

Enhancing cotton yield and fiber quality via the optimization of within-boll yield components with potassium application under limited drip irrigation in arid regions

Xiaojuan Shi^{a,1}, Xianzhe Hao^{b,c,1}, Yonglin Yang^{d,1}, Nannan Li^a, Feng Shi^a, Yu Tian^a, Humei Zhang^a, Hao Li^d, Ping Liu^b, Jun Wang^{b,c,*}, Honghai Luo^{a,**}

^a College of Agriculture, Shihezi University, Shihezi, Xinjiang 832003, China

^b Xinjiang Academy of Agricultural and Reporting Science, Shihezi, Xinjiang 832000, China

^c Key Laboratory of Northwest Oasis Water-Saving Agriculture, Ministry of Agriculture and Rural Affairs, Shihezi, Xinjiang 832000, China

^d Shihezi Academy of Agricultural Sciences, Shihezi, Xinjiang 832000, China

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ABSTRACT

Increasing the cotton yield and fiber quality under a limited water supply is crucial for sustainable cotton production in arid regions facing water scarcity due to global warming. The objectives of this study were to investigate the effects of potassium application on the cotton yield and fiber quality under limited drip irrigation and enhance water-saving, high-yield cotton production in arid areas. A three-year field experiment was conducted from 2021–2023 via a split-plot experimental design, with two drip irrigation amounts (W_1 : 500, conventional drip irrigation; W_2 : 425 mm, limited drip irrigation) as the main plot and three potassium application levels (K_1 , K_2 and K_3 : 48, 144 and 240 kg ha⁻¹, respectively) as the sub plot. The effects of the drip irrigation mode and potassium application level on the cotton yield and fiber quality were explored by assessing the differences in parameters such as the basic yield composition and the within-boll yield composition. The lint and cottonseed yield under the W_2 treatment were 8.1 % and 5.7 % greater, respectively, than those under the W_1 treatment. Under the W_2 treatment, the lint yield increased by 22.0 and 15.1 % at the K_2 and K_3 application levels, and seed yield increased by 18.9 and 17.0 %, compared with those at the K_1 application level. The best results were obtained under the W_2K_2 treatment, with 3614 kg ha⁻¹ lint and 4457 kg ha⁻¹ cottonseed. While the fiber characteristics remained stable, the W_2K_2 treatment exhibited an appropriate micronaire value and a higher Q score than those, at 4.1 (AA) and 32.3, respectively. Notably, under the W_2K_2 treatment, the boll weight (BW) and lint percentage (LP) significantly increased by 4.2–13.7 % and 2.5–6.2 %, respectively, and the boll density (BD) increased by 6.6–15.5 % compared with those under the other treatments (W_1K_1 , W_1K_2 , W_1K_3 , and W_2K_1) from 2022–2023. These BW and LP increases could be attributed to single-boll biomass accumulation (SBA) and fiber percentage (fiber PCT) increases of 3.3–12.5 % and 6.5–16.7 %, respectively. An examination of the within-boll yield components revealed that under the W_2K_2 treatment, the lint index (LI), lint per seed (LPS), and individual fiber weight (IFW) values increased by 6.6–12.2 %, 6.6–12.2 %, and 2.9–12.8 %, respectively, compared with those under the other treatments. Under limited drip irrigation, applying an appropriate amount of potassium could optimize the yield of within-boll components while promoting SBA. These findings provide a foundation for enhancing basic yield components, ultimately achieving synchronized cotton yield and fiber quality increases. This irrigation and fertilizer management strategy provides new insights to ensure cotton yield enhancement and sustainable development in arid and semiarid regions.

* Corresponding author at: Xinjiang Academy of Agricultural and Reporting Science, Shihezi, Xinjiang 832000, China.

** Corresponding author.

E-mail addresses: 108689011@qq.com (J. Wang), luohonghai79@163.com (H. Luo).

¹ These authors contributed equally to this work.

1. Introduction

With global warming, the frequency and intensity of abiotic stress have increased, with a particularly notable increase in drought stress, which has led to increasingly severe water scarcity and limited agricultural production in more than one-third of the arable land area, resulting in a nearly 70 % decrease in global crop yields (Hu et al., 2018; Seleiman et al., 2020). Potassium, which is the most abundant monovalent cation in plants, accounts for 2–10 % of the total plant dry matter (Srivastava et al., 2019; Kumar et al., 2021). Moreover, many studies have shown that potassium can alleviate the negative effects of drought stress on crops and imposes compensatory effects on the crop yield and quality (Lv et al., 2007; Zhao et al., 2020).

Cotton is a globally important bulk cash crop and fiber crop, and approximately 70 % of the global cotton-growing area is affected by drought stress (Wu et al., 2022); additionally, cotton is more notably affected by potassium availability than other crops are (Hu et al., 2017). Previous studies have revealed that increasing potassium fertilizer application (K_2O 150–300 kg ha⁻¹) at the squaring and boll-setting stages of cotton increases the cotton yield potential, fiber length, fiber strength and maturity by promoting fiber development (Zhao et al., 2020). Therefore, it is necessary to study the effects of potassium application on the cotton yield and fiber quality under water-limited conditions to provide a theoretical basis for achieving efficient cotton production with low water consumption.

Most previous studies have focused on analyzing the lint yield of cotton via basic yield components (total number of bolls per unit area, boll weight and lint percentage) (Dong et al., 2010). However, the lint yield is a complex trait that must be calculated on the basis of within-boll yield components. Worley et al. (1974) reported that the major component of the lint yield was the boll number, followed by the lint per seed and lint per boll. More precisely, the lint per boll component refers to the single-boll fiber biomass, and the boll weight and lint percentage are determined by fiber and seed biomasses (Li et al., 2022; Guo et al., 2023); thus, the cotton yield is closely related to within-boll yield components (Coyle and Smith, 1997). Fiber and cottonseed biomasses are closely related to the number of seeds per boll and the lint per seed (Worley et al., 1976). Furthermore, increasing the fiber density and the individual fiber weight effectively increases the fiber biomass per boll and lint yield (Groves et al., 2016). In addition, the fiber quality is closely related to within-boll yield components; for example, the fiber quality is negatively associated with the number of seeds per boll and fiber density (Coyle and Smith, 1997); however, because of the inconsistencies in the fiber quality in response to environmental factors and cultivation practices (Tariq et al., 2018), we used a composite index (i.e., the Q score, normalized between 0 and 1 for the fiber length, fiber strength, uniformity, and micronaire value) to assess the fiber quality. Although recent studies have entailed the utilization of within-boll yield components to explain the effects of environmental factors on the cotton yield (Li et al., 2022; Guo et al., 2023), the impact of potassium application on these yield traits and their relationships with the cotton yield and fiber quality under limited water availability have received little attention.

China is a major cotton-growing region worldwide (Yang et al., 2021), and Xinjiang has become the most important cotton-growing region in China because of its abundant sunshine, advanced drip irrigation technology, and mature simplified cultivation technology (Zhang et al., 2018; National Bureau of Statistics of China, 2023). However, Xinjiang exhibits a typical arid or semiarid climate, and regional drought constrains the sustainable development of cotton cultivation (Feng et al., 2017). In previous studies, agricultural water consumption reduction via engineering and agronomic water reduction practices has been proposed, but with the increase in the cotton cultivation area exacerbating the water scarcity problem in cotton cultivation (Guo and Shen, 2016), further development of the biological water-saving potential of cotton remains a popular and difficult issue in existing

research. To address this issue, we previously conducted experiments involving limited drip irrigation. The cotton yield and fiber quality respond differently to limited drip irrigation under different agronomic practices (Rao et al., 2016). In preliminary research, a series of studies were conducted by combining limited drip irrigation with variations in the planting density and nitrogen fertilizer amount. Limited drip irrigation still leads to a decrease in dry matter in reproductive organs, resulting in a reduction in cotton production (Luo et al., 2016; Niu et al., 2016). Previous studies have demonstrated the positive effects of potassium on the cotton yield and fiber quality. However, studies on within-boll yield components under potassium application and limited drip irrigation have not been reported. Therefore, we hypothesized that increasing potassium application under limited drip irrigation could optimize within-boll yield components, promote fiber and cottonseed biomass accumulation, and ultimately achieve simultaneous cotton yield and fiber quality improvements.

The aims of this study were to 1) explore the effects of potassium application on the cotton yield and fiber quality under limited drip irrigation, 2) analyze the impact of potassium application on (basic and within-boll) yield components under limited drip irrigation, and 3) elucidate the relationships between (basic and within-boll) yield components and cotton yield and fiber quality via Mantel tests. The results of this study could provide new strategies for water-saving, high-yield, high-quality and efficient cotton production methods in arid and semi-arid areas.

2. Materials and methods

2.1. Experimental site

A three-year field experiment was conducted with cotton cultivar Xinshi K21 at the Shihezi Scientific Observatory and Experimental Station for Efficient Water Use in Crops (45°38'N, 86°09'E), Ministry of Agriculture, Xinjiang Academy of Agricultural Reclamation, Shihezi, Xinjiang, China, from 2021 to 2023. In this experiment, the basic soil samples were obtained from the 0 to 20 cm soil layer in 2021, as detailed in Table 1. Temperature (mean, maximum, and minimum) and precipitation data were collected from the Wulan Wusu Weather Station near the experimental field (Shihezi, Xinjiang, China) for May to October period between the three cotton-growing seasons (Fig. 1). The average rainfall amounts in 2021, 2022 and 2023 were 83.6, 84.6 and 80.6 mm, respectively. However, the maximum rainfall (38.10 mm) occurred in September 2023. The mean temperatures in 2021, 2022 and 2023 were 20.1°C, 21.1°C and 21.0°C, respectively.

2.2. Experimental design and field management

The experiment followed a two-factor split-plot design. Different drip irrigation amounts were applied in the main plot, while the various potassium fertilizer treatments were applied in sub plot. Two drip amounts were employed: conventional drip irrigation (W₁, 500 mm)

Table 1
Soil physical and chemical properties in this experiment.

