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# Optimization of appropriate boron fertilization application range for two cotton (*Gossypium hirsutum* L.) varieties in boron-deficient soils

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## Abstract

**Background** Boron (B) constitutes a critical yield constraint in global cotton production. Although B application plays a vital role in cotton yield, research gaps persist regarding cultivar-specific B requirements, vertical canopy dynamics, and precision management protocols in B-deficient agroecosystems.

**Results** In this study, we investigated the effects of B application rates on yield variation and spatial variation across two varieties at three locations. In Yancheng, applying 2.5 kg·hm<sup>-2</sup> of boron resulted in yield increases of 14.7%–25.9%, and in Xinghua, applying 2.0 kg·hm<sup>-2</sup> of boron achieved yield increases of 17.30%–20.58%. The optimal B application rates determined by quadratic function fitting were 1.90–2.36 kg·hm<sup>-2</sup> of boron for CCRI 425 and 2.05–2.36 kg·hm<sup>-2</sup> for Siza 3. Vertical canopy analysis revealed that the middle canopy (FB5–8), contributing 48.2% of total yield, responded significantly to B application rates.

**Conclusions** Cultivar-tailored B application within 1.90–2.36 kg·hm<sup>-2</sup> reconciles yield maximization. The boll number, especially those in the middle canopy, responded significantly to B application rates and was the main factor contributing to differences in yield formation. These findings underscore the necessity of location- and cultivar-specific B management.

**Keywords** Cotton (*Gossypium hirsutum* L.), Boron fertilizer, Yield components, Quadratic modeling, Vertical canopy distribution

## Introduction

Cotton (*Gossypium hirsutum* L.) cultivation areas have demonstrated a consistent annual decline following nationwide agricultural restructuring initiatives (Feng et al. 2024; Wang et al. 2022). Despite this, total cotton production has remained stable through increased yield

per unit area (Feng et al. 2022). However, this masks persistent productivity gaps in the Yellow River and Yangtze River basins (Tang et al. 2024; Wang et al. 2022), indicating substantial yield potential through agronomic measures (Zhang et al. 2024).

Precise boron (B) application significantly increases cotton yields. B deficiency is a major factor limiting cotton yield, as B primarily regulates pollen tube growth, floral organ development, and ultimately yield formation (Garcia-Sanchez et al. 2020; Gimeno et al. 2012). Over 33 million hectares of arable land in China suffer from B deficiency (Liu et al. 2024). This deficiency is particularly severe in cotton-growing regions

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of the Yangtze River basins, where rainfall is abundant (Lu et al. 2023). This is because plants primarily utilize highly soluble forms of B, boric acid and borate ions, which are prone to leaching during precipitation and irrigation (Brdar-Jokanovic 2020; Garcia-Sanchez et al. 2020), thereby exacerbating soil B depletion under intensive cultivation (Dhassi et al. 2019). Currently, field trials demonstrate that boric acid application at  $13.5 \text{ kg}\cdot\text{hm}^{-2}$  increases cotton yield by 17% in the Yangtze region (Li et al. 2016), confirming B as a critical yield-limiting factor. Although B supplementation effectively addresses deficiency, the sufficient-to-toxic threshold remains remarkably narrow (Dridi et al. 2018; Lopes et al. 2023). Excessive B application induces phytotoxicity manifestations through growth inhibition, morphological aberrations (Simón-Grao et al. 2018), and marginal leaf chlorosis or necrosis (Saraf et al. 2017). Thus, precise B application is critical for maximizing cotton yield. Substantial genotypic variation in B utilization efficiency exists among cultivars, with efficient genotypes demonstrating superior adaptation to low-B environments (Liu et al. 2024; Pommerrenig et al. 2018). The growth cycle further modulates varietal nutrient requirements (Huang et al. 2024), yet the B requirements of varieties with different growth cycles remain unquantified. Notably, B exhibits limited phloem mobility in cotton (Landi et al. 2019). Owing to its indeterminate growth habit, distinct canopy strata demonstrate developmental asynchrony (Liu et al. 2025). However, vertical canopy B dynamics remain uncharacterized in cotton.

Fertilizer efficiency models provide a robust framework for optimizing input-productivity relationships. The spatial heterogeneity in soil B availability presents significant management challenges. Therefore, optimizing boron management to enhance cotton yields represents a key focus in crop nutrition research. For single-nutrient investigations, quadratic (Q) models represent established analytical tools (Luo et al. 2024). Given the polygenic inheritance of yield traits and the critical influence of B management, this study aimed to (1) determine the yield potential of two varieties with various growth cycles across different soil conditions through optimized B management and establish yield-maximizing B application ranges through Q models; (2) validate the optimal range through yield component (boll density, boll mass, biomass allocation, and abscission rates) of column planting trials; and (3) use vertical canopy analysis to reveal the response of different canopy cotton bolls to B application and their contribution to yield. The ultimate objective was to establish soil-specific B management protocols for maximizing seed cotton production, thereby providing a scientific basis for precision nutrient management in B-deficient agroecosystems.

