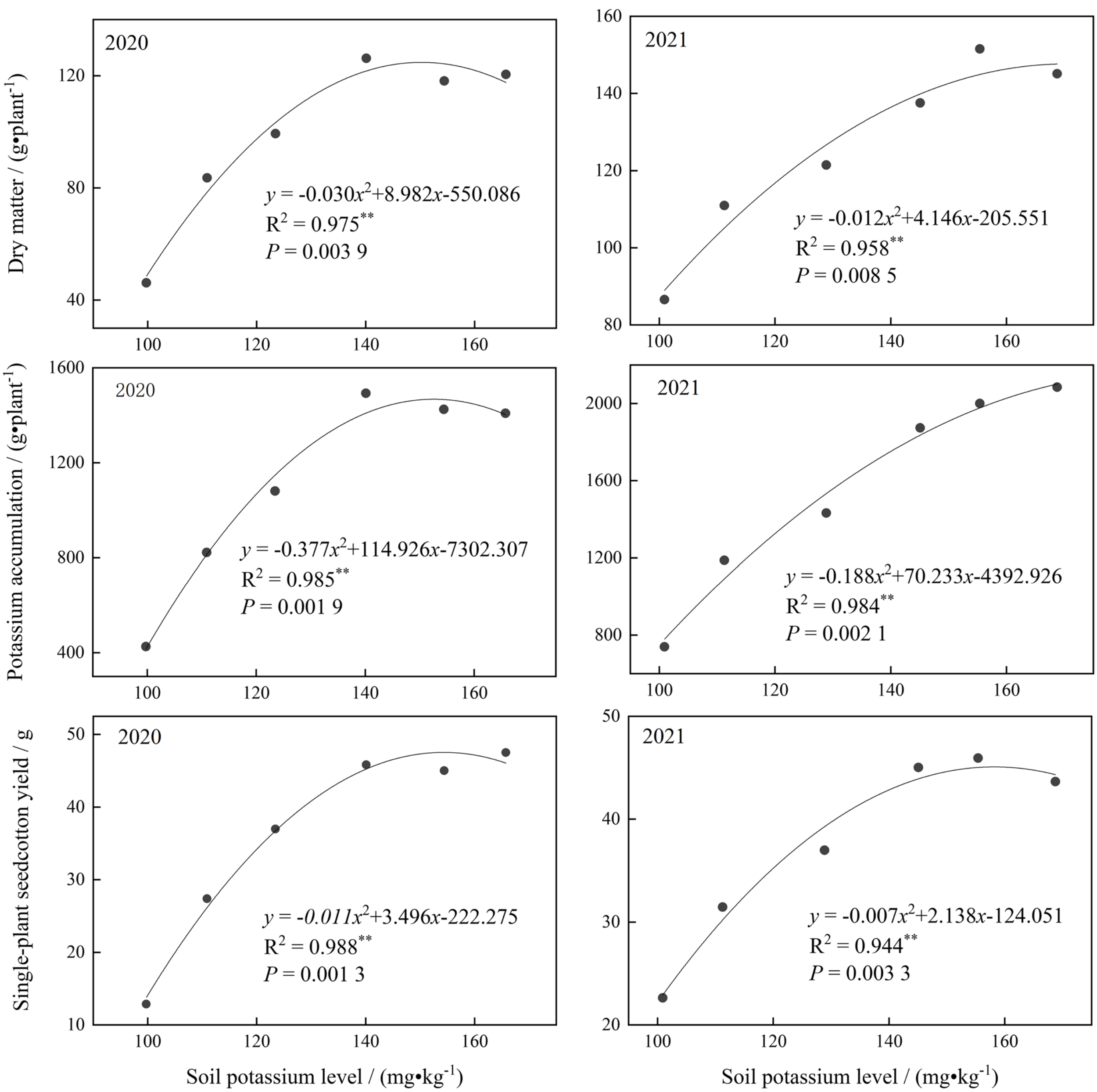

Fig. 7 Relationship between soil K level and plant K content, dry matter mass and single-plant seed cotton yield during 2020 and 2021. ** indicates significant differences at the 0.01 probability levels

generally applied in the field to ensure that the cotton plant has enough nutrients. Reasonable application of fertilizer can effectively increase N, P, and K contents and crop yield (Feng et al. 2023; Khalifa et al. 2012; Xu and Li 2014). However, excessive fertilizer or hypo-fertilization will inhibit the absorption of nutrients by crops, which is not conducive to the improving of fertilizer utilization, yield and quality (Byju and Anand 2009). Appropriate K supply promotes the absorption of N, P, and K by plants (Shukla et al. 2009), increases the distribution and transfer rate of nutrients to reproductive organs, and contributes to high yields (Kang et al. 2018).

