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EFFECTS OF POTASSIUM FERTILIZER ON THE PHYSIOLOGICAL MECHANISMS OF COTTON FIBER QUALITY

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Abstract

Endogenous hormones are a key factor in cotton fiber quality. Studying the relationship among endogenous hormone contents and fiber quality can provide a theoretical basis for exploring physiological measurements to improve fiber quality. The relationships among endogenous hormone contents and fiber quality for different boll positions and potassium (K) conditions were investigated for the main cultivar 'Xinluzao 24.' We used eight application rates of K fertilizer (K_2O 0, 37.5, 75, 112.5, 150, 37.5 and sprayed 1% K_2SO_4, 75 and sprayed 1% K_2SO_4, and 150 and sprayed 1% K_2SO_4 kg ha^{-1} under field conditions). We then measured the contents of indoleacetic acid (IAA), gibberellin (GA_3), zeatin (Z), and abscisic acid (ABA) in relation to changes in fiber quality indices. Results showed that application of K fertilizer significantly increased the contents of IAA, GA_3, and Z in the upper and middle boll, and decreased the contents of ABA in the upper, middle, and the lower boll. Compared with the control, applying K fertilizer between 37.5 kg K_2O ha^{-1} and 112.5 kg K_2O ha^{-1} can significantly increase the length, uniformity, strength, micronaire, and maturity of fiber in three parts of the plant. However, excessive application of K fertilizer can reduce fiber uniformity, strength, and micronaire in these locations. Through comprehensive comparison, we determined that the optimal application of K fertilizer for regulating endogenous hormones and improving fiber quality was a basal application of 75 kg K_2O ha^{-1} and a spray application of 1% K_2SO_4. The endogenous hormones IAA, GA_3, and Z can improve cotton fiber quality, but ABA can inhibit cotton fiber quality. Results indicate that reasonable applications of potassium fertilizer could regulate endogenous hormones and improve fiber quality.

Key words: Potassium nutrition, Cotton, Endogenous hormones, Fiber quality.

Introduction

Cotton (*Gossypium hirsutum* L.), the king of natural fibers, is of prime importance in the economy of many countries, providing renewable natural fiber resources for the global textile industry (Zhang *et al*., 2015). The yield and quality of cotton are influenced by genetics and environmental conditions (Ramey, 1986; Reddy *et al*., 1999; Lokhande & Reddy, 2015). Fertilizer management has a decisive effect on fiber quality, and potassium (K) is one of the major mineral nutrients impacting cotton plant growth, development, lint yield, and fiber quality (Kerby *et al*., 1985; Cassman *et al*., 1990; Reddy & Zhao, 2005; Derrick *et al*., 2013). K deficiency has negative effects on cotton plant photosynthesis (Bednarz *et al*., 1998; Reddy & Zhao, 2005; Hu *et al*., 2015), biomass production (Zhao *et al*., 2001; Reddy & Zhao, 2005; Gerardeaux *et al*., 2010), lint yield (Pettigrew, 2003; Li *et al*., 2012), and fiber quality (Pettigrew *et al*., 1996). The impact of K is not always visible and consistent in terms of improvement in fiber quality parameters (Bauer *et al*., 1998). However, researchers have reported that K can be conducive to fiber elongation, increased thickness of the secondary fiber wall, and enhancement of fiber strength (Cassman *et al*., 1990; Read *et al*., 2005; Pervez *et al*., 2005a; Yang *et al*., 2008; Temiz *et al*., 2009; Kaur *et al*., 2011; Waraich *et al*., 2011). K has the greatest impact on fiber maturity and micronaire, less on length and strength, and little effect on uniformity (Pettigrew, 2003; Zhao *et al*., 2013). It is often reported that K nutrition can also influence endogenous hormone content (Liu *et al*., 2006). Research shows that spraying K significantly increases IAA content in the boll shell within 30 days after blossom in the middle and upper bolls. Additionally, the differences in IAA content between the middle and upper boll shells tend to narrow with the intensification of potassium applications. ZR content in the middle and upper boll fiber peaks thirty days after blossom, while ZR content at the tenth day after blossom in the middle boll is higher than that after 50 days.

Considerable evidence indicates that endogenous hormones play a decisive role in regulating cotton fiber growth and development (Beasley & Ting, 1973; Beasley & Ting, 1974; Naithani *et al*., 1982; Dasani & Thaker, 2006). *In vitro* culture of ovules indicated that IAA plays an important role in fiber development, and that ABA inhibits fiber development (Beasley & Ting, 1973). Addicott (1982) observed that ABA content was higher in mature cotton fruits than in young, healthy fruits. Related information shows that GA_3 and IAA help the fiber elongation process, and that ABA is counterproductive. Increases in ZR are beneficial for differentiation of fiber and the extension of the fiber enrichment period. Brassinosteroids (BRs) affect cotton fiber initiation and elongation, ethylene promotes cotton fiber elongation, and GAs stimulate cotton fiber differentiation and elongation. Additionally, ZR content has a significant or very significant positive correlation with fiber length and maturity (Gokani & Thaker, 2002; Du *et al*., 2004; Seagull & Giavalis, 2004; Cheng *et al*., 2005; Pervez *et al*., 2005a; Chen, 2006; Dasani & Thaker, 2006; Fuller *et al*., 2009;Liao *et al*., 2009; Xiao *et al*., 2010).