## Materials and methods

### Experimental design

The study utilized two cotton cultivars: early-maturing CCRI 425 (98-day growth cycle) and medium-early-maturing Siza 3 (130-day growth cycle). Field trials were conducted during the 2020 growing season at two locations in Jiangsu Province, China: Dafeng Original Seed Farm ( $33^{\circ}20'N$ ,  $120^{\circ}46'E$ ) in Yancheng and Old Agricultural Technology Grain Growing Family Farm, Lao-wei Village ( $32^{\circ}92'N$ ,  $119^{\circ}85'E$ ) in Xinghua. Column planting experiments occurred during the 2021 growing season at Nanjing Agricultural University's Pailou Experimental Station ( $118^{\circ}50'E$ ,  $32^{\circ}02'N$ ). Initial topsoil (0–20 cm) nutrient status appears in Table S1. Soil available B concentrations measured  $0.36 \text{ mg}\cdot\text{kg}^{-1}$  (Yancheng),  $0.31 \text{ mg}\cdot\text{kg}^{-1}$  (Xinghua), and  $0.24 \text{ mg}\cdot\text{kg}^{-1}$  (Nanjing), classifying all sites as mildly B-deficient ( $0.2\text{--}0.5 \text{ mg}\cdot\text{kg}^{-1}$ ) with distinct soil textures: loam (Yancheng), sandy loam (Xinghua), and clay (Nanjing). Meteorological data are presented in Fig. S1.

Field experiments followed a split-plot design with varieties (CCRI 425 and Siza 3) as main plots and seven B application rates (0, 1.0, 1.5, 2.0, 2.5, 3.0,  $3.5 \text{ kg}\cdot\text{hm}^{-2}$ ) as subplots. Borax ( $\text{Na}_2\text{B}_4\text{O}_7\cdot 10\text{H}_2\text{O}$ ; 11.3% B) was homogenized with dry topsoil (0–20 cm depth) as a basal fertilizer. At Yancheng, subplots measured  $15\times 3 \text{ m}^2$  with planting densities of 37 050 plants $\cdot\text{hm}^{-2}$  for Siza 3 and 90 000 plants $\cdot\text{hm}^{-2}$  for CCRI 425. At Xinghua, subplots of  $15\times 2.4 \text{ m}$  were planted with both cultivars at a uniform density of 49 500 plants $\cdot\text{hm}^{-2}$ . All treatments featured three replicates. Standard fertilizer comprised  $180 \text{ kg}\cdot\text{hm}^{-2}$  of pure N (40% at trefoil stage and 60% at flowering stage),  $100 \text{ kg}\cdot\text{hm}^{-2}$  of  $\text{P}_2\text{O}_5$  (trefoil stage), and  $180 \text{ kg}\cdot\text{hm}^{-2}$  of  $\text{K}_2\text{O}$  (trefoil stage). Other management followed local high-yield protocols.

Column planting experiments with CCRI 425 were arranged in a randomized block design using polyvinyl chloride (PVC) columns (49 cm height $\times$ 23 cm diameter) under rainout shelter conditions. Seven B treatments (0, 1.0, 1.5, 2.0, 2.5, 3.0, and  $3.5 \text{ kg}\cdot\text{hm}^{-2}$  of pure B) were replicated three times. Nutrient conditions and cultivation management mirrored field trial protocols.

### Measurements

#### Yield and yield components

The seed cotton yield in the field trial was determined at physiological maturity through complete boll harvest from  $4 \text{ m}^2$  ( $2\times 2 \text{ m}$ ) quadrats per plot. Ten uniform plants per treatment were sampled at boll maturation from each column trial, with air-dried bolls counted and weighed.

### Economic benefits analysis

Economic returns from B fertilization were calculated by subtracting B fertilizer costs from revenue generated by yield increases. Additional revenue was derived from increased seed cotton yield at ¥9.1 kg<sup>-1</sup>, while B fertilizer costs were based on application rate at ¥3.22 kg<sup>-1</sup>.

### Phenological monitoring

Ten tagged plants per block underwent longitudinal assessment of floral development (total flowers, pigmentation stages at the 1st–3rd fruiting nodes), boll formation dynamics (total bolls and nodal distribution), and boll abscission rate. Measurements occurred at 15-day intervals from first flowering.