Soil property	Value
Soil class	Sandy loam
Soil bulk density	1.54 (g cm ⁻³)
Nitrogen	42.2 (g kg ⁻¹)
Available phosphorous	19.81 (mg kg ⁻¹)
Available potassium	274.28 (mg kg ⁻¹)
pH	8.58
Electrical conductivity	279.7 (μs cm ⁻¹)
Organic matter	15 (g kg ⁻¹)
Available calcium	54.33 (g kg ⁻¹)
Available magnesium	18.41 (g kg ⁻¹)
Available sulfur	1.05 (g kg ⁻¹)

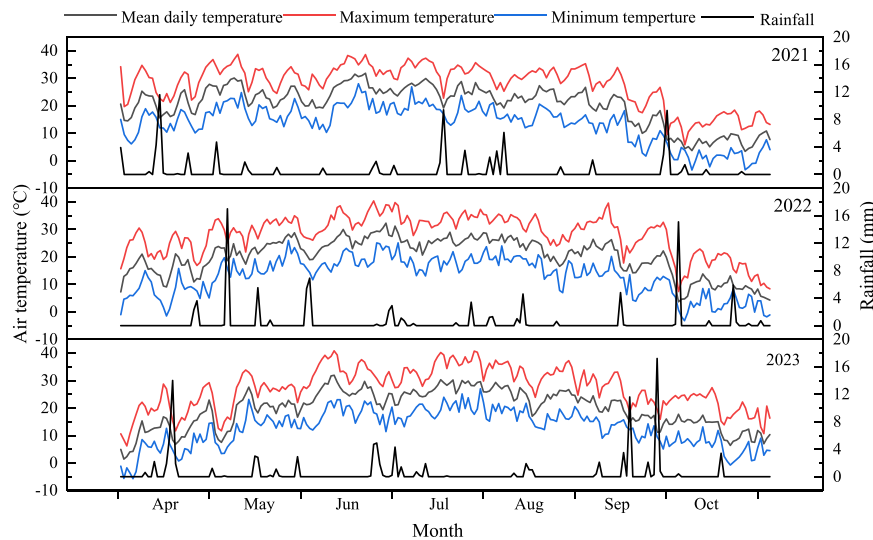


Fig. 1. Daily air temperature and rainfall during the cotton-growing season (April 1–October 31) from 2021–2023.

and limited drip irrigation (W_2 , 425 mm) (Niu et al., 2016). The irrigation amounts employed under conventional drip irrigation were 173.0, 270.0 and 57.0 mm at the initial flowering, boll-filling and boll-opening stages, respectively. Compared with those under the W_1 treatment, the irrigation amounts under limited drip irrigation were 38.0 % and 15 % lower at the initial flowering and boll-opening stages, respectively. The irrigation amounts under the W_2 treatment were 106.5, 270 and 48.5 mm at the initial flowering, boll-filling and boll-opening stages, respectively. Three potassium application levels were adopted, namely, low (K_1 , K_2O : 48 kg ha⁻¹), medium (K_2 , K_2O : 144 kg ha⁻¹), and high (K_3 , K_2O : 240 kg ha⁻¹). Potassium fertilizer was applied in various proportions, namely, 15 % at the initial flowering stage, 79 % at the flowering and boll-opening stage and 6 % at the boll-opening stage. Each experimental plot was 10 m long and 6.84 m wide (68.4 m²), and each treatment was replicated four times for a total of 24 plots.

The planting dates in 2021, 2022 and 2023 were April 24, April 24 and May 2, respectively. The harvest dates in 2021, 2022 and 2023 were September 30, October 16 and October 9, respectively. The chemical fertilizers used were urea (N, 46.0 %), ammonium dihydrogen phosphate (N, 12.0 %; P_2O_5 , 61.0 %) and potassium sulfate (K_2O , 50.0 %). N and P_2O_5 fertilizers were applied at levels of 240 and 130 kg ha⁻¹, respectively. All fertilizers were applied in drip mode as follow-up fertilizers with water, and other field management measures were implemented according to local cotton production standards.

2.3. Sampling and measurements

The dynamic boll number and single-boll biomass accumulation were monitored and measured according to the vertical distribution of the fruiting branches, which were divided into upper (fifth and beyond fruiting branches, UFB) and lower (first to fourth fruiting branches, LFB) parts.

2.3.1. Dynamic boll number (DBN)

The number of bolls on six uniformly growing cotton plants in each plot was surveyed. In 2021, the number of bolls per plant was investigated at 10-d intervals starting from the squaring stage. To reduce human errors, the number of bolls was investigated at 15-d intervals starting from the squaring stage from 2022 to 2023.

2.3.2. Single-boll biomass accumulation (SBA) and fiber, seed, and shell percentages

On the day when the first fruit node of the lower (first to fourth

fruiting branches) and upper (fifth and beyond fruiting branches) parts of the cotton plants bloomed, the white flowers were labeled, and the boll age was calculated from the day of flower labeling. Starting from a boll age of 10 d, six bolls with uniform growth and development features were collected every 10 d from 9:00–10:00 am to determine upper, lower and total single-boll mass accumulation values and calculate the total percentage (%) of the various components (fiber, seed and shell percentages).

The bolls were divided into three parts: boll shells, seeds and fibers. The fiber samples were naturally dried to a constant weight, while the boll shells and cotton seeds were dried at 80°C to a constant weight. Moreover, the seed biomass, fiber biomass and shell biomass were determined separately via weighing, and the percentage (%) of each boll component (seed, fiber and shell) was calculated. The single-boll biomass accumulation value is determined as the sum of the seed, fiber and shell biomasses of a single cotton boll. The single-boll mass accumulation value can be calculated as follows:

Single – boll biomass accumulation (SBA, g)

$$= \text{fiber biomass} + \text{seed biomass} + \text{shell biomass} \quad (1)$$

$$\text{Fiber / seed / shell percentage (\%)} = \frac{\text{fiber / seed / shell biomass}}{\text{single – boll biomass}} \times 100\% \quad (2)$$

2.3.3. Cotton yield and fiber quality

Three sample points were selected for each treatment at harvest to investigate the boll density (bolls ha⁻¹). At the sample points, cotton was picked, dried, ginned and weighed to determine the lint yield (kg ha⁻¹) and cottonseed yield (kg ha⁻¹), as well as to calculate the boll weight (g boll⁻¹) and lint percentage (%).

The weighed fiber samples were used to determine the fiber quality, and the fiber samples were sent to the Cotton Quality Supervision, Inspection and Monitoring Center of the Ministry of Agriculture (Anyang, Henan, China) to obtain high-volume instrument (HVI) index data (uniformity (%), length (mm), strength (cN tex⁻¹), and micronaire value). The Q score was calculated as follows (Li et al., 2022):

$$Q\text{score} = 15\% \times U + 50\% \times L + 10\% \times FS + 25\% \times MV \quad (3)$$

where FS is the strength (cN tex⁻¹), L is the length (mm), U is the uniformity (%), and MV is the micronaire value.

2.3.4. Within-boll yield components

Twenty-five fuzzy seeds were selected for each treatment, and their weights were determined and recorded as A values (replicated three times within a range of 0.20 g). Notably, relevant parameters such as the seed index (g) and lint index (g) were calculated. On the basis of the data obtained in Section 1.3.2, the parameters of the within-boll yield components were calculated as follows (Groves et al., 2016):

$$\text{Seed index (SI, g)} = \frac{A}{25} \times 100 \quad (4)$$

$$\text{Seeds number (SN, no.)} = \frac{\text{seed yield} \times 1000}{\text{seed index}} \times 100 \quad (5)$$

$$\text{Seeds per boll (SPB, no.)} = \frac{\text{SN}}{\text{BN}} \quad (6)$$

$$\text{Individual fiber weight (IFW, ug)} = \text{fiber length (ch)} \times \frac{\text{uniformity}}{100} \times \text{micronaire value} \quad (7)$$

$$\text{Lint per seed (LPS, g)} = \frac{\text{lint yield}}{\text{seed number}} \quad (8)$$

$$\text{Fibers per seed (FPS, no.)} = \frac{\text{LPS (g)}}{\text{IFW (ug)}} \times 10^6 \quad (9)$$

$$\text{Lint index (LI, g)} = \text{LPS} \times 100 \quad (10)$$

$$\text{Seed surface area (SSA, mm}^2\text{)} = 35.74 + 6.59 \times \text{SI} \quad (11)$$

$$\text{Fiber density (FD, fibers mm}^{-2}\text{)} = \frac{\text{FPS}}{\text{SSA}} \quad (12)$$

2.4. Statistical analysis

Two-way mixed-effects analysis of variance (ANOVA) of the drip irrigation amount and potassium application level was performed via IBM SPSS Statistics 25.0 statistical software, and significant differences were determined at $P < 0.05$ via Duncan's method. One-way ANOVA was used to compare data differences among years. Pearson correlation analysis was employed to analyze the relationships between the internal yield components of cotton bolls and the number of bolls and boll biomass. The relationships of the lint yield, cottonseed yield and fiber quality with within-boll yield components were analyzed via the Mantel test. Origin 21.0 was used for figure generation.

Logistic equations (Yang et al., 2011) were used to obtain the single-boll biomass:

$$Y = \frac{K}{1 + ae^{bt}} \quad (13)$$

where Y denotes the single-boll mass accumulation (g) corresponding to a given boll age (d), K denotes the maximum single-boll biomass accumulation (g), t denotes the boll age (d), and a and b are constants.

The rapid accumulation onset time t_1 (boll age, d) and end time t_2 (boll age, d) of single-boll mass accumulation are as follows:

$$t_1 = \frac{1}{b} \ln \left(\frac{2 + \sqrt{3}}{a} \right), t_2 = \frac{1}{b} \ln \left(\frac{2 - \sqrt{3}}{a} \right) \quad (14)$$

The rapid accumulation duration T (d) of single-boll mass accumulation is as follows:

$$T = t_2 - t_1 \quad (15)$$

The emergence time t_0 (DAE) of the maximum single-boll mass accumulation rate is as follows:

$$t_0 = -\frac{\ln a}{b} \quad (16)$$

For $t = t_0$, the maximum rate and theoretical maximum of single-boll mass accumulation are as follows:

$$V_m = -\frac{bK}{4} \quad (17)$$

$$Y_m = \frac{K}{1 + ae^{bt_0}} \quad (18)$$

3. Results

3.1. Cotton yield and basic yield components

Both drip irrigation and potassium application significantly affected the cotton yield and its basic components (boll weight, boll density and lint percentage) (except for the boll density, lint percentage and cottonseed yield in 2021) (Table 2). The cotton yield increased with decreasing drip irrigation amount, and the lint and cottonseed yields were 8.1 % and 5.7 % greater (except for the cottonseed yield in 2021), respectively, under W_2 than under W_1 . The cotton yield and its components exhibited a trend of initial increase followed by a subsequent decrease with increasing potassium fertilizer application. Compared to the K_1 treatment, the K_2 and K_3 treatments yielded significant increases in lint yield (16.0 and 13.6 %) and cottonseed yield (10.0 and 11.3 %). Moreover, these treatments also led to notable enhancements in boll weight, boll density, and lint percentage relative to the K_1 treatment, with specific increases of 5.5 and 5.3 % in boll weight, 12.4 and 13.7 % in density, and 3.9 and 2.3 % in lint percentage. The interaction between drip irrigation and potassium application showed that the lint and cottonseed yields were lowest under the W_1K_1 treatment, which were 7.0–27.3 % and 2.6–18.1 % lower than those under the other treatments (W_1K_2 , W_1K_3 , W_2K_1 , W_2K_2 , and W_2K_3) from 2022 to 2023. The lint and cottonseed yields were greatest under the W_2K_2 treatment, followed by those under the W_2K_3 treatment.