Reports of the separate influence of K on seed yield, fiber quality, and endogenous hormones have been received over the past decade. Thus, there is insufficient information regarding K influence on fiber quality and endogenous hormones, and also the correlation between fiber quality and endogenous hormones. Therefore, the objectives of this research were to: (i) identify K fertilizer doses and management that may improve fiber yield and quality, (ii) discuss the correlation between fiber quality and endogenous hormones, and (iii) understand the regulated pathways and physiological mechanisms underlying the role of K in improving fiber quality.

Materials and Methods

Experimental material and design: The trial was located at the Experimental Farm of the Fertilizer Institute of Agriculture, Changji City (87°27′ E, 44°15′ N), in northern Xinjiang, China. The area has a semi-arid climate, and the average annual temperature was 7.2 °C in 2013. The hottest month is July (mean daily maxima and minima of 27.2°C and 22.6°C, respectively), whereas January is the coldest (mean daily maxima and minima of –12.2°C and –20.4°C, respectively). The area has a mean annual precipitation of 194.3 mm with a mean annual surface evaporation of 1988.5 mm, a frost-free period of 175 d, annual sunshine hours of 3110 h, and total annual solar radiation of 5560 MJ m^{-2}. Surface soil (0–0.2 m) had 7.8 pH (H_2O), 17.2 g kg^{-1} organic matter, 1.2 g kg^{-1} total nitrogen, 0.9 g kg^{-1} total phosphorus, 6.7 g kg^{-1} total K, 32.3 mg kg^{-1} available nitrogen, 8.0 mg kg^{-1} 0.5 M $NaHCO_3$-P, and 207 mg kg^{-1} NH_4OAc-K.

Eight treatments of K fertilizer (K_2O) at five different levels (0, 37.5, 75, 112.5, 150) were applied using three management methods (37.5 and spraying 1% K_2SO_4, 75 and spraying 1% K_2SO_4, and 150 and spraying 1% K_2SO_4 kg ha^{-1}, referred to as K_0, K_1, K_2, K_3, K_4, K_5, K_6, and K_7 respectively, among which, K_5, K_6, and K_7 were management designs of K fertilizer. Treatments were arranged in a randomized complete block design with four replicates. All treatments received 300 kg ha^{-1} of N as urea; the treatments were applied by drip irrigation in three different stages: 180 kg ha^{-1} before sowing, 60 kg ha^{-1} at the bud stage, and 60 kg ha^{-1}at the flower boll stage. K fertilizer (potassium sulphate with 40% K_2O) and 150 kg ha^{-1} of P_2O_5 as TSP (triple superphosphate with 46% P_2O_5) were added to the topsoil before sowing by broadcast application and then mixed by conventional tillage (0–0.3 m depth). The spray applications of K fertilizer were applied during blossing and boll-forming stages. The area of each experimental block was 64 m^2 (6.4 m×10 m).

The cotton variety used was XinluZao 24, a standard cotton variety for the region. The cotton was planted in row spacings of 0.5 m, 0.3 m, 0.5 m, and 0.3 m and plant spacing within the rows of 0.1 m. The density was 195,000–225,000 plants ha^{-1}. Cotton seeds were sowed on April 25, 2013. The frequency of drip irrigation was seven days. The first irrigation was applied on June 15 (bud stage) and there were a total of 10 or 11 irrigations throughout the period of crop production. Weeds were controlled by manual removal. Control of pests and diseases was provided as needed during the growing season, according to local recommendations. All other production practices followed recommended practices.

Harvest and sample analysis: After all harvestable bolls had matured, boll and fiber data were obtained from 30 boll samples, hand-harvested at 8-m lengths from the four center rows in each block. The cotton bolls in the first and second nodes in the third through sixth branches of each individual were marked as lower bolls. The cotton bolls in the first and second nodes in the seventh through ninth branches of each individual were marked as middle bolls, while those in the first and second nodes in the tenth or following branches of each individual were marked as upper bolls. Fiber properties for each sample were determined using a HFT 900 testing instrument in the Quality Inspection Center, Agricultural Academy of Xinjiang.

Purification and extraction of endogenous plant hormones were carried out according to Chen *et al.* (1996) with some modifications. About 0.5–1.0g of fresh cotton fibers were weighed and quickly refrigerated. After refrigeration, cotton fibers were ground into powder and 5 ml of 80% methyl alcohol solution was added at a W:V ratio of 1:10–20. The extract was completely sealed and refrigerated at 4°C for 12 h, then centrifuged for 30 m at 2,000×g. The leached solution was removed, and 3,000 µL (80%) cold methyl alcohol solution was added and shaken for several hours, then centrifuged for 20 m. The supernatant solution was dried with nitrogen. Petroleum ether and distil liquid (supernatant solution at ratio of 1:1) were shaken until distinct differences were observed. The solution was left to settle and the petrol ether was removed and the methyl alcohol solution was retained. The methyl alcohol extract was dried with nitrogen at pH 2, extracted three times with equal volume of glacial acetic acid, and shaken in a mechanical shaker. The entire methanol organic phase was combined and the water phase was adjusted to pH 2.8. Glacial acetic acid and ethyl acetate (2,000 µL each) were added and shaken. Extraction was carried out three times with 2,000 µL of ethyl acetate. The entire ethyl acetate phase was combined and dried with nitrogen. It was then extracted three times with 2,000 µL buthanol, and dried with nitrogen until it reduced to 1,000 µL. The filtrate was passed through a 0.45 um membrane and 0.1 µL samples were analyzed by high performance liquid chromatography (HPLC) to separate and determine the concentration of IAA, GA_3, ABA, and ZR in cotton fibers with a mobile phase mixture of acetonitrile and water (volume ratio 4:6) at a flow rate of 1,000 µL min^{-1} with an injection volume of 0.1 uL detector wavelength set at 254 nm.