### Biometric analysis

At 10, 17, 24, 31, and 38 days post-anthesis (DPA), 5 bolls from the 4th–6th fruiting branches (FB) were sampled per treatment for dimensional analysis (length × width) and biomass accumulation.

### Statistical analysis

Data underwent normality (Shapiro–Wilk test) and homoscedasticity (Levene's test) verification in SPSS 20.0 (IBM Corp., Armonk, USA) after initial processing in Excel 2022 (Microsoft Corp., Redmond, USA), and Shapiro–Wilk and Levene's test results was shown in Table S2. Data violating assumptions were log-transformed, and all analyzed data met parametric requirements. Significant differences identified through analysis of variance (ANOVA) prompted post-hoc multiple comparisons using Fisher's LSD test ( $\alpha=0.05$ ). For yield components, a two-way ANOVA was applied to the field experiment. One-way ANOVA was used for the column planting experiment. Optimal B application rates were determined using quadratic modeling (Q-model), where the B rate served as the independent variable and the yield as the dependent variable. Model fitting utilized the “ggplot2” package in R software (version 4.3.3; R Foundation for Statistical Computing, Vienna, Austria).

## Results

### Response of seed cotton yield and yield components to B fertilizer

Seed cotton yields for both cultivars across the field trial demonstrated unimodal responses to increasing B application rate (0–3.5 kg·hm<sup>-2</sup>). At Yancheng, maximum yields for CCRI 425 and Siza 3 occurred at 2.5 kg·hm<sup>-2</sup> of B, representing increases of 25.89% and 17.34%, respectively, relative to the no B application controls. Similarly, at Xinghua, peak yields occurred at 2.0 kg·hm<sup>-2</sup> of B, corresponding to enhancements of 14.75% (CCRI 425) and 20.58% (Siza 3). Economic

benefits followed parallel trends, with maximum benefits at optimal B rates: CCRI 425 (¥7 599.5 hm<sup>-2</sup>) and Siza 3 (¥4 560.2 hm<sup>-2</sup>) at 2.5 kg·hm<sup>-2</sup> of B at Yancheng; CCRI 425 (¥3 751.9 hm<sup>-2</sup>) and Siza 3 (¥5 617.4 hm<sup>-2</sup>) at 2.0 kg·hm<sup>-2</sup> of B at Xinghua (Table 1). Among yield components, boll number exhibited a substantially higher coefficient of variation (CV) (4.2%–6.6%) than boll weight per boll (0.9%–2.2%). ANOVA indicated a significant cultivar effect ( $P<0.05$ ) on both yield and components, while B application significantly influenced only yield and boll number.

### Optimal B application rates for two cotton varieties in field trials

The coefficients of determination ( $R^2$ ) for the Q model of optimal B fertilizer application rates in field trials for two varieties exceeded 0.82 ( $P<0.05$ ), revealing a critical agronomic threshold beyond which yield returns to B application diminished. CCRI 425 achieved maximum yields of 3 982 kg·hm<sup>-2</sup> (Yancheng) and 3 115 kg·hm<sup>-2</sup> (Xinghua) at 2.36 and 1.90 kg·hm<sup>-2</sup> of B, respectively (Fig. 1a). Siza 3 attained peak yields of 3 298 kg·hm<sup>-2</sup> (Yancheng) and 3 557 kg·hm<sup>-2</sup> (Xinghua) at 2.36 and 2.05 kg·hm<sup>-2</sup> of B, respectively (Fig. 1b). These results establish optimal B application ranges of 1.90–2.36 kg·hm<sup>-2</sup> for CCRI 425 and 2.05–2.36 kg·hm<sup>-2</sup> for Siza 3.