3.2. Fiber quality

The fiber length, fiber strength, uniformity and Q score remained stable across the different drip irrigation amounts and potassium application rates, and only the micronaire value significantly differed between the treatments with different drip irrigation amounts and potassium application rates (Table 3). The average micronaire value under W_2 was 4.0, which was 7.3 % greater than that under W_1 . Among the three potassium application rates, the micronaire values under the K_2 treatment were 5.7 % and 3.4 % higher than those under the K_1 and K_3 treatments, respectively. The interaction between the drip irrigation amount and the potassium application rate revealed that the fiber length decreased significantly, by 2.0 %, under K_3 in 2022 for both drip irrigation methods, and the fiber strength increased significantly, by 4.6 %, under the W_1K_1 treatment compared with that under the other treatments in 2023. As one of the indicators for fiber quality evaluation, the micronaire values were divided into three levels: A, B and C. The A-level values range from 3.7 to 4.2 (AA), corresponding to the highest quality; the B-level values range from 3.5 to 3.6 (BB1) and 4.3 to 4.9 (BB2) and correspond to an average quality; and the C-level values are ≤ 3.4 (CC1) and ≥ 5.0 (CC2), corresponding to the lowest quality. From 2021–2023, micronaire values under W_1K_1 and W_1K_3 treatments were 8.3 % and 7.1 % lower than the average reduction of other treatments, respectively, and fiber quality was average quality, whereas the values under the W_2K_2 , W_2K_3 and W_1K_2 treatments ranged from 3.7–4.2 (A level).

Table 2

Effects of drip irrigation pattern and potassium application on the cotton yield and basic yield components from 2021 to 2023.

Year	Treatment	Boll weight (g boll ⁻¹)	Boll density (bolls*10 ⁴ ha ⁻¹)	Lint yield (kg ha ⁻¹)	Lint percentage (%)	Cottonseed yield (kg ha ⁻¹)
2021	W ₁	4.4 b	162.8 a	3112.1 a	42.9 b	4135.8 a
	W ₂	5.1 a	156.8 a	3172.4 a	44.2 a	4000.1 a
	K ₁	4.9 a	156.4 a	3094.5 b	43.4 a	4032.8 a
	K ₂	4.9 a	164.8 a	3256.5 a	44.2 a	4116.8 a
	K ₃	4.5 b	158.2 a	3075.7 b	43.1 a	4054.3 a
	W ₁ K ₁	4.8 b	163.9 ab	3160.3 b	42.9 b	4210.5 a
	W ₁ K ₂	4.4c	169.7 a	3166.3 b	43.3 b	4152.0 a
	W ₁ K ₃	3.9 d	154.9 ab	3009.6c	42.7 b	4044.8 ab
	W ₂ K ₁	4.9 b	148.9 b	3028.7 bc	43.9 ab	3855.1 b
	W ₂ K ₂	5.4 a	159.9 ab	3346.7 a	45.0 a	4081.5 ab
	W ₂ K ₃	5.0 b	161.6 ab	3141.8 bc	43.5 ab	4063.7 ab
	ANOVA (P value)					
	W	***	ns	ns	**	ns
	K	***	ns	**	ns	ns
	W*K	***	ns	**	ns	ns
2022	W ₁	4.7 b	155.2 b	3143.3 b	42.6 b	4242.9 b
	W ₂	5.0 a	165.0 a	3639.2 a	44.1 a	4577.8 a
	K ₁	4.6 b	142.3 b	2790.9 b	42.1 b	3815.2 b
	K ₂	4.9 a	167.3 a	3672.3 a	44.3 a	4622.7 a
	K ₃	5.0 a	170.8 a	3710.5 a	43.7 a	4793.1 a
	W ₁ K ₁	4.5 d	142.8 d	2648.5 e	41.0 d	3791.3 d
	W ₁ K ₂	4.8c	155.7c	3252.6c	43.6 bc	4262.7c
	W ₁ K ₃	4.9 bc	167.1 b	3528.7 b	43.2c	4674.7 b
	W ₂ K ₁	4.8c	141.8 d	2933.3 d	43.3 bc	3839.2 d
	W ₂ K ₂	5.1 a	178.8 a	4092.0 a	45.0 a	4982.8 a
	W ₂ K ₃	5.1 ab	174.4 a	3892.2 a	44.1 ab	4911.4 ab
	ANOVA (P value)					
	W	***	***	***	***	***
	K	***	***	***	***	***
	W*K	ns	***	**	*	**
2023	W ₁	4.8 b	147.8 *	2980.2 b	42.6 b	4027.7 b
	W ₂	4.9 a	158.9 *	3174.4 a	43.2 a	4167.4 a
	K ₁	4.7 b	146.0 b	2862.5 b	42.4c	3893.7 b
	K ₂	4.9 a	156.9 a	3215.3 a	43.5 a	4176.7 a
	K ₃	4.9 a	157.1 a	3154.0 a	42.9 b	4222.3 a
	W ₁ K ₁	4.7 d	144.2 b	2800.3 e	42.4c	3816.3 d
	W ₁ K ₂	4.7 cd	146.2 b	3026.0 cd	42.9 bc	4047.0 bc
	W ₁ K ₃	4.8 bc	152.8 b	3114.2 bc	42.6 bc	4219.8 ab
	W ₂ K ₁	4.7 d	147.7 b	2924.7 d	42.4c	3971.1 cd
	W ₂ K ₂	5.1 a	167.5 a	3404.7 a	44.1 a	4306.4 a
	W ₂ K ₃	4.9 b	161.4 a	3193.9 b	43.2 b	4224.8 ab
	ANOVA (P value)					
	W	**	***	***	**	*
	K	**	**	***	***	**
	W*K	**	*	**	*	ns
	Year	ns	ns	ns	*	**

Two irrigation amounts (W₁ and W₂) and three potassium application levels (K₁, K₂, and K₃) were employed. Each value represents the mean (n=3). The effects of the K rate, drip irrigation mode, and K rate × drip irrigation interaction in a given year were assessed via mixed-effects two-way ANOVA, and the different lowercase letters following the values denote significant differences at the *P* = 0.05 level. ns indicates *p* > 0.05; * and ** indicate significance at the 0.05 and 0.01 levels, respectively.

3.3. Dynamic boll number

The dynamic number of bolls showed a trend of increasing and then decreasing with the advancement of days after squaring, and the peak of dynamic number of bolls appeared at 20–30 days after squaring. Compared with that under K₁, the dynamic boll number of the various parts of fruit branches significantly increased under K₂ and K₃. At 80 d after squaring, the dynamic boll number of the upper fruiting branches under W₂K₁ reached only 3.0 per plant (Fig. 2i–iii), and the dynamic boll number of the upper fruiting branches under W₂K₁ was 49.4 % lower than that under the other treatments. Between 20 and 80 d after squaring, the dynamic boll number of the upper fruiting branches was greatest under the K₂ and K₃ treatments for W₂, with average values of 6.2 and 6.3 per plant, respectively, which were, on average, 3.9 % and 4.4 % greater, respectively, than those under the K₂ and K₃ treatments for W₁.

At 80 d after squaring, the dynamic boll number of the lower fruiting branches under the W₁K₁, W₁K₂, W₁K₃ and W₂K₁ treatments averaged 4.4 per plant (Fig. 2 iv–vi), whereas the dynamic boll number of the

lower fruiting branches under the W₂K₂ and W₂K₃ treatments were 6.2 and 5.5 per plant, respectively, which were on average 40.9 % and 25.6 % greater than those under the above four treatments (W₁K₁, W₁K₂, W₁K₃ and W₂K₁).

From 20 to 80 d after squaring, the total dynamic boll number (Fig. 2 vii–ix) was greatest under the K₂ and K₃ treatments for W₂, reaching 13.3 no. plant⁻¹ in both cases up to 80 d after squaring, corresponding to increases of 17.6 %, 10.5 %, 11.5 %, and 34.4 % compared with those under W₁K₁, W₁K₂, W₁K₃, and W₂K₁ treatments, respectively.

3.4. Single-boll biomass accumulation and logistic equations

Single-boll biomass accumulation simulations were performed via Eq. (12). Since all the R² values converged to close to 1 (Fig. 3), single-boll biomass accumulation exhibited a sigmoidal growth pattern conforming with the logistic function.

Under K₁, W₂ resulted in 2.0 % lower single-boll biomass accumulation in the upper fruiting branches (Fig. 3i–ii) than that under W₁, and W₂K₁ resulted in only 6.2 g of biomass accumulation in the upper

Table 3

Effects of the drip irrigation amount and potassium application rate on the fiber quality from 2021 to 2023.

Year	Treatment		Length (mm)	Uniformity (%)	Strength (cN tex ⁻¹)	Micronaire value	Q score
2021	Irrigation	W ₁	31.7 a	84.8 b	32.3 a	3.6 b	32.7 a
		W ₂	31.0 b	85.3 a	32.3 a	4.1 a	32.5 a
	Potassium	K ₁	31.5 a	85.0 a	32.6 a	3.9 ab	32.7 a
		K ₂	31.3 a	85.3 a	31.7 a	3.9 a	32.6 a
		K ₃	31.3 a	84.9 a	32.6 a	3.7 b	32.6 a
	Irrigation×Potassium	W ₁ K ₁	31.8 a	84.8 a	32.4 a	3.5c	32.7 a
		W ₁ K ₂	31.6 a	85.1 a	31.5 a	3.7c	32.6 a
		W ₁ K ₃	31.7 a	84.6 a	32.9 a	3.6c	32.7 a
		W ₂ K ₁	31.1 a	85.3 a	32.8 a	4.2 a	32.7 a
		W ₂ K ₂	31.0 a	85.5 a	31.9 a	4.1 a	32.5 a
		W ₂ K ₃	31.0 a	85.2 a	32.3 a	3.9 b	32.5 a
	Source of variance	W	*	ns	ns	***	ns
		K	ns	ns	ns	*	ns
		W*K	ns	ns	ns	ns	ns
2022	Irrigation	W ₁	30.6 a	84.6 a	31.2 a	4.0 b	32.1 a
		W ₂	30.5 a	84.4 a	31.6 a	4.2 a	32.1 a
	Potassium	K ₁	31.0 a	84.6 a	31.9 a	4.0 b	32.3 a
		K ₂	30.5 ab	84.3 a	31.3 a	4.3 a	32.1 ab
		K ₃	30.1 b	84.6 a	31.0 a	4.1 ab	31.9 b
	Irrigation×Potassium	W ₁ K ₁	31.2 a	84.6 a	31.6 a	3.8c	32.4 a
		W ₁ K ₂	30.6 ab	84.5 a	31.4 a	4.1 b	32.1 a
		W ₁ K ₃	30.1 b	84.6 a	30.6 a	4.0 bc	31.8 a
		W ₂ K ₁	30.8 ab	84.6 a	32.2 a	4.1 b	32.3 a
		W ₂ K ₂	30.5 ab	84.1 a	31.2 a	4.4 a	32.1 a
		W ₂ K ₃	30.2 b	84.7 a	31.3 a	4.2 ab	32.0 a
	Source of variance	W	ns	ns	ns	**	ns
		K	*	ns	ns	*	ns
		W*K	ns	ns	ns	ns	ns
2023	Irrigation	W ₁	31.5 a	84.1 a	32.3 a	3.7 a	32.5 a
		W ₂	31.7 a	84.4 a	31.5 b	3.7 a	32.6 a
	Potassium	K ₁	31.8 a	84.4 a	32.4 a	3.5 b	32.7 a
		K ₂	31.5 a	84.4 a	31.5 ab	3.8 a	32.5 a
		K ₃	31.5 a	83.9 a	31.8 b	3.8 a	32.5 a
	Irrigation×Potassium	W ₁ K ₁	31.9 a	84.6 a	33.1 a	3.6 bcd	32.8 a
		W ₁ K ₂	31.5 a	84.0 a	31.7 b	3.9 ab	32.5 a
		W ₁ K ₃	31.3 a	83.6 a	32.1 ab	3.6 cd	32.3 a
		W ₂ K ₁	31.6 a	84.2 a	31.8 b	3.4 d	32.5 a
		W ₂ K ₂	31.6 a	84.8 a	31.4 b	3.8 abc	32.6 a
		W ₂ K ₃	31.7 a	84.2 a	31.4 b	4.0 a	32.6 a
	Source of variance	W	ns	ns	*	ns	ns
		K	ns	ns	ns	*	ns
		W*K	ns	ns	ns	*	ns
	Year		***	***	**	***	***