Statistical analysis: Statistical analyses were performed with Statistical Product and Service Solutions (SPSS) software. Comparisons of means were performed using Duncan's multiple range analysis test (α = 0.05). The figures were mapped using Origin 8.0.

Results

Effect of K rates and management on seed cotton yield and dry matter weight: The application of soil K fertilizer (from 37.5 kg K_2O ha^{-1} to 112.5 kg K_2O ha^{-1}) had a significant effect on seed yield, but further K fertilizer supply (K_4) had no significant effect on seed yield. The K_2 treatment provided the highest yield, an increase of 618 kg ha^{-1} (+19.4%). K_2 was followed by the K_1 treatment (+16.5%), the K_3 treatment (+13.5%), and the K_4 treatment (+4.6%) (Fig. 1). Cotton seed yield was also significantly affected by basal and spray applications of K fertilizer (K_5 and K_6), increasing by 12.2% and 17.0%, respectively, compared with the control treatment (K_0). However, the K_7 treatment provided the same mean as the control treatment (K_0) (Fig. 1-a).

Similar results were obtained for dry matter accumulation in the mature stage, with the K_6 treatment and K_2 treatments resulting in the greatest increases at 2032 kg ha^{-1} (+22.2%) and 1667 kg ha^{-1} (+18.2%), respectively (Fig. 1-b).

Effect of K rates and management on K accumulation: K rates and management had a significant effect on K accumulation in roots and stems in the mature stage. The K_6 and K_2 treatments caused considerable improvement in K accumulation in roots and stems by 52.9% and 61.9%, and 39.8% and 48.6%, respectively, compared to treatments that received no K fertilizer (Fig. 2). In leaves, bolls, and the whole plant, K accumulation significantly increased with increasing K rates, while K accumulation decreased when K application rates exceeded 75 kg K_2O ha^{-1} (Fig. 2). For K management purposes, the K_6 treatment resulted in the highest K accumulation, an increase of 60 kg ha^{-1} (+29.6%) (Fig. 2).

Effect of K rates and management on endogenous hormones: K fertilizer, whether used solely as base fertilizer or base fertilizer plus foliage spray, significantly increased IAA content in all parts of the boll fiber compared with treatments that did not receive K fertilizer (Fig. 3-a). IAA content in the upper, middle, and lower portions of the boll fiber rose with an increase of 0 to 112.5 kg ha^{-1} in the K supply. In K_3, IAA content was highest in the upper, middle, and lower part of the boll, containing 0.188, 0.202, and 0.153 μg $g^{-1}\cdot FW^{-1}$, which was 4.18, 3.05, and 4.05 times that of the control treatment (K_0). However, in K_4, which received an overdose of K, IAA content in all boll parts was notably lower than that of K_2 and K_3. The most desirable effect of base fertilizer plus foliage spray was found in group K_6: IAA content in the upper, middle and lower boll was 3.43 2.58, and 3.66 times, respectively, that of the control treatment (K_0). Comparing base fertilizer and base fertilizer plus foliage spray, IAA content of K_5 in all parts of the cotton boll fiber was notably higher than that of K_1, indicating that IAA content is conducive to physiological regulation in the development process of cotton fiber. Comparison of IAA content in different parts of the boll fiber showed a similar distribution: middle > upper > lower, which indicates that IAA mainly regulates the growth of middle and upper cotton boll fiber in the late growth stage of cotton.

Analysis of variance of GA_3 and Z content in cotton fiber for different K supply rates is illustrated in Fig. 3-b,c. K applications can increase GA_3 and Z content in both the middle and upper boll fiber. Comparing each of the K application rates, GA_3 and Z content of all parts of the boll fiber in K_2, K_3, and K_6 were remarkably higher than that in other experiments. It is worth mentioning that in K_3, GA_3 and Z content in the upper, middle, and lower boll fiber reached 0.495, 0.528, and 0.466μg $g^{-1}\cdot FW^{-1}$ and 0.404, 0.437, and 0.375μg $g^{-1}\cdot FW^{-1}$, respectively. When comparing the base fertilizer and the corresponding base fertilizer plus foliage spray, only GA_3 and Z content in the middle and upper boll fiber in K_5 and K_1 had a difference that reached a notable level. The change in GA_3 and Z content in different parts of the boll fiber followed the same distribution pattern as that of IAA: middle > upper > lower.