### Agronomic trait responses within optimal threshold ranges

Q-model identified B rates for minimizing boll abscission rates: CCRI 425 exhibited minima of 37.5% (Yancheng) and 31.7% (Xinghua) at 1.99 and 1.90 kg·hm<sup>-2</sup>, respectively (Fig. 2a). Siza 3 exhibited minima of 46.6% (Yancheng) and 25.8% (Xinghua) at 2.01 and 2.32 kg·hm<sup>-2</sup>, respectively (Fig. 2b). Boll numbers varied significantly ( $P<0.05$ ) with developmental stages under B fertilizer. Q-models indicated a non-linear relationship peaking within optimal B ranges: CCRI 425 attained maxima of 10.7 bolls·plant<sup>-1</sup> (Yancheng) and 13.8 (Xinghua) bolls·plant<sup>-1</sup> at 2.24 and 2.06 kg·hm<sup>-2</sup> of B, respectively (Fig. 3a). Siza 3 achieved 15.2 and 13.0 bolls·plant<sup>-1</sup> at 1.99 kg·hm<sup>-2</sup> of B in both locations (Fig. 3b). Boll size displayed developmental-stage-dependent responses. At 38 DPA, the B application significantly increased the maximum boll size by 16.9%–17.7% (CCRI 425) and 30.0%–30.8% (Siza 3) versus controls. Q-models demonstrated size maxima except for Siza 3 in Yancheng: CCRI 425 peaked at 18.1 cm<sup>3</sup> (Yancheng: 1.98 kg·hm<sup>-2</sup> of B) and 19.3 cm<sup>3</sup> (Xinghua: 2.11 kg·hm<sup>-2</sup> of B) (Fig. 3c), Siza 3 reached 14.8 cm<sup>3</sup> (Yancheng: 1.65 kg·hm<sup>-2</sup>) and 15.1 cm<sup>3</sup> (Xinghua: 2.03 kg·hm<sup>-2</sup>) (Fig. 3d).

### Validation of optimal B application rate in column planting trials

Vertical canopy-layer analysis in Nanjing revealed that the lower canopy (FB1–4) contributed 23.01% of total yield

**Table 1** Effect of boron rate on cotton yield, yield components, and economic benefits at Yancheng and Xinghua (Cultivars: CCRI 425 and Siza 3)

| Cultivars   | B rate /<br>(kg·hm <sup>-2</sup> ) | Yancheng                                                  |                   |                                                  |                                                 | Xinghua                                              |                   |                                                  |                                                 |
|-------------|------------------------------------|-----------------------------------------------------------|-------------------|--------------------------------------------------|-------------------------------------------------|------------------------------------------------------|-------------------|--------------------------------------------------|-------------------------------------------------|
|             |                                    | Boll number<br>/(10 <sup>4</sup><br>no.hm <sup>-2</sup> ) | Boll weight<br>/g | Seed cotton<br>yield /<br>(kg·hm <sup>-2</sup> ) | Economic<br>benefits /<br>(¥·hm <sup>-2</sup> ) | Boll number<br>/(10 <sup>4</sup> ·hm <sup>-2</sup> ) | Boll weight<br>/g | Seed cotton<br>yield /<br>(kg·hm <sup>-2</sup> ) | Economic<br>benefits /<br>(¥·hm <sup>-2</sup> ) |
| CCRI 425    | 0                                  | 81.9 e                                                    | 3.9 a             | 3 229 e                                          | –                                               | 61.3 d                                               | 4.5 a             | 2 800 c                                          | –                                               |
|             | 1.0                                | 89.1 d                                                    | 4.0 a             | 3 588 d                                          | 3 263.7 e                                       | 64.3 bc                                              | 4.6 a             | 2 980 b                                          | 1 634.8 c                                       |
|             | 1.5                                | 92.7 c                                                    | 4.1 a             | 3 833 bc                                         | 5 491.6 c                                       | 65.3 b                                               | 4.6 a             | 3 023 b                                          | 2 024.5 c                                       |
|             | 2.0                                | 97.2 b                                                    | 4.1 a             | 4 012 a                                          | 7 118.9 ab                                      | 71.2 a                                               | 4.5 a             | 3 213 a                                          | 3 751.9 a                                       |
|             | 2.5                                | 99.9 a                                                    | 4.1 a             | 4 065 a                                          | 7 599.5 a                                       | 69.3 a                                               | 4.5 a             | 3 104 a                                          | 2 758.4 b                                       |
|             | 3.0                                | 96.3 b                                                    | 4.1 a             | 3 973 ab                                         | 6 760.7 b                                       | 66.8 b                                               | 4.5 a             | 3 012 b                                          | 1 919.5 c                                       |
|             | 3.5                                | 89.1 d                                                    | 4.1 a             | 3 710 c                                          | 4 365.8 d                                       | 63.3 c                                               | 4.4 a             | 2 832 c                                          | 279.9 d                                         |
|             | CV/%                               | 6.6                                                       | 1.8               | 7.8                                              | 210.43                                          | 5.2                                                  | 1.4               | 4.8                                              | 414.19                                          |
| Siza 3      | 0                                  | 50.7 c                                                    | 5.7 a             | 2 895 d                                          | –                                               | 54.4 d                                               | 5.5 a             | 3 003 e                                          | –                                               |
|             | 1.0                                | 53.7 b                                                    | 5.7 a             | 3 073 c                                          | 1 616.6 d                                       | 60.3 b                                               | 5.5 a             | 3 360 c                                          | 3 245.5 c                                       |
|             | 1.5                                | 54.8 b                                                    | 5.7 a             | 3 171 b                                          | 2 506.8 c                                       | 62.8 b                                               | 5.4 a             | 3 454 b                                          | 4 099.3 b                                       |
|             | 2.0                                | 57.0 a                                                    | 5.8 a             | 3 341 a                                          | 4 052.2 a                                       | 66.3 a                                               | 5.4 a             | 3 621 a                                          | 5 617.4 a                                       |
|             | 2.5                                | 57.0 a                                                    | 5.9 a             | 3 397 a                                          | 4 560.2 a                                       | 64.8 a                                               | 5.5 a             | 3 571 a                                          | 5 160.7 a                                       |
|             | 3.0                                | 54.4 b                                                    | 5.9 a             | 3 257 ab                                         | 3 284.5 b                                       | 61.3 b                                               | 5.5 a             | 3 429 c                                          | 3 866.9 b                                       |
|             | 3.5                                | 52.2 bc                                                   | 6.0 a             | 3 149 bc                                         | 2 300.1 c                                       | 57.9 c                                               | 5.5 a             | 3 236 d                                          | 2 109.0 d                                       |
|             | CV/%                               | 4.2                                                       | 2.2               | 5.3                                              | 213.61                                          | 6.6                                                  | 0.9               | 6.2                                              | 230.20                                          |
| Variety (V) |                                    | ***                                                       | **                | ***                                              | ***                                             | *                                                    | *                 | *                                                | *                                               |
| Boron (B)   |                                    | ***                                                       | ns                | ***                                              | ***                                             | ***                                                  | ns                | ***                                              | ***                                             |
| V×B         |                                    | ***                                                       | ns                | ***                                              | ***                                             | *                                                    | ns                | *                                                | *                                               |