Two irrigation amounts (W₁ and W₂) and three potassium application rates (K₁, K₂, and K₃) were used. Each value represents the mean (n=3). The effects of the K rate, drip irrigation mode, and K rate × drip irrigation interaction in a given year were assessed via mixed-effects two-way ANOVA, and the different lowercase letters following the values denote significant differences at the $P=0.05$ level. ns indicates $p > 0.05$; * and ** indicate significance at the 0.05 and 0.01 levels, respectively.

fruiting branches at 50 d. Under the K₂ and K₃ levels, the plants under W₂ exhibited 10.8 % and 8.5 % greater single-boll biomass accumulation in the upper fruiting branches, respectively, than did the plants under W₁, and the highest single-boll biomass accumulation in the upper fruiting branches was obtained under the W₂K₂ treatment, reaching 7.0 g at a boll age of 50 d, which was 2.8–11.9 % greater than those under the other treatments.

At a boll age of 50 d, the single-boll biomass accumulation in the lower fruiting branches (Fig. 3 iii–iv) was only 6.1 and 5.9 g for limited and conventional drip irrigation under K₁, which were on average 2.3–15.0 % and 4.0–11.9 % lower, respectively, than those under W₁K₂, W₁K₃, W₂K₂, and W₂K₃. The single-boll biomass accumulation in the lower fruiting branches was 7.3 % and 10.8 % greater under W₂ than under W₁ at the K₂ and K₃ application rates, respectively. The highest single-boll biomass accumulation in the lower fruiting branch activity was observed in the W₂K₂ treatment group, followed by that in the W₂K₃ treatment group.

Under both drip irrigation amounts, the K₂ and K₃ application rates resulted in 10.8 % and 5.3 % greater total single-boll biomass accumulation (Fig. 3v–vi) values, respectively, than did the K₁ application rate. The total single-boll biomass accumulation was greatest under the W₂K₂ treatment, reaching 6.9 g by a boll age of 50 d, which was 3.3–12.5 %

greater than those under the other treatments.

3.5. Characteristic parameters of single-boll biomass accumulation

On the basis of the logistic equations shown in Fig. 3, the relevant single-boll biomass accumulation parameters were obtained via Eqs. (13)–(17) (Table 4). During the whole boll growth period, the t_1 , t_2 and t_0 values of single-boll biomass accumulation under W₂ conditions occurred 4.1, 17.0 and 2.7 d earlier, respectively, than those under W₁ conditions. The duration of rapid single-boll biomass accumulation under W₂ conditions was 38.9 % shorter than that under W₁ conditions, and the maximum accumulation rate (V_m) was 11.5 % greater than that under W₁ conditions. In addition, the V_m values under W₂K₂ and W₂K₃ were 0.152 and 0.148 g m⁻² d⁻¹, respectively, which were 13.3 % and 10.4 % greater, respectively, than those under the W₂K₁ treatment. A similar trend was observed under conventional drip irrigation. The V_m values under W₁K₂ and W₁K₃ were 0.137 and 0.130 g m⁻² d⁻¹, respectively, which were 15.6 % and 10.3 % greater, respectively, than those under the W₁K₁ treatment. The theoretical maximum value (Y_m) of single-boll biomass accumulation was greatest under the W₂K₂ treatment (6.3 g), which was 2.6–12.5 % greater than that under the other treatments.

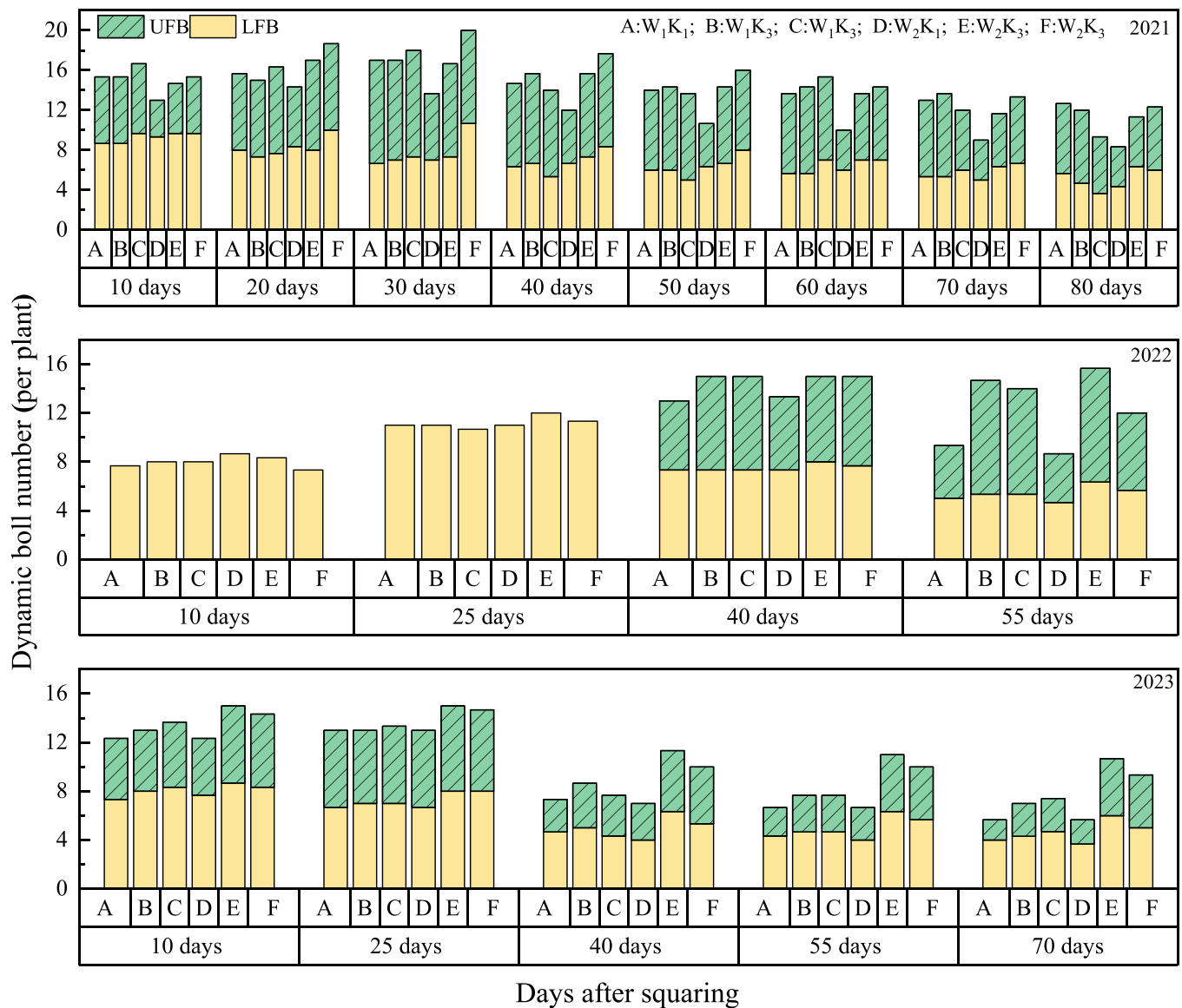


Fig. 2. Effects of the drip irrigation amount and potassium application rate on the dynamic boll number (DBN) from 2021–2023. Two irrigation amounts (W_1 and W_2) and three potassium application rates (K_1 , K_2 , and K_3) were examined. Each value represents the mean ($n=3$). UFB stands for upper fruiting branch, LFB stands for lower fruiting branch.

3.6. Fiber, seed, and shell percentages

Both the drip irrigation method and the potassium application rate significantly affected the percentage of each component of cotton bolls (Fig. 4). With decreasing drip irrigation amount, the fiber and seed percentages significantly increased, whereas the shell percentage significantly decreased. The W_1K_1 treatment exhibited the lowest fiber percentage, which was 5.5 % lower than that under the W_2K_1 treatment. Under both drip irrigation amounts, increasing the application amount of potassium fertilizer led to an increase in the fiber percentage. The fiber percentage first increased but then decreased with increasing potassium application rate. Compared with that under the K_1 treatment, the fiber percentage increased by 5.0 % and 3.1 % under the K_2 and K_3 treatments, respectively. Compared with that under the W_1 treatment, the fiber percentage under the K_2 and K_3 treatments increased by 7.3 % and 8.2 %, respectively, at a boll age of 10–30 d.

The seed percentage of W_2 plants was significantly greater than that of W_1 plants by 9.2 % at a boll age of 10–20 d under the K_3 application level in 2023. There was no significant difference in the seed percentage

between the W_1 and W_2 treatments under the K_1 and K_2 application levels. In 2023, under W_2 conditions, the seed percentage at a boll age of 10 d was 3.3 % and 3.8 % lower under the K_1 treatment than under the K_2 and K_3 treatments, respectively. Under W_1 conditions, the seed percentage was significantly lower under the K_3 treatment than under the K_1 and K_2 treatments, namely, by 4.6 % and 5.1 %, respectively. At a boll age of 30–50 d in 2023, the highest seed percentage was found under W_2K_2 , which was 2.4–5.3 % greater than that under the other treatments, but there was no significant difference among the treatments.