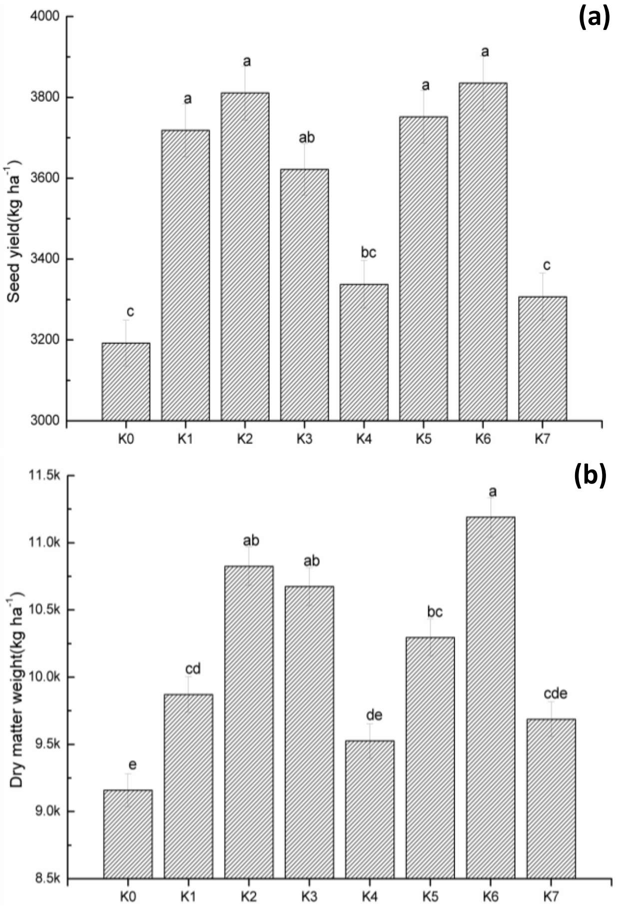

Fig. 1. Effect of K rates and management on seed cotton yield (a) and dry matter weight (b). K_0: without potassium (K) application; K_1: applications of 37.5 kg K_2O ha^{-1}; K_2: applications of 75 kg K_2O ha^{-1}; K_3: applications of 112.5kg K_2O ha^{-1}; K_4: applications of 150 kg K_2O ha^{-1}; K_5: applications of 37.5 kg K_2O ha^{-1} and spray applications of 1% K_2SO_4; K_6: applications of 75 kg K_2O ha^{-1} and spray applications of 1% K_2SO_4; K_7: applications of 150 kg K_2O ha^{-1} and spray applications of 1% K_2SO_4. Values represent the mean of three observations. Vertical bars are the standard errors of the means.

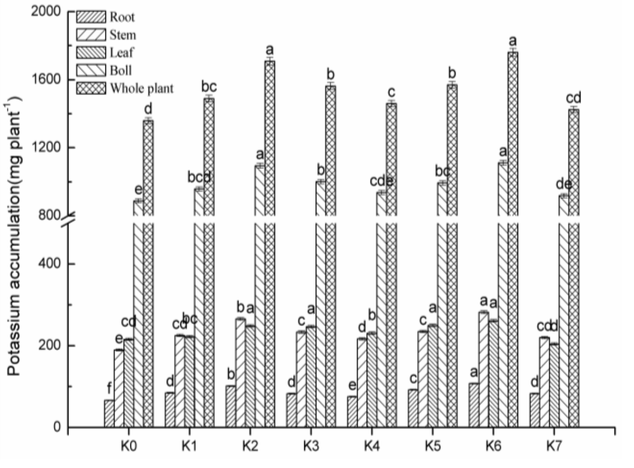

Fig. 2. Effect of K rates and management on K accumulation. K_0: without potassium (K) application; K_1: applications of 37.5 kg K_2O ha^{-1}; K_2: applications of 75 kg K_2O ha^{-1}; K_3: applications of 112.5kg K_2O ha^{-1}; K_4: applications of 150 kg K_2O ha^{-1}; K_5: applications of 37.5 kg K_2O ha^{-1} and spray applications of 1% K_2SO_4; K_6: applications of 75 kg K_2O ha^{-1} and spray applications of 1% K_2SO_4; K_7: applications of 150 kg K_2O ha^{-1} and spray applications of 1% K_2SO_4. Values represent the mean of three observations. Vertical bars are the standard errors of the means.