CV coefficient of variation; One-way ANOVA: different lowercases within the same variety and column indicate significant difference among B application rates ( $P < 0.05$ ); Two-way ANOVAs: \*\*\*, \*\*, \*, and ns represent the  $P < 0.001$ , 0.01, 0.05, and  $> 0.05$ , respectively

and achieved maximum productivity (22.73% increase) at 2.5 kg·hm<sup>-2</sup> of B. The middle canopy (FB5–8), accounting for 47.72% of total yield, peaked at 17.65% higher productivity under this rate. The upper canopy (FB9+), representing 29.14% of yield, was optimized at a 22.14% increase with 2.5 kg·hm<sup>-2</sup> of B. B application significantly influenced boll number and seed cotton weight per boll across sites ( $P < 0.05$ ). Boll number exhibited a higher CV than boll weight, with lower canopy branches exhibiting greater boll densities. Maximum increases in boll number (14.7%) and boll weight (3.9%) occurred predominantly at 2.5 kg·hm<sup>-2</sup> of B (Table 2). CCRI 425 in Nanjing reached its peak at 2.25 kg·hm<sup>-2</sup> of B, yielding 57.6 g·plant<sup>-1</sup>, aligning with the established optimal range (Fig. 4a). Q-models further identified critical optima within this range: minimum boll abscission rate (56.40%) at 2.17 kg·hm<sup>-2</sup> of B (Fig. 4b), maximum boll number (11.9 plant<sup>-1</sup>) at 2.15 kg·hm<sup>-2</sup> of B (Fig. 4c), peak boll size (21.3 cm<sup>3</sup>) at 1.97 kg·hm<sup>-2</sup> of B (Fig. 4d).

Discussion

B deficiency remains a key limiting factor for yield in cotton cultivation systems. This study examined two cotton varieties with distinct growth cycles under different soil types in the Yangtze River Basin. The region's

soil B concentration (0.24–0.36 mg·kg<sup>-1</sup>) falls within a range exhibiting high fertility responsiveness (Xu et al. 2017). Both cultivars exhibited significant yield enhancements with B supplementation, with seed cotton yields increasing by 25.89% (CCRI 425) and 17.34% (Siza 3) at Yancheng and 14.74% (CCRI 425) and 20.58% (Siza 3) at Xinghua relative to no B application controls. These responses underscore B as a primary yield-limiting factor under local conditions. While supplemental B fertilizer mitigates yield declines in B-deficient areas, the exceptionally narrow therapeutic window between B deficiency ( $< 0.5$  kg·hm<sup>-2</sup>) and toxicity ( $> 2.0$  kg·hm<sup>-2</sup>) thresholds demands precise optimization to maximize yield and resource efficiency (Brdar-Jokanovic 2020). Under-application constrains yield potential, while over-application risks phytotoxicity in subsequent crops (Bogiani et al. 2014). Compounding this challenge, substantial spatial heterogeneity in soil B availability across edaphic and climatic gradients necessitates location-specific management strategies (Garcia-Sanchez et al. 2020).