The shell percentage of the W_2 plants was 6.1 %, 6.7 % and 7.5 % lower than that of the W_1 plants under the K_1 , K_2 and K_3 application levels, respectively. The shell percentage first decreased but then increased with increasing potassium application rate, and the shell percentage under K_1 was the highest. Under W_1 conditions, the shell percentage was 3.9 % and 2.2 % lower under the K_2 treatment than under the K_1 and K_3 treatments, respectively. A similar trend was observed under limited drip irrigation (W_2), where the shell percentage under the K_2 treatment was 4.4 % and 1.4 % lower than that under the

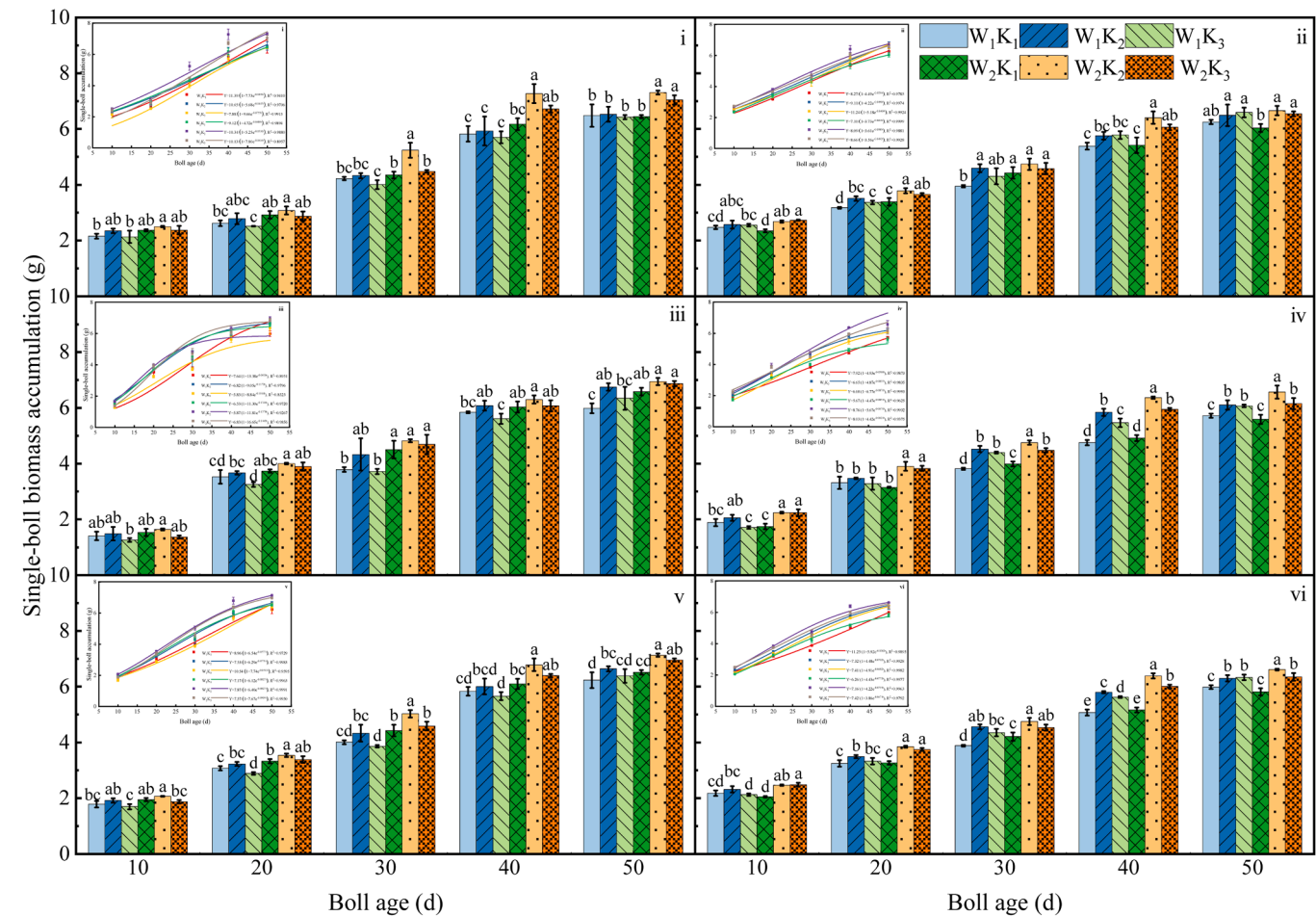


Fig. 3. Logistic equation fitting of single-boll biomass accumulation for each treatment in 2021 and 2023. Two irrigation amounts (W_1 and W_2) and three potassium application rates (K_1 , K_2 , and K_3) were examined. Each value represents the mean ($n=3$). i: 2021-UFB-SBA; ii: 2023-UFB-SBA; iii: 2021-LFB-SBA; iv: 2023-LFB-SBA; v: 2021-T-SBA; vi: 2023-T-SBA. SBA stands for single-boll biomass accumulation. UFB stands for upper fruiting branch, LFB stands for lower fruiting branch, and T stands for average of upper and lower fruiting branches.

Table 4
Logistic equation parameters for single-boll biomass accumulation from 2021–2023. Two irrigation amounts (W_1 and W_2) and three potassium application rates (K_1 , K_2 , and K_3) were examined.

Vertical distribution	Treatment	Rapid accumulation onset time (t_1 , d)	Rapid accumulation end time (t_2 , d)	Maximum rate emergence time (t_0 , d)	Rapid accumulation duration (T , d)	Maximum rate (V_m , g m ⁻² d ⁻¹)	Theoretical maximum (Y_m , g boll ⁻¹)
2021	W_1K_1	9.7	55.4	47.0	45.7	0.129	6.2
	W_1K_2	6.8	40.9	46.0	34.2	0.145	6.4
	W_1K_3	14.3	65.8	51.2	51.5	0.135	6.7
	Average	10.3	54.0	48.0	43.8	0.136	6.4
	W_2K_1	6.0	37.8	45.3	31.9	0.148	6.3
	W_2K_2	6.5	38.4	46.4	31.9	0.163	6.9
	W_2K_3	7.9	36.9	50.9	29.0	0.172	7.0
	Average	6.8	37.7	47.5	30.9	0.161	6.7
2023	W_1K_1	12.1	81.0	44.5	69.0	0.107	5.4
	W_1K_2	2.6	40.1	37.5	37.5	0.128	5.5
	W_1K_3	4.0	42.6	39.8	38.6	0.126	5.6
	Average	6.2	54.6	40.6	48.4	0.121	5.5
	W_2K_1	2.2	36.3	37.2	34.1	0.121	5.0
	W_2K_2	1.6	34.7	36.0	33.2	0.142	5.8
	W_2K_3	0.5	39.6	33.8	39.1	0.125	5.3
	Average	1.4	36.9	35.7	35.5	0.129	5.4

K_1 and K_3 treatments, respectively. The shell percentage was lowest under W_2K_2 , with a value that was 1.4–9.9 % lower than those under the other treatments.

3.7. Within-boll yield components

The drip irrigation pattern and potassium application rate significantly affected within-boll yield components (Table 5). With decreasing

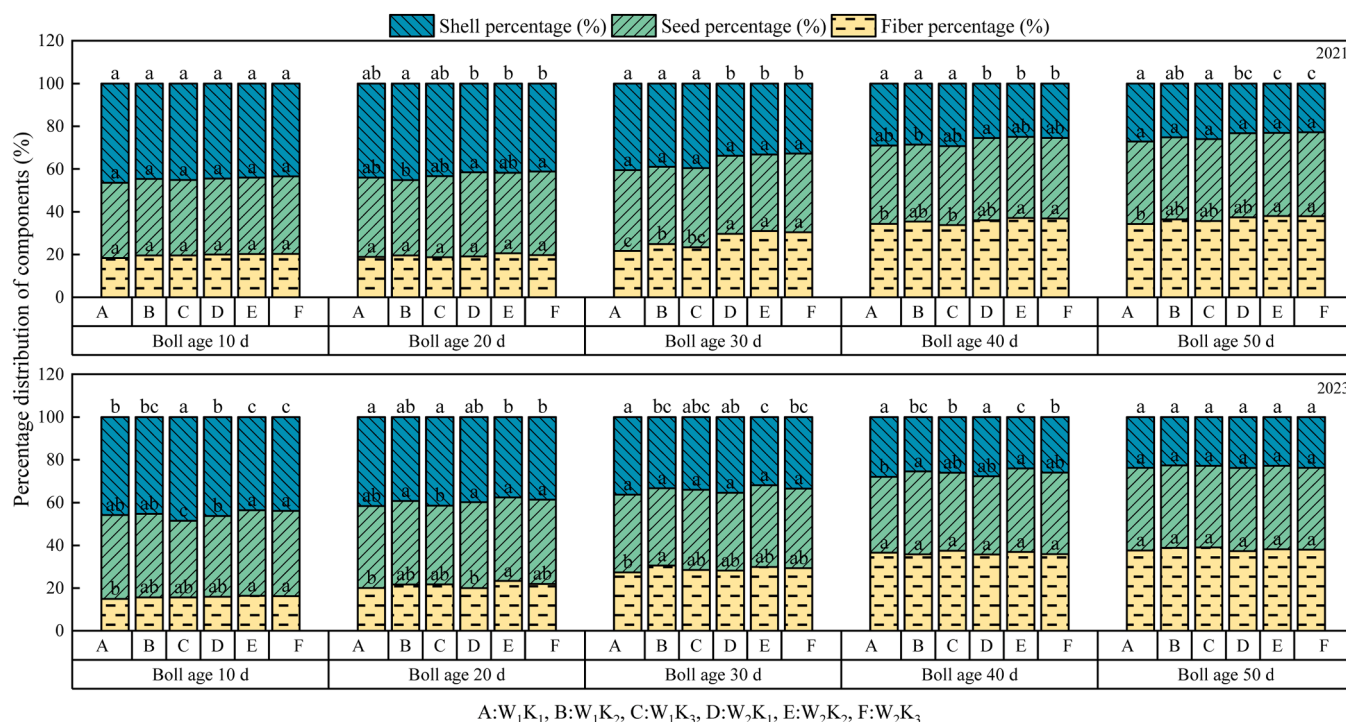


Fig. 4. Effects of the drip irrigation amount and potassium application rate on the distribution indices of boll components in 2021 and 2023. Two irrigation amounts (W_1 and W_2) and three potassium application rates (K_1 , K_2 , and K_3) were examined. Each value represents the mean ($n=3$). The fiber percentage (fiber PCT), seed percentage (seed PCT), and shell percentage (shell PCT) under the different treatments were quantified via one-way analysis of variance (ANOVA) and Duncan's test in the same year, and the different lowercase letters following the values denote significant differences at the $P=0.05$ level.

drip irrigation amount, the fiber density decreased, whereas the other parameters increased. Compared with those under the W_1 treatment, the lint per seed, lint index and individual fiber weight under the W_2 treatment significantly increased by 4.6 %, 4.6 % and 8.7 %, respectively, and the fiber density under the W_2 treatment decreased by 4.7 %. Increasing the application rate of potassium fertilizer could improve the within-boll yield components. Compared with those under the K_1 treatment, the seed number, lint per seed, and lint index under the K_2 and K_3 treatments increased by 9.2 % and 10.3 %, 6.5 % and 3.0 %, and 6.5 % and 3.0 %, and 2.0 % and 1.0 %, respectively. The fiber density was 3.6 % and 4.6 % greater under the K_2 and K_3 treatments than for the K_1 treatment, respectively, in 2021 and 2022. The fiber density of K_1 was 6.2 % and 3.1 % greater, respectively, than those under the K_2 and K_3 treatments in 2023, reaching a significant difference only in 2022. Under the interaction effect of the drip irrigation pattern and potassium application rate, the greatest seed number, lint per seed, lint index and individual fiber weight values were observed under the W_2K_2 treatment, followed by those under the W_2K_3 treatment, with 9.4 %, 8.1 %, 8.6 % and 3.3 % and 8.6 %, 3.3 %, 8.8 %, and 5.5 % greater average values, respectively, than those under the W_1K_1 , W_1K_2 , W_1K_3 , and W_2K_1 treatments, respectively. The seed index and seed surface area were lowest under the W_1K_1 treatment and were significantly lower than those under the W_1K_3 treatment, namely, by 3.7 % and 1.8 %, respectively, in 2023, with no significant differences among the other treatments. The number of seeds per boll under the various treatments differed significantly only in 2022; the number of seeds per boll under W_2K_3 was significantly greater than those under W_1K_1 , W_1K_2 and W_2K_1 , namely, by 6.1 %, 4.7 % and 5.0 %, respectively; and the number of seeds per boll under the W_2K_3 treatment did not significantly differ from those under the W_1K_2 and W_2K_2 treatments.