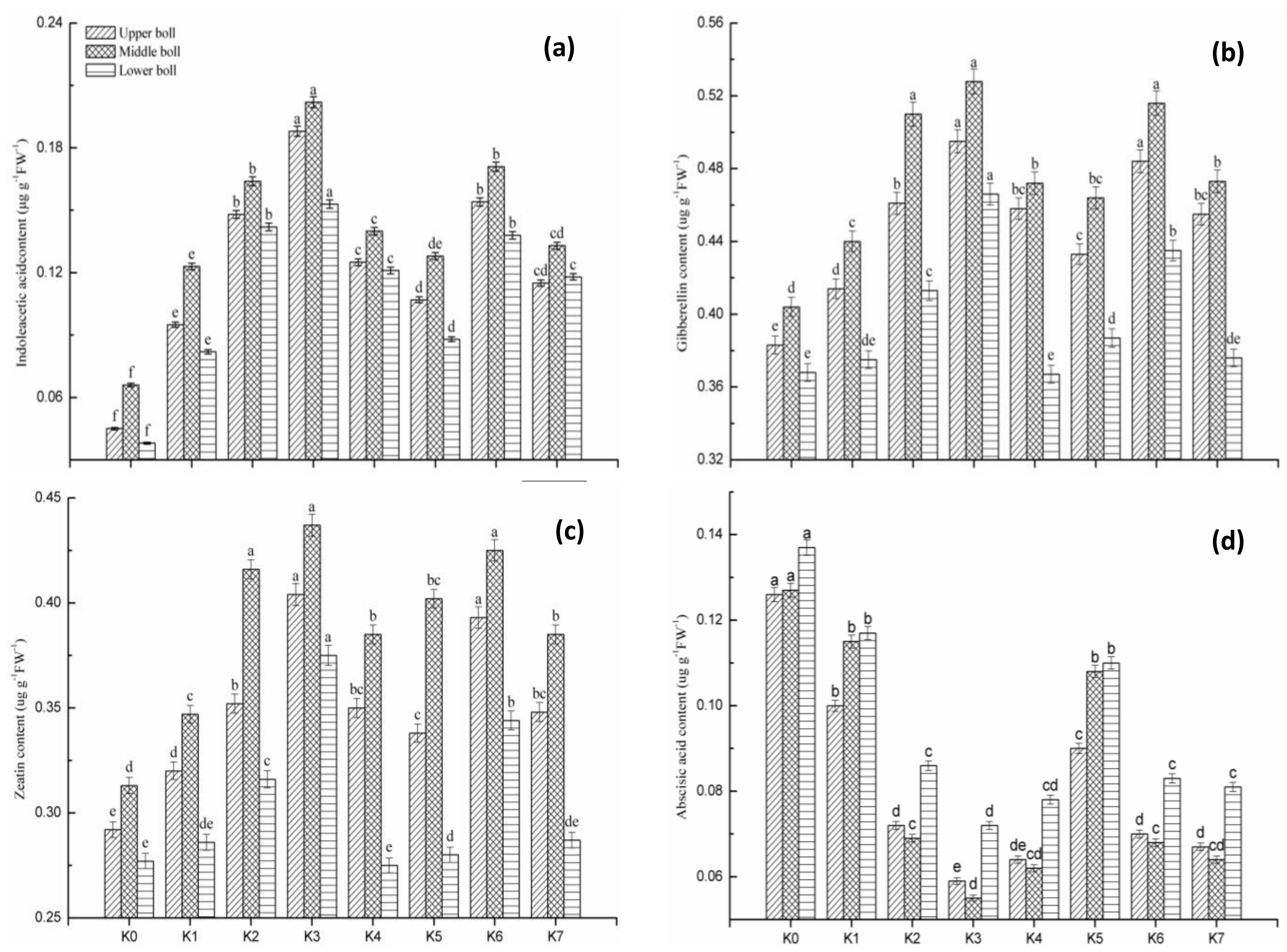

Fig. 3. Effect of K rates and management on endogenous hormone content. K_0: without potassium (K) application; K_1: applications of 37.5 kg K_2O ha^{-1}; K_2: applications of 75 kg K_2O ha^{-1}; K_3: applications of 112.5kg K_2O ha^{-1}; K_4: applications of 150 kg K_2O $ha^{-1;}$ K_5: applications of 37.5 kg K_2O ha^{-1} and spray applications of 1% K_2SO_4; K_6: applications of 75 kg K_2O ha^{-1} and spray applications of 1% K_2SO_4; K_7: applications of 150 kg K_2O ha^{-1} and spray applications of 1% K_2SO_4. Values represent the mean of three observations. Vertical bars are the standard errors of the means. FW: Fresh Weight.

Fig. 3-d shows that applying K fertilizer can significantly reduce ABA content in every part of the cotton boll fiber; this was particularly noticeable in K_3 with reductions of 53.07%, 56.77%, and 47.46% compared with the control treatment (K_0). ABA content of the upper, middle, and lower boll fiber in K_2, K_3, K_4, K_6, and K_7 was notably lower than that in K_1 and K_5. The change of ABA content in different parts of the boll fiber had an opposite distribution to that of IAA, GA_3, and Z content: lower > middle > upper.

Effect of K rates and management on fiber quality: Figure 4 shows the impact of K on fiber quality in the upper cotton bolls: except for K_4, fiber lengths in the upper cotton bolls that received K applications had a significant increase compared to the control treatment (K_0), and the increase in K_2, K_3, and K_6 was the highest (1.09–1.15 mm higher than that of the control treatment, K_0) (Fig. 4-a). This indicates that spraying K can increase fiber length within a certain range, but that an overdose of K fertilizer could hinder increases in the upper fiber length. Spraying K significantly improved the uniformity, strength, fiber maturity index, and micronaire of the upper fiber, among which, the uniformity, strength, and fiber maturity index were relatively superior in K_6 (1.5%, 1.6 $cNtex^{-1}$, and 0.4 higher than the control treatment (K_0)) (Fig. 4-b,c,f).