In this study, the accumulation of N, P, and K followed a similar trend to the variation in dry matter accumulation, showing an upward trend as the growth period progressed. There was a difference between the nutrient absorption of different soil K levels during different growth periods, the difference was not significant at the earlier growing stage, but there was a significant difference at the flowering stage, the flowering and boll stage, and the boll opening stage. This was because the period from flowering to boll opening was the peak of nutrient absorption of cotton (Genget al. 2015). The nutrient uptake in K4 was not significantly different from that in K5 and K6 in the three later stages above. The difference rule was consistent over the two years. The reproductive organ is the largest and final sink in cotton plants. Nutrient transport from cotton plants to reproductive organs is closely related to yield and quality formation (Gormus and Yucel 2002). These results showed that the accumulation percentage of N and P in reproductive organs gradually increased as the cotton grew, and the difference between different treatments was significant at the boll opening stage. The N and P distribution of reproductive organs in K4 was not significantly different from that in K5 and K6 at the boll opening stage. However, the K distribution of vegetative organs and reproductive organs under different soil K levels was significantly different at each period, and the significance of the difference was consistent in 2020 and 2021. With the increase in soil K levels, the K allocation ratio of reproductive organs showed an overall decreasing trend. However, the distribution percentages of K in vegetative organs and reproductive organs between K4 and K5, and K6 were almost not significantly different in the growth process. The soil K level of K4 was an inflection point for the nutrient uptake and partitioning of cotton. Once the soil K level reaches the K4 level, there will be no more increase in the nutrient uptake of cotton plants or in the nutrient content or proportion of cotton bolls. Therefore, the application of K fertilizer should be emphasized in the production of high-yield cotton, and the K level of the soil should be emphasized when applying K fertilizer.

Relationship between nutrient content and dry matter accumulation

Plant nutrient accumulation is the result of the combined action of dry matter weight and nutrient content (Ao et al. 2008). The results showed that the significant differences in cotton plant uptake of N and P under different soil K levels were caused by differences in dry matter in this study. However, the significant difference in K uptake of cotton plants under different soil K levels was contributed by the common difference in dry matter weight and K content. The effects of dry matter weight and K content on cotton plant K accumulation were not consistent in 2020 and 2021. In addition, the seed cotton production efficiency of nutrients at different soil K levels in 2020 was higher than that in 2021. The proportion of dry matter distributed in reproductive organs accounted for 43%~53% and 37%~44% in 2020 and 2021, respectively. The proportion of reproductive organs in K, N and P accumulation accounted for 77%86%, 58%69%, and 50%~67% in 2020, compared with 52%~72%, 50%~55%, and 52%~62% in 2021. These results indicated that dry matter accumulation and nutrient uptake in reproductive organs in 2021 were lower than those in 2020. Therefore, the seed cotton production efficiency of nutrients in 2021 was lower than that in 2020, which also led to differences in some factors that affected the greater K accumulation in cotton plants in the two years. At present, we speculated that this could be caused by the prosperous growth of cotton due to more rain in 2021.

Previous studies showed that K application significantly increased the seed cotton yield, but at a soil K level of 127~134 $mg \cdot kg^{-1}$, 80 $kg \cdot ha^{-1}$ K_2O was sufficient to improve the seed cotton yield (Tsialtas et al. 2016), while at a soil K level of 86.3~91.8 $mg \cdot kg^{-1}$, 300 $kg \cdot ha^{-1}$ K_2O could significantly increase the seed cotton yield (Hu et al. 2018), and it also significantly increased plant biomass (Hu et al. 2015) and K content in reproductive organs (Hu et al. 2016a). Therefore, the application of fertilizer must be based on soil nutrient levels. In this experiment, when the soil K level was higher than that of K4, the dry matter accumulation, nutrient uptake, proportion of K accumulation in reproductive organs, nutrient production efficiency and single-plant seed cotton yield no longer increased or decreased significantly. Therefore, the soil K level of K4 (140.13~145.10 $mg \cdot kg^{-1}$) was able to provide sufficient K for cotton growth. It is speculated that K fertilizer is not required when the soil available K content is higher than K4. The results of previous studies also showed the same tendency (Hsu 1976; Zhang et al. 1991). However, most of the cotton varieties used at present is transgenic insect-resistant cotton, and the cotton yield is higher than before. Thus, for modern high-yield cotton varieties, the research data in this article further provide a theoretical basis for K fertilizer management in cotton fields. Fertilizer application is a technical solution to the issue of inadequate soil nutrients for crop growth. Our study elucidated the impact of soil available K levels on cotton growth, nutrient efficiency, and yield. This lays the groundwork for future recommendations on fertilization strategies, especially reduced the application amount. It should also be noted that these conclusions were based on data from micro plots, where density and field management were based on local cotton planting techniques. If applied to other cotton fields, production issues such as density need to be considered.

Conclusions

The soil K content showed a significantly positive relationship with both dry matter mass and K accumulation in cotton plants. There were significant differences in dry matter accumulation, single-plant seed cotton yield, nutrient uptake, and the proportion of K accumulation in reproductive organs among different soil K levels. There was a significant difference between K4 (140.13~145.10 mg·kg^{-1}) and lower K level treatments (K1 and K2), but no significant difference between K4 and higher K level treatments (K5 and K6) in dry matter mass, single-plant seed cotton yield, nutrient accumulation and distribution and seed cotton production efficiency of N, P, and K. Therefore, in this study, the soil K level of K4 was able to provide sufficient K for cotton growth in our experiment. Therefore, when the soil K level reaches 140.13 mg·kg^{-1}, further increase of soil K concentration no longer have significant positive effect on cotton growth.

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Authors' contributions
Dong HL, Li PC, and Zheng CS designed the experiment. Shao JJ performed the field and lab work with help from Sun M, Feng WN, and Jin YN. Shao JJ analyzed the data and led the writing of the manuscript. All authors read and approved the final manuscript.

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Availability of data and materials
The datasets used during this study can be provided on reasonable request.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

Competing interests
None of the authors have any conflict of interest.

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