3.8. The relationship between various parameters and cotton yield and fiber quality

According to Pearson correlation analysis (Table 6), several variables were found to be significantly or extremely positively correlated with lint and cottonseed yields. These variables include boll weight, boll density, lint percentage, dynamic boll number, single-boll biomass accumulation, fiber percentage, seed index, lint per seed, seed number, lint index, seed surface area, and individual fiber weight (all $P < 0.05$ or $P < 0.01$). In contrast, shell percentage was significantly ($P < 0.05$) or extremely ($P < 0.01$) negatively correlated with lint and cottonseed yields.

Table 6 illustrates the correlations between various parameters and fiber quality. The basic yield components (boll weight, lint percentage), the dynamic boll number of the lower fruiting branches, single-boll biomass accumulation, within-boll yield components (seed index, lint per seed, seeds number, lint index, seed surface area) exhibited significant or highly significant positive correlations with fiber strength, uniformity, and micronaire value. Furthermore, fiber uniformity demonstrated a strong positive correlation with boll density, while both fiber uniformity and micronaire value showed significant positive correlations with fiber percentage, seed percentage, and individual fiber weight. The analysis also revealed a significant or highly significant positive correlation between Q score and several factors, including single-boll biomass accumulation, seed percentage, lint per seed, lint index, and individual fiber weight. Conversely, fiber uniformity and micronaire value displayed significant negative correlations with shell percentage and fiber density.

3.9. The correlation between various parameters

The Pearson correlation coefficients of the different parameters are shown in Table 7. The basic yield components (boll weight, boll density, and lint percentage) exhibited significant or highly significant positive

Table 5

Effects of the drip irrigation pattern and potassium application rate on within-boll yield components from 2021–2023.

Year	Treatment	SI (g)	SN (no. $\times 10^5$ ha $^{-1}$)	SPB (no.)	LPS (g)	LI (g)	SSA (mm 2)	IFW (ug)	FD (fibers mm $^{-2}$)
2021	W ₁ K ₁	5.57 a	756.13 a	46.26 a	0.042 b	4.17 b	72.44 a	3.76c	111.45 a
	W ₁ K ₂	5.57 a	745.93 a	43.98 a	0.042 b	4.23 b	72.41 a	3.87 bc	109.12 a
	W ₁ K ₃	5.54 a	729.97 a	47.36 a	0.041 b	4.11 b	72.25 a	3.74c	111.07 a
	W ₂ K ₁	5.37 a	718.67 a	49.06 a	0.042 b	4.19 b	71.13 a	4.34 a	98.08 b
	W ₂ K ₂	5.59 a	731.01 a	46.24 a	0.046 a	4.57 a	72.55 a	4.3 a	103.83 ab
	W ₂ K ₃	5.47 a	743.27 a	46.56 a	0.042 b	4.21 b	71.77 a	4.05 b	104.8 ab
	W ₁	5.56 a	744.01 a	45.87 a	0.042 b	4.17 b	72.37 a	3.79 b	110.54 a
	W ₂	5.47 a	730.98 a	47.29 a	0.042 a	4.32 a	71.82 a	4.23 a	102.24 b
	K ₁	5.47 a	737.4 a	47.66 a	0.042 b	4.18 b	71.79 a	4.05 a	104.77 a
	K ₂	5.58 a	738.47 a	45.11 a	0.044 a	4.4 a	72.48 a	4.08 a	106.47 a
	K ₃	5.50 a	736.62 a	46.96 a	0.042 b	4.16 b	72.01 a	3.89 b	107.93 a
	W	ns	ns	ns	*	*	ns	***	**
	K	ns	ns	ns	*	*	ns	*	ns
	W*K	ns	ns	ns	ns	ns	ns	ns	ns
	Year	***	*	***	**	**	***	**	*
2022	W ₁ K ₁	5.60 a	677.63 d	49.03 b	0.038c	3.8c	72.61 a	3.87 d	101.21 a
	W ₁ K ₂	5.58 a	763.68c	49.69 b	0.042 b	4.21 b	72.52 a	4.14 bc	102.44 a
	W ₁ K ₃	5.58 a	838.61 b	50.95 ab	0.041 b	4.15 b	72.49 a	3.97 cd	105.68 a
	W ₂ K ₁	5.55 a	691.98 d	49.53 b	0.042 b	4.19 b	72.31 a	4.48 a	94.32 b
	W ₂ K ₂	5.53 a	901.02 a	51.17 ab	0.045 a	4.48 a	72.18 a	4.24 b	104.24 a
	W ₂ K ₃	5.52 a	889.98 a	52.02 a	0.043 b	4.3 b	72.12 a	4.21 b	102.22 a
	W ₁	5.58 a	759.97 b	49.89 a	0.041 b	4.05 b	72.54 a	3.99 b	103.11 a
	W ₂	5.53 a	827.66 a	50.91 a	0.043 a	4.32 a	72.20 a	4.31 a	100.26 b
	K ₁	5.57 a	684.81 b	49.28 b	0.040c	3.99c	72.46 a	4.18 a	97.76 b
	K ₂	5.56 a	832.35 a	50.43 ab	0.043 a	4.34 a	72.35 a	4.19 a	103.34 a
	K ₃	5.55 a	864.29 a	51.49 a	0.042 b	4.23 b	72.30 a	4.09 a	103.95 a
	W	ns	***	ns	***	***	ns	***	ns
	K	ns	***	*	***	***	ns	ns	**
	W*K	ns	**	ns	ns	ns	ns	**	ns
	Year	***	*	***	**	**	***	**	*
2023	W ₁ K ₁	5.27 b	724.53 b	51.09 a	0.038 d	3.83 d	70.46 b	3.77c	106.97 ab
	W ₁ K ₂	5.36 ab	754.68 ab	52.05 a	0.040 bc	3.99 bc	71.08 ab	3.85 bc	107.07 ab
	W ₁ K ₃	5.46 a	772.47 ab	50.53 a	0.040 bc	3.97 bc	71.75 a	3.63c	112.89 a
	W ₂ K ₁	5.40 ab	736.22 b	49.94 a	0.039 cd	3.94 cd	71.29 ab	3.6c	113.4 a
	W ₂ K ₂	5.36 ab	804.54 a	48.29 a	0.042 a	4.19 a	71.04 ab	4.25 a	100.49 b
	W ₂ K ₃	5.46 ab	774.5 ab	48.84 a	0.041 ab	4.08 ab	71.70 ab	4.14 ab	100.9 b
	W ₁	5.36 a	750.56 a	51.23 a	0.039 b	3.93 b	71.09 a	3.75 b	108.98 a
	W ₂	5.40 a	771.75 a	49.03 a	0.041 a	4.07 a	71.34 a	4 a	104.93 a
	K ₁	5.33 b	730.37 b	50.52 a	0.039 b	3.88 b	70.87 b	3.69 b	110.19 a
	K ₂	5.36 ab	779.61 a	50.17 a	0.041 a	4.09 a	71.06 ab	4.05 a	103.78 a
	K ₃	5.46 a	773.48 a	49.69 a	0.040 a	4.03 a	71.72 a	3.88 ab	106.9 a
	W	ns	ns	ns	**	**	ns	*	ns
	K	*	*	ns	**	**	*	*	ns
	W*K	ns	ns	ns	ns	ns	ns	*	*
	Year	***	*	***	**	**	***	**	*

Two irrigation amounts (W₁ and W₂) and three potassium application rates (K₁, K₂, and K₃) were examined. Each value represents the mean (n=3). The seed index (SI), seed number (SN), seeds per boll (SPB), lint per seed (LPS), lint index (LI), seed surface area (SSA), individual fiber weight (IFW) and fiber density (FD) under the different treatments were quantified via mixed-effects two-way ANOVA and Duncan's test in the same year, and the different lowercase letters following the values denote significant differences at the $P=0.05$ level. ns indicates $p > 0.05$; * and ** indicate significance at the 0.05 and 0.01 levels, respectively.

correlations with one another. These components also demonstrated significant or highly significant positive correlations with several factors, including the dynamic boll number of lower fruiting branches, total dynamic boll number, single-boll biomass accumulation in each part, fiber percentage, and within-boll yield components (seed index, lint per seed, seed number, lint index, and seed surface area). Conversely, they showed highly significant negative correlations with the shell percentage. Furthermore, boll density, displayed a highly significant positive correlation with the dynamic boll number of upper fruiting branches, while boll weight and lint percentage were significantly or highly significantly positively correlated with the seed percentage and individual fiber weight. Additionally, boll weight exhibited a highly significant negative correlation with the fiber density.

The dynamic boll number and single-boll biomass accumulation, as well as the boll component percentage (fiber and seed percentages) exhibited significant or highly significant positive correlations with each other. Moreover, dynamic boll number of lower fruiting branches, total dynamic boll number, single-boll biomass accumulation in each part and the boll component percentage (fiber and seed percentages) showed significant or highly significant positive correlations with various within-boll yield components, including seed index, lint per seed, seed

number, lint index, seed surface area, or individual fiber weight. Notably, a highly significant positive correlation was observed between the dynamic boll number of the upper fruiting branches and seed number. In contrast, shell percentage was significantly or highly significantly positively correlated with within-boll yield components, such as seed index, lint per seed, seed number, lint index, seed surface area, and individual fiber weight, while maintaining a highly significant negative correlation with fiber density.

The within-boll yield components, encompassing seed index, lint per seed, seed number, lint index, seed surface area, and individual fiber weight exhibited significant to highly significant positive correlations among themselves. Notably, individual fiber weight demonstrated a highly significant negative correlation with fiber density.

4. Discussion

With increasingly severe climate change and frequent drought stress, developing methods to achieve high cotton yields and quality with a limited water supply is crucial for sustainable cotton production in arid or semiarid areas. Cotton boll development plays a pivotal in determining the cotton yield and fiber quality, and drought stress can

Table 6

Correlation analysis of the various parameters with the cotton yield and fiber quality.