The significantly higher coefficient of CV for boll number (4.2%–6.6%) versus boll weight (0.9%–2.2%) (Table 2) indicates boll number's greater sensitivity to environmental fluctuations, establishing it as the principal yield

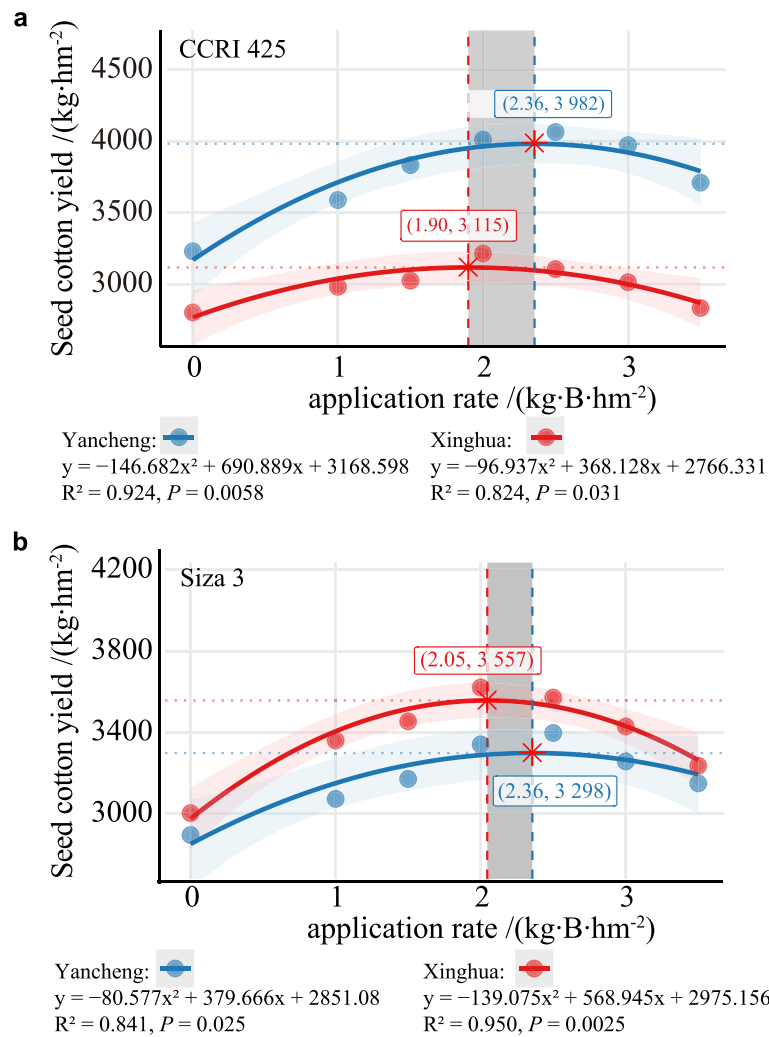


**Fig. 1** Quadratic relationships between B application rate and seed cotton yield. Response curves for CCRI 425 (**a**) and Siza 3 (**b**) at Yancheng and Xinghua. Asterisk denotes yield maxima. Gray shading indicates optimal B ranges

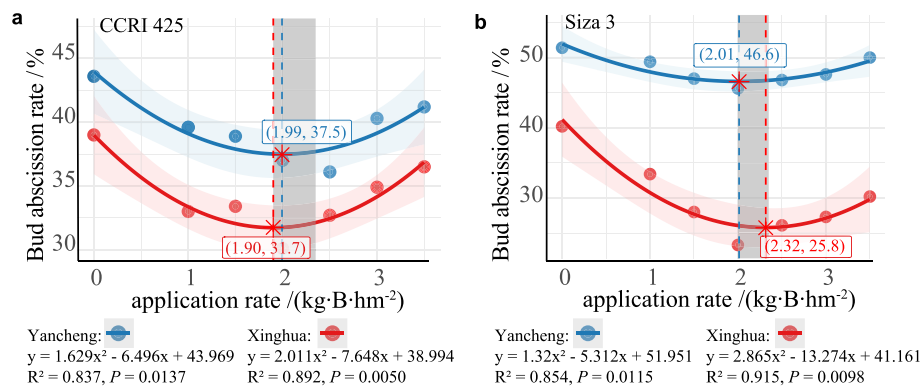


**Fig. 2** Quadratic relationships between B application rate and bud abscission rate. Response curves for CCRI 425 (**a**) and Siza 3 (**b**) at Yancheng and Xinghua. Asterisks denote bud abscission rate minimum. Gray shading indicates optimal B ranges