Except for K_7, the fiber length in the middle cotton bolls that received K applications had a significant increase compared with the control treatment (K_0), and the increase in K_6 was the greatest (0.90 mm higher than control group), followed by that in K_1 and K_2 (0.7 and 0.80 mm higher than the control treatment, respectively (K_0) (Fig. 4-a). This indicates that within a certain range, spraying K can increase fiber length of the middle cotton boll, but an overdose can negatively affect it, which is also in line with the change of upper fiber length. The uniformity of K_2, K_3, and K_6 was highest (0.7–1 % higher than that of the control treatment (K_0)) (Fig. 4-b). In K_3, K_5, and K_6, the strength was improved the most (1.3–1.9 cN tex^{-1} higher than the control treatment (K_0)) (Fig. 4-c). For all treatments except K_4, micronaire increased notably in comparison to the control treatment (K_0) (Fig. 4-e), while spraying K had little effect on elongation and fiber maturity (Fig. 4-d,f).

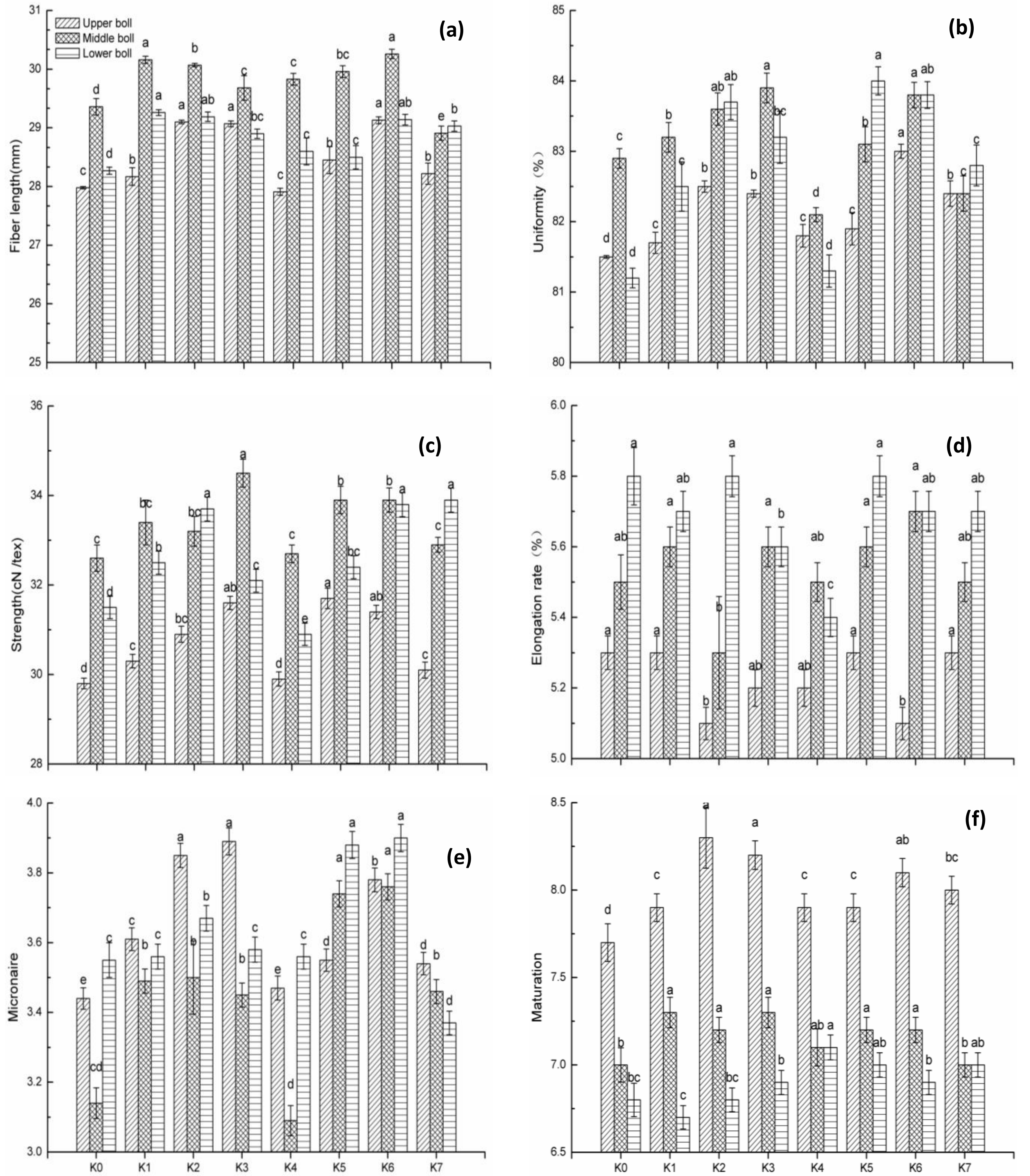

Fig. 4. Effect of K rates and management on cotton fiber quality. K_0: without potassium (K) application; K_1: applications of 37.5 kg K_2O ha^{-1}; K_2: applications of 75 kg K_2O ha^{-1}; K_3: applications of 112.5kg K_2O ha^{-1}; K_4: applications of 150 kg K_2O ha^{-1}; K_5: applications of 37.5 kg K_2O ha^{-1} and spray applications of 1% K_2SO_4; K_6: applications of 75 kg K_2O ha^{-1} and spray applications of 1% K_2SO_4; K_7: applications of 150 kg K_2O ha^{-1} and spray applications of 1% K_2SO_4. Values represent the mean of three observations. Vertical bars are the standard errors of the means.