	Lint yield	Cottonseed yield	Fiber length (mm)	Uniformity (%)	Fiber strength (cN tex ⁻¹)	Micronaire value	Q score
BW	0.729**	0.504*	-0.151	0.832**	0.579*	0.787**	0.438
BD	0.904**	0.925**	-0.243	0.539*	0.331	0.393	0.137
LP	0.819**	0.549*	-0.100	0.806**	0.712**	0.753**	0.499*
UFB-DBN	0.697**	0.814**	-0.027	0.189	0.361	-0.055	0.124
LFB-DBN	0.852**	0.702**	-0.158	0.729**	0.518*	0.657**	0.361
T-DBN	0.863**	0.883**	-0.105	0.457	0.454	0.256	0.228
UFB-SBA	0.878**	0.681**	-0.081	0.846**	0.675**	0.748**	0.515*
LFB-SBA	0.862**	0.683**	-0.075	0.783**	0.634**	0.697**	0.480*
T-SBA	0.886**	0.694**	-0.079	0.828**	0.666**	0.735**	0.506*
Fiber PCT	0.743**	0.636**	-0.391	0.609**	0.369	0.572*	0.088
Seed PCT	0.413	0.219	0.177	0.559*	0.242	0.630**	0.488*
Shell PCT	-0.773**	-0.579*	0.163	-0.770**	-0.407	-0.788**	-0.363
SI	0.825**	0.638**	-0.112	0.745**	0.511*	0.675**	0.402
LPS	0.830**	0.581*	-0.065	0.811**	0.629**	0.726**	0.500*
SN	0.934**	0.984**	-0.38	0.432	0.383	0.384	0.012
SPB	-0.018	0.037	-0.184	-0.328	0.108	-0.096	-0.228
LI	0.830**	0.581*	-0.065	0.811**	0.629**	0.726**	0.500*
SSA	0.825**	0.638**	-0.112	0.745**	0.511*	0.675**	0.402
FD	-0.234	-0.043	0.034	-0.621**	-0.155	-0.842**	-0.360
IFW	0.560*	0.281	-0.064	0.818**	0.441	0.963**	0.496*

* and ** denote extremely significant differences at $P < 0.05$ and $P < 0.01$, respectively. BW: boll weight (g), BD: boll density (bolls $\times 10^4$ ha⁻¹), LP: lint percentage (%), DBN: dynamic boll number (no. plant⁻¹), SBA: single-boll biomass accumulation (g), fiber PCT: fiber percentage (%), seed PCT: seed percentage (%), shell PCT: shell percentage (%), SI: seed index (g), LPS: lint per seed (g), SN: seed number (no. $\times 10^5$ ha⁻¹), SPB: seeds per boll (no), LI: lint index (g), SSA: seed surface area (mm²), IFW: individual fiber weight (ug), FD: fiber density (fibers mm⁻²).

significantly reduce the number of bolls and boll weight, leading to decreased cotton yields and potentially lower fiber quality. Numerous studies have demonstrated that the application of potassium fertilizer can optimize boll development and positively affects cotton yield and fiber quality (Read et al., 2006; Ali et al., 2023). To investigate study the effect of potassium fertilizer under limited drip irrigation on the cotton yield and fiber quality, and to explore the relationships among dynamic boll number, boll biomass, basic and within-boll yield components, cotton yield and fiber quality, we conducted a 3-year field experiment. Our findings indicate that a reasonable application of potassium fertilizer under limited drip irrigation could promote the development of fibers and seeds, synchronously optimize basic and within-boll yield components, ultimately improve cotton yield and fiber quality.

4.1. Effects of limited drip irrigation and potassium fertilizer on the cotton yield and fiber quality

The cotton yield (lint and cottonseed yields) depends on a combination of genotypes, environmental factors and cultivation practices (Patil et al., 2023). In this study, the lint and cottonseed yields were significantly greater (by 10.3 % and 4.6 %, respectively) under limited drip irrigation than under conventional drip irrigation in the medium and high potassium treatments. Under both drip irrigation amounts, lint yield increased significantly with elevated potassium application levels. Specifically, compared to the low-potassium treatment, yields increase by 16.0 % and 13.6 % under medium and high potassium application levels, respectively. These findings are consistent with previous research results (Ali et al., 2018; Hafeez et al., 2019). Across the treatments, both drip irrigation and potassium application significantly affected the cottonseed yield, which increased by 9.4 % and 8.0 %, respectively, under limited drip irrigation with additional application of potassium fertilizers (K₂ and K₃). Both limited drip irrigation and potassium application notably increased the lint and cottonseed yields, and the combination of limited drip irrigation and a medium potassium level was the most effective. The fiber quality is governed mainly by both genetic and environmental factors, with environmental factors accounting for one-third of the overall effect on the fiber quality (Yagmur et al., 2014; Elsamman et al., 2024). Inconsistent findings have been reported for the effects of the drip irrigation amount and potassium application rate on the fiber quality (Gormus and Yucel, 2002; Tariq et al., 2018). In this

study, compared with that under conventional drip irrigation, limited drip irrigation increased the micronaire value, which is similar to previous research. A reasonable increase in potassium application increased the micronaire value but imposed no significant effect on the fiber strength, fiber uniformity or fiber length (Minton and Ebelhar, 1991; Pettigrew et al., 2005; Tariq et al., 2018). However, Gormus and Yucel (2002) reported that potassium application (K₂O) at 150 kg ha⁻¹ was beneficial for increasing the fiber length and strength, but the fiber uniformity and micronaire value decreased (Sun et al., 2024). In view of the different findings regarding the effects of potassium fertilizer application on the various fiber quality indicators, the effect of potassium fertilizer application on the fiber quality has not been comprehensively evaluated. Therefore, the fiber quality was comprehensively assessed via the Q score (Li et al., 2022). In this study, the Q score under limited drip irrigation did not significantly differ from that under conventional drip irrigation. Notably, a reasonable increase in potassium fertilizer application (medium potassium) increased the Q score and micronaire value, indicating that a reasonable increase in potassium fertilizer application could increase the fiber quality and fiber maturity, which is conducive to meeting the requirements of fiber processing.

4.2. Analyzing the differences in cotton yield formation based on the basic and within-boll yield components

The cotton yield is usually a composite index that is closely related to the boll density, boll weight and lint percentage. In previous studies, the basic yield components (boll weight, boll density, and lint percentage) responded differently to a limited water supply and potassium availability (Zhang et al., 2015; Witt et al., 2020). In this study, additional potassium fertilizer application under limited drip conditions facilitated the optimization of the basic yield components, indicating that the positive effect of potassium fertilizer application on cotton boll development compensated for the negative effects of the limited water supply on the boll density and boll weight (Hu et al., 2015; Ju et al., 2021).

Boll density is one of the important factors affecting cotton yield. According to the correlation analysis, the lint and cottonseed yields were positively and significantly correlated with the boll density. Increasing the spatial and temporal distribution of boll densities facilitates lint and cottonseed yields improvement (Bablu et al., 2015; Wu et al., 2018). Drought stress may increase the rate of cotton boll abscission, leading to

Table 7
Correlation analysis between basic and within-boll yield components.

Parameters	BW	BD	LP	UFB-DBN	LFB-DBN	TDB-N	UFB-SBA	LFB-SBA	T-SBA	Fiber PCT	Seed PCT	Shell PCT	SI	LPS	SN	SPB	LI	SSA	FD	IFW
BW	1	0.580*	0.813**	0.167	0.833**	0.513*	0.865**	0.801**	0.847**	0.545*	0.731**	-0.831**	0.658**	0.741**	0.568*	-0.046	0.741**	0.658**	-0.637**	0.812**
BD		1	0.607**	0.785**	0.793**	0.909**	0.779**	0.787**	0.797**	0.705**	0.319	-0.688**	0.716**	0.650**	0.894**	-0.271	0.650**	0.716**	-0.16	0.378
LP			1	0.351	0.785**	0.576*	0.893**	0.888**	0.906**	0.682**	0.566*	-0.825**	0.863**	0.946**	0.587*	-0.119	0.946**	0.863**	-0.431	0.790**
UFB-DBN				1	0.502*	0.900**	0.483*	0.568*	0.537*	0.494*	-0.006	-0.341	0.453	0.391	0.780**	-0.066	0.391	0.453	0.259	-0.039
LFB-DBN					1	0.816**	0.924**	0.858**	0.906**	0.709**	0.548*	-0.833**	0.695**	0.763**	0.745**	-0.088	0.763**	0.695**	-0.447	0.672**
T-DBN						1	0.745**	0.773**	0.773**	0.651**	0.271	-0.621**	0.610**	0.593**	0.878**	-0.084	0.593**	0.610**	-0.037	0.27
UFB-SBA							1	0.930**	0.981**	0.733**	0.543*	-0.847**	0.828**	0.886**	0.714**	-0.158	0.886**	0.828**	-0.52*	0.793**
LFB-SBA								1	0.984**	0.791**	0.595**	-0.919**	0.832**	0.872**	0.705**	-0.215	0.872**	0.832**	-0.464	0.738**
T-SBA									1	0.777**	0.581*	-0.901**	0.845**	0.895**	0.722**	-0.191	0.895**	0.845**	-0.501*	0.778**
Fiber PCT										1	0.154	-0.792**	0.645**	0.701**	0.667**	-0.086	0.701**	0.645**	-0.252	0.522*
Seed PCT											1	-0.725**	0.514*	0.233	0.505*	-0.174	0.514*	0.505*	-0.672**	0.707**
Shell PCT												1	-0.761**	-0.806**	-0.609**	0.167	-0.806**	-0.761**	0.590**	-0.801**
SI													1	0.949**	0.597**	-0.368	0.949**	1.000**	-0.366	0.708**
LPS														1	0.592**	-0.211	1.000**	0.949**	-0.38	0.775**
SN															1	0.149	0.592**	0.597**	-0.074	0.323
SPB																1	0.219	-0.368	0.219	-0.176
LI																	1	0.949**	-0.38	0.775**
SSA																		1	0.708**	-0.366
FD																			1	-0.867**
IFW																				1

* and ** denote extremely significant differences at $P < 0.05$ and $P < 0.01$, respectively. BW: boll weight (g), BD: boll density (bolls $\times 10^4$ ha $^{-1}$), LP: lint percentage (%), DBN: dynamic boll number (no. plant $^{-1}$), SBA: single-boll biomass accumulation (g), fiber PCT: fiber percentage (%), seed PCT: seed percentage (%), shell PCT: shell percentage (%), SI: seed index (g), LPS: lint per seed (g), SN: seed number (no. $\times 105$ ha $^{-1}$), SPB: seeds per boll (no), LI: lint index (g), SSA: seed surface area (mm 2), IFW: individual fiber weight (ug), FD: fiber density (fibers mm $^{-2}$).

an uneven spatial distribution of boll formation and ultimately reducing the boll number per plant (Lv et al., 2007). We found that boll density was closely related to the dynamic boll number in different temporal and spatial distributions. The dynamic boll number of upper fruiting branches decreased significantly by 35.8–57.3 % under the low-potassium treatment with conventional drip irrigation. In contrast, the dynamic boll number of lower fruiting branches under the medium and high potassium treatments with limited drip irrigation increased by 40.9 % and 25.6 %, respectively, compared with the other treatments at 80 d after squaring. These findings indicate that potassium fertilizer application under a limited water supply could decrease the rate of cotton boll abscission and increase the boll number per plant, ultimately increase the boll number (Hu et al., 2015).