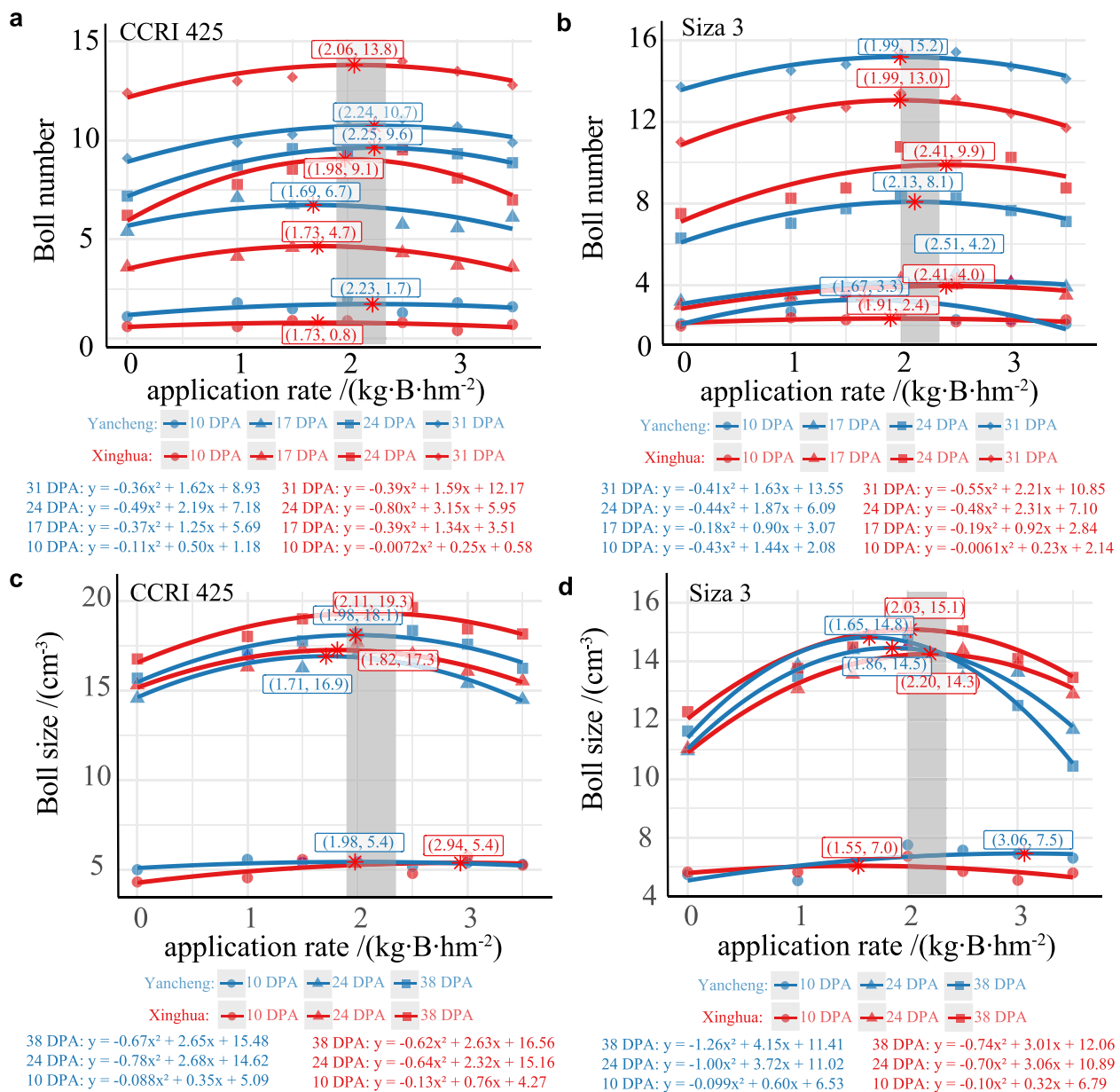


**Fig. 3** B-dependent optimization of boll number and size. Quadratic relationships between B application rate and boll number and boll size. Response curves for CCRI 425 (**a**, **c**) and Siza 3 (**b**, **d**) at Yancheng and Xinghua. DPA days post-anthesis. Asterisks denote boll number and boll size maxima. Gray shading indicates optimal B ranges