Spraying potassium especially increased the fiber length of lower cotton bolls: treatments that received K had fiber lengths that were 0.23–0.92 mm longer than treatments that did not receive K applications (Fig. 4-a). Except for K_4, uniformity and strength both improved significantly after the K applications: 1.3–2.8% and 0.6–2.4 cN tex^{-1}, respectively, both of which were higher than the control treatment (K_0) (Fig. 4-b,c). Spraying K had no significant effect on fiber elongation of the lower cotton bolls. Meanwhile, in terms of micronaire and maturity, K applications had less significant impacts on lower fiber than on the upper and middle cotton bolls.

Relationship between fiber quality and endogenous hormones: The results of correlation analysis (Table 1) showed that IAA, GA_3, and Z in the upper, middle, and lower boll fiber were positively related to fiber length, uniformity, strength, micronaire, and the maturity index. However, the correlation was only significant and very significant in the upper boll fiber with a correlation index r = 0.651* - 0.689*. The ABA in the upper, middle, and lower boll fiber was negatively related to fiber length, uniformity, strength, micronaire, and the maturity index. ABA was positively related to elongation, but the relationship was not significant. In addition, only the ABA in the upper boll fiber had a significantly negative correlation to fiber uniformity and the maturity index with a correlation index r = -0.691* and -0.741*, respectively, indicating that IAA, GA_3, and Z in endogenous hormones can facilitate improvement of fiber quality, while ABA inhibits improvement. Therefore, the regulation of balance in endogenous hormones is crucial in improving cotton fiber quality.

Table 1. The correlation coefficients between endogenous hormones of fiber and quality traits.

Position of bolls	Endogenous hormone	Fiber length (mm)	Uniformity (%)	Strength ($cN·tex^{-1}$)	Elongation rate (%)	Micronaire	Maturation
Upper	IAA	0.787**	0.762*	0.650*	-0.689*	0.838**	0.881*
	GA_3	0.713*	0.822**	0.571	-0.684*	0.723*	0.814*
	Z	0.762*	0.817**	0.666*	-0.651*	0.761*	0.764*
	ABA	-0.495	-0.691*	-0.371	0.559	-0.538	-0.741*
Middle	IAA	0.346	0.556	0.721*	0.133	0.433	0.627
	GA_3	0.308	0.551	0.649*	0.047	0.467	0.491
	Z	0.318	0.506	0.708*	0.110	0.563	0.490
	ABA	-0.058	-0.088	-0.257	0.109	-0.065	-0.100
Lower	IAA	0.593	0.491	0.418	-0.379	0.127	0.296
	GA_3	0.378	0.144	0.312	--	0.360	-0.103
	Z	0.427	0.120	0.309	-0.062	0.251	-0.142
	ABA	-0.454	-0.613	-0.297	0.561	-0.042	-0.521

Note: IAA: indoleacetic acid; GA_3: gibberellin; ZR: zeatin; ABA: abscisic acid.

*means significant difference at the 0.05 level, **means significant difference at the 0.01 level

Discussion

Potassium (K) is known as a "quality element" in crop production. Numerous studies have demonstrated that spraying K can increase protein and essential amino acid content in grain crops as well as the soluble solid and Vc content in fruit. It also decreases the nitrate content in vegetables and increases Vc content and soluble sugar in vegetables. In addition, K applications can facilitate improvement of seed yield, fiber quality, strength, uniformity, and micronaire in cotton and linen crops (Read *et al*., 2005; Pervez *et al*., 2005a; Pettigrew, 2008; Guo *et al*., 2009; Temiz *et al*., 2009; Dong *et al*.,2010; Kaur *et al*., 2011; Kashyap *et al*., 2012; Rajeev, 2012).

Potassium also plays an active part in the physiological regulation of crops (David *et al*., 1996; Zhu *et al*., 1998; Tu *et al*., 2000; Neenu & Sudharmaidevi, 2012), facilitating physiological functions, such as ion transport, stomatal regulation, protein synthesis, enzymatic reaction, as well as the regulation of hormones and gene expression. Cotton is a crop that is "potassium-philic," and studies have shown the effects of K on improvement of the physiological mechanisms regulating cotton fiber quality (Li *et al*., 2012; Derrick *et al*., 2013). Although K is one of the major plant nutrients underpinning crop yield and quality, use of K fertilizer for cotton production has not been popular in Xinjiang, the largest cotton-growing region in China. This is mainly because the content of K in farmland is already high (100–300 mg /kg NH_4OAc-K), and unit yield is relatively low, meaning the total quantity of K required is relatively small. Other fertilizers, such as organic manure (roots and straws) are typically applied before planting each year, and this maintains a moderate level of available K in the soil (Dong *et al*., 2004). However, cotton yields have steadily increased over the last ten years, prompting greater attention to K fertilization in China.

In the present study, we found that application of K resulted in significant increases in seed yield, dry matter weight, and K accumulation per plant. Higher accumulation of K at harvest has been found to be related to high cotton seed yield (Gormus & Yucel, 2002; Waraich *et al*., 2011). However, we also found that excessive K fertilizer (150 kg K_2O ha^{-1}) reduces seed yield, dry matter weight, and K accumulation per plant, a finding in accordance with Adeli & Varco (2002) and Pervez *et al*. (2005b).