In addition, the boll weight and lint percentage are important factors influencing the cotton yield. According to the correlation analysis shown in Table 6, the lint yield was highly significantly positively correlated with the boll weight and lint percentage, and the cottonseed yield was significantly positively correlated with the boll weight. In this three-year experiment, the highest boll weight and lint percentage were obtained under the medium-potassium treatment with limited drip irrigation, which increased significantly by 4.7–10.8 % and 3.0–6.9 %, respectively, compared with those under the other treatments (W₁K₁, W₁K₂, W₁K₃, and W₂K₁). In summary, maintaining medium potassium levels under limited drip irrigation optimizes the basic yield components and compensates, ultimately significantly increased the cotton yield. Increased boll weight is based on single-boll biomass accumulation. Notably, the boll weight and lint percentage were significantly and positively correlated with single-boll biomass accumulation, fiber percentage and seed percentage. These findings suggest that the increases in the boll weight and lint percentage could be attributed to the increase in single-boll biomass accumulation, fiber percentage, and seed percentage under limited drip irrigation and reasonable potassium fertilization (Rogiers et al., 2017). Water deficits limit the translocation of photosynthetic products to cotton bolls, which is not conducive to cotton boll biomass accumulation (Zhao et al., 2018). Many studies have also shown that a longer duration of rapid cotton boll biomass accumulation is detrimental to cotton boll maturity and does not promote cotton boll biomass accumulation (Andrade et al., 2000; Gwathmey and Clement, 2010). In this study, the application of additional potassium fertilizer under limited drip irrigation increased single-boll biomass accumulation, possibly because potassium fertilization promoted earlier rapid cotton boll biomass accumulation, increased the maximum rate of boll biomass accumulation, shortened the duration of rapid accumulation, and ultimately increased the boll biomass. Single-boll biomass can be regarded as the sum of the shell biomass, fiber biomass and seed biomass of each boll. Consistent with the findings of Hu et al. (2015), under limited drip irrigation, the fiber and seed percentages increased by 8.5 % and 3.6 %, respectively, in response to increased potassium fertilizer application (medium-potassium application treatment) compared with those under the low-potassium application level. Potassium fertilization affected single-boll biomass accumulation mainly via cotton boll development, and the single-boll biomass was positively correlated with the fiber and seed percentages. Therefore, increased potassium application of fertilizer under limited drip irrigation promoted the distribution of boll biomass to fibers and cottonseeds, advanced bolls into the rapid accumulation stage, increased the maximum accumulation rate, and facilitated the increase of boll biomass, which ultimately improved the boll weight and the lint percentage. (Hu et al., 2015; Saad et al., 2016).

However, Coyle and Smith (1997) reported complex relationships between yield components that could be further decomposed into more detailed within-boll yield components, the effects of the various drip irrigation amounts and potassium application rates on within-boll yield components are largely unexplored. The lint yield per boll can be expressed as the product of the number of seeds per boll and the lint per seed value (Worley et al., 1976). Consistent with the findings of Yagmur

et al. (2014), the lint index, lint per seed and individual fiber weight were greater under limited drip irrigation than under conventional drip irrigation, which facilitated the optimization of the within-boll yield components under appropriate water stress. Previous studies have indicated that maintaining an appropriate K^+ concentration promotes fiber development and enhances cotton boll biomass accumulation (Wakeel et al., 2011; Hamoda, 2017). This finding is consistent with the findings of previous studies, the medium and high potassium treatments increased the lint per seed, individual fiber biomass and lint index values and that medium-potassium treatment implementation imposed the greatest effect on the fiber biomass under limited drip irrigation (Guo et al., 2016; Fang et al., 2017), suggesting that a reasonable increase in potassium fertilization under limited drip irrigation increased the individual fiber weight, lint per seed and boll lint index (Sezener et al., 2015). According to the Pearson's correlation analysis shown in Table 6, the increase in lint yield was due to the optimization of the within-boll yield components, i.e., the lint per seed, individual fiber weight and lint index values increase simultaneously. Further analysis via Pearson's correlation (Table 7) revealed that the within-boll yield components (seed index, lint per seed, seed number, lint index, seed surface area and individual fiber weight) were significantly and positively correlated with the basic yield components (boll weight and lint percentage). Changes in the within-boll yield components can also be used to explain the intrinsic factors that enhance single-boll biomass accumulation and the percentage of the boll biomass under limited drip irrigation in combination with potassium fertilizer application.

The boll weight is mainly composed of lint per boll and cottonseed per boll. The lint yield per boll can be expressed as the product of the number of seeds per boll and the lint per seed (Worley et al., 1976), whereas the lint per seed is a function of the seed surface area, fiber density and individual fiber weight (Groves et al., 2016; Virk et al., 2023). The results revealed that the lint per seed and individual fiber weight increased under the medium and high potassium treatments, and the combination of limited drip irrigation and medium-potassium level was optimal. The fiber percentage was positively correlated with the seed surface area, lint per seed, individual fiber weight, lint index, seed index, and seed number, but the seed surface area and seed index remained stable across the different treatments. This indicated that a reasonable increase in potassium application under limited drip irrigation increased the fiber percentage due to increases in the individual fiber weight, lint per seed, lint index and seed number. The seed biomass is determined by the number of seeds per boll and the seed index. In this study, the seed surface area and seed index remained stable under both drip irrigation amounts, which is consistent with the results of a previous study (Feng et al., 2011). The application of potassium fertilizer increased the seed surface area and the seed index and was positively correlated with the seed percentage. These findings suggest that increased potassium application under limited drip irrigation is beneficial in improving seed percentage by increasing seed surface area and seed index (Sezener et al., 2015). Overall, the medium-potassium treatment under limited drip irrigation resulted in the optimization of the within-boll yield components (seed surface area, lint per seed, individual fiber weight and lint index), promoted the development of cotton fibers and cottonseed, and ultimately increased single-boll biomass accumulation, fiber percentage and seed percentage, contributing to the increase in the boll weight.

The lint percentage is an important factor influencing the lint yield and can be used as an indicator to assess fiber and cottonseed development. It was revealed that the lint percentage increased significantly, by 2.1–6.9 %, under the medium-potassium treatment with limited drip irrigation compared with that under the other treatments. The lint percentage was expressed as the ratio of the fiber biomass to the seed cotton biomass. Hu et al. (2015) reported that potassium fertilizer application changed the distribution of biomass within cotton bolls and increased the percentage of the fiber biomass, thereby increasing the lint percentage. From the viewpoint of within-boll yield components, the

lint percentage can be expressed as the product of the lint per seed value and the seed index (Groves et al., 2016). In this study, the lint percentage was positively correlated with the lint percentage per seed. Therefore, the increase in the lint percentage under limited drip irrigation could be attributed to the increased application of potassium fertilizer (K_2 , 144 kg ha^{-1}) to promote cotton fiber development and increase the lint per seed and the fiber percentage in the boll biomass.

4.3. Analyzing the relationship in fiber quality with respect to the basic yield and within-boll yield components

The key quality factors of cotton fibers are the fiber length, strength, micronaire value and uniformity. These factors not only impact the processing efficiency of cotton fibers but also influence the final fiber product quality (Meredith et al., 1991; Zhang et al., 2023). Our research revealed that the combination of limited drip irrigation and potassium fertilizer application provided the optimal micronaire values. The micronaire value is indicative of the thickness and maturity of cotton fibers, which are crucial in textile production and quality assessment (Zhao et al., 2013). The Pearson's correlation analysis results revealed a significant positive correlation between the micronaire value and the basic yield components (boll weight, boll number, and lint percentage), dynamic boll number of lower fruiting branch, single-boll biomass accumulation, and fiber percentage. Moreover, the micronaire value was strongly positively correlated with within-boll yield components (seed index, lint per seed, seed number, lint index, seed surface area, individual fiber weight, and fiber density), whereas no significant differences in the seed index, seed surface area, or fiber density were detected between treatments. Thus, increases in the lint per seed, seed number, lint index, and individual fiber weight were the primary factors influencing the improvement in the fiber quality of cotton bolls under limited drip irrigation.

This study focused mainly on the effects of additional potassium fertilization under limited drip irrigation on cotton yield and fiber quality levels and their relationships with basic yield components and within-boll yield components. However, there are remaining research gaps and directions that should be addressed in the future. The effects of potassium fertilization under limited drip irrigation on the economic efficiency and resource utilization of cotton and the ecological environment are important research directions. An investigation of these effects would enable a more comprehensive assessment of the feasibility of the use of increased potassium fertilization under limited drip irrigation for sustainable cotton development.

5. Conclusion

This study investigated the impacts of potassium application on cotton yield and quality under limited drip irrigation, focusing on boll development and within-boll yield components. The results demonstrated that, compared to other treatments, the W_2K_2 treatment significantly enhanced lint and cottonseed yields. Furthermore, Limited drip irrigation combined with medium-potassium treatment was beneficial in increasing the Q score and maintaining the micronaire value within a suitable range (3.7–4.2), thereby enhancing fiber maturity and making the cotton fiber more suitable for processing requirements. The analysis of the basic yield components revealed that the increase in the boll density was due mainly to the increase in the dynamic boll number per plant in different parts, whereas the increases in the boll weight and lint percentage were driven by the increase in single-boll biomass accumulation. According to the logistic equations established in this study revealed that the medium-potassium treatment led to an earlier onset of rapid cotton boll biomass accumulation and an increased maximum accumulation rate. Further analysis was mainly due to the optimization of within-boll yield components (lint per seed, individual fiber weight and lint index) by potassium fertilizer. In summary, under limited drip irrigation (425 mm), potassium application at 144 kg ha^{-1} (K_2O)

effectively promoted fiber and seed development and optimized within-boll yield components, ultimately significantly increasing cotton yield and improving fiber quality. The results of this study provide new insights for achieving simultaneous cotton yield and fiber quality improvements in arid and semiarid regions.

CRediT authorship contribution statement

Honghai Luo: Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization. **Xiaojuan Shi:** Writing – review & editing, Writing – original draft, Software, Investigation, Formal analysis, Data curation. **Xianzhe Hao:** Writing – review & editing, Investigation, Data curation. **Humei Zhang:** Investigation. **Hao Li:** Methodology. **Ping Liu:** Writing – review & editing, Supervision. **Jun Wang:** Writing – review & editing, Supervision, Conceptualization. **Yonglin Yang:** Writing – review & editing, Supervision. **Nannan Li:** Investigation. **Feng Shi:** Investigation. **Yu Tian:** Investigation.

Declaration of Competing Interest

All the authors have approved the manuscript and agree with submission to the esteemed journal. There are no conflicts of interest to declare.

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Data availability

Data will be made available on request.

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