The present study determined changes in endogenous hormones in relation to K application methods in different parts of the cotton boll fiber. The result showed that in the range of 0–112.5 kg K_2O ha^{-1}, the IAA content increased in the upper, middle, and lower boll fiber, and the contents of GA_3 and Z increased significantly in the upper and middle boll fiber with the increase in amount of K supplied. The result is in line with that of high quality cotton in the study of Liu *et al*. (2006). However, an overdose of K (150 kg K_2O ha^{-1}) will lead to lower IAA, GA_3, and Z contents in different parts of the boll fiber in comparison to applications of 75 kg K_2O ha^{-1} and 112.5 kg K_2O ha^{-1}, and even less than the IAA, GA_3, and Z contents in the lower boll fiber in the control group (0 kg K_2O ha^{-1}). This demonstrated that only reasonable K application can regulate the endogenous hormone system in cotton fiber.

Compared with the control group, spraying K can significantly reduce ABA content in fiber in different parts of cotton bolls. Treatments that received 112.5 kg K_2O ha^{-1} were the most notable in this respect, with 53.07%, 56.77%, and 47.46% lower ABA content than the control group, respectively. In the management of K fertilizer, a basal application of 75 kg K_2O ha^{-1} and a spray application of 1% K_2SO_4 had the most desired regulation of endogenous hormones in boll fiber; it had a similar effect as a 112.5 kg K_2O ha^{-1} application of fertilizer. Compared with the control group, spraying K in the range of 37.5–112.5 kg K_2O ha^{-1} markedly increased fiber length, uniformity, strength, micronaire, and maturity index in the upper, middle, and lower bolls, while it had no significant impact on elongation. This result is in agreement with the study of Jiang *et al.* (2006) and Guo *et al.* (2009). However, an overdose of K (150 kg K_2O ha^{-1}) is not conducive to the improvement of uniformity, strength, and micronaire in upper, middle, and lower boll fiber, and had no significant difference from the control group. The result is similar with that of Guo *et al.* (2009) and Li *et al.* (1997). The impact K fertilizer management on cotton fiber quality is in accordance with the regulation effect of endogenous hormones, with the optimum effect found in a basal application of 75 kg K_2O ha^{-1} and spray application of 1% K_2SO_4.

In order to further examine and verify the physiological mechanisms underlying improvement in cotton quality by K, this experiment carried out a correlation analysis on endogenous hormones and fiber quality in the upper, middle, and lower cotton boll fiber. The results showed that IAA, GA_3, and Z in boll fiber have a positive relation with fiber length, uniformity, specific strength, micronaire value, and ripeness index, particularly in the upper cotton bolls, with a significant and extremely significant level of correlation. The correlation coefficient r was between 0.650 and 0.881, which is consistent with that of Liu *et al*. (2006). However, the result is slightly different from the study of Bai *et al*. (2008), where GA_4 was negatively related to fiber length, specific strength, and micronaire value. The inconsistency may be caused by the different kinds of gibberellin and experimental conditions. This requires further study. ABA in cotton boll fiber is negatively related to fiber length, uniformity, specific strength, micronaire value, and ripeness index, which is consistent with that of Gokani *et al*. (1998); however, the correlation was not significant. Only ABA in the upper cotton bolls was negatively related with uniformity and ripeness index at a significant level, and the correlation coefficients were –0.691 and 0.741, respectively. The results were completely different from those of Bai *et al*. (2008). This calls for further investigation. In conclusion, K can facilitate the improvement of cotton fiber quality through regulation of the physiological mechanisms underlying distribution of endogenous hormones. Future research should focus on a more comprehensive study of the molecular biology mechanisms.

Conclusion

K applications can significantly increase IAA, GA_3, and Z contents in upper and middle cotton boll fiber, and decrease ABA content in upper, middle, and lower cotton boll fiber. Spray applications of K at 112.5 kg K_2O ha^{-1} and the combination of a basal application of 75 kg K_2O ha^{-1} and spray application of 1% K_2SO_4 result in the optimum regulation of endogenous hormones, such as IAA, GA_3, Z, and ABA in cotton boll fiber.

Compared with the control group, spray applications of K within the range of 37.5–112.5 kg K_2O ha^{-1}can all markedly increase seed yield, dry matter weight, K accumulation, fiber length, uniformity, strength, micronaire, and maturity index, while an overdose of K (150 kg K_2O ha^{-1}) is counterproductive. In K fertilizer management, a basal application of 75 kg K_2O ha^{-1} and spray application of 1% K_2SO_4 have the best effect in improving the quality of cotton fiber.

The correlation between fiber quality of different parts of the cotton boll and endogenous hormone content in relation to different K supply methods indicates that, the contents of IAA, GA_3, and Z are positively related to fiber length, uniformity, strength, micronaire, and maturity index, while that of ABA is negatively related to those indices. However, the correlation is only significant and very significant in the upper cotton boll fiber. The results show that the quality of cotton fiber can be improved by the distribution of endogenous hormones in cotton fiber through the regulation of spray applications of K, which also provides the theoretical basis for discussing the physiological mechanisms underlying improvements in cotton fiber quality through reasonable supplies of the nutrient element.

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