determinant. Boll abscission, a natural adaptive mechanism, accounts for 70% of the total number of nodes (Ertok et al. 2003). Intercellular separation in abscission zones constitutes the primary mechanism (Gupta et al. 2020), with histological evidence showing connective tissue fractures in shed bolls (Yu et al. 2024). Boron deficiency increases boll shedding rates. Boron deficiency induces the formation of brown petiole rings, which impede phloem transport and photosynthetic efficiency, compromise cell wall integrity, and disrupt hormonal regulatory

mechanisms (Chen et al. 2023; Li et al. 2017; Lilay et al. 2024; Voxeur et al. 2014). B facilitates photoassimilate translocation to reproductive sinks (Panter et al. 2023), supporting boll development and biomass accumulation (Wahid et al. 2020). Adequate B ensures cell wall integrity through the formation of the rhamnogalacturonan II-B (RG-II-B) complex, therefore stabilizing the pectin network and regulating cell division (Gimeno et al. 2012). Furthermore, B's role in nucleic acid metabolism, carbohydrate allocation, phenolic metabolism, and plant

**Table 2** Canopy-stratified yield response to B fertilization (Nanjing, CCRI 425)

| B rate /<br>(kg·hm <sup>-2</sup> ) | Boll number per plant |       |        |        | Boll weight /g |        |        |         | Seed cotton yield per plant /g |         |        |        |
|------------------------------------|-----------------------|-------|--------|--------|----------------|--------|--------|---------|--------------------------------|---------|--------|--------|
|                                    | FB1–4                 | FB5–8 | FB9+   | Total  | FB1–4          | FB5–8  | FB9+   | Average | FB1–4                          | FB5–8   | FB9+   | Total  |
| 0                                  | 2.2 c                 | 4.5 b | 2.8 c  | 9.5 c  | 5.0 b          | 5.3 b  | 5.0 b  | 5.1 a   | 11.0 d                         | 23.8 c  | 14.0 c | 48.8 d |
| 1.0                                | 2.4 b                 | 4.8 a | 3.0 b  | 10.2 b | 5.1 ab         | 5.4 ab | 5.1 ab | 5.2 a   | 12.2 c                         | 25.9 b  | 15.3 b | 53.4 c |
| 1.5                                | 2.5 ab                | 4.9 a | 3.2 a  | 10.6 a | 5.2 a          | 5.5 a  | 5.1 ab | 5.3 a   | 13.0 bc                        | 26.9 ab | 16.3 a | 56.2 b |
| 2.0                                | 2.6 a                 | 4.9 a | 3.2 a  | 10.7 a | 5.2 a          | 5.6 a  | 5.2 a  | 5.3 a   | 13.5 b                         | 27.4 a  | 16.6 a | 57.5 a |
| 2.5                                | 2.6 a                 | 5.0 a | 3.3 a  | 10.9 a | 5.2 a          | 5.6 a  | 5.2 a  | 5.3 a   | 13.5 a                         | 28.0 a  | 17.1 a | 58.6 a |
| 3.0                                | 2.5 ab                | 5.0 a | 3.3 a  | 10.8 a | 5.1 ab         | 5.5 a  | 5.1 ab | 5.2 a   | 12.7 c                         | 27.5 a  | 16.8 a | 57.0 a |
| 3.5                                | 2.4 b                 | 4.8 a | 3.1 ab | 10.3 b | 5.0 b          | 5.5 a  | 5.0 b  | 5.1 a   | 12.0 c                         | 26.4 b  | 15.5 b | 53.9 c |
| CV/%                               | 5.6                   | 3.5   | 5.7    | 4.6    | 1.7            | 1.9    | 1.6    | 1.6     | 7.2                            | 10.1    | 9.2    | 10.0   |

CV coefficient of variation; One-way ANOVA: different lowercases within the column indicate significant difference among B application rates ( $P < 0.05$ )

hormone regulation enhances the tolerance to boll shedding, thereby ensuring yield stability (Papadakis et al. 2018). The observed abscission reduction with optimal B application aligns with studies showing 63%–75% boll number increases following foliar B supplementation (Mehran et al. 2023; Wahid et al. 2020).

Fertilizer efficiency models provide a robust framework for optimizing input-productivity relationships. Q-models represent established tools for single-nutrient optimization (Luo et al. 2024). Crop yield response depends not only on applied B but also on indigenous soil B supply, which represents a key determinant requiring further characterization for effective management (Ahmed et al. 2018). Site-specific yield variability in this study ( $R^2 > 0.82$ ) reflected differences in native B availability, with diminishing returns beyond optimal thresholds due to bioavailability constraints, cultivar-specific uptake saturation, and incipient phytotoxicity (Simón et al. 2013). The Q-models quantified optimal B application rates at 1.90–2.36 kg·hm<sup>-2</sup> in CCRI 425 and at 2.05–2.36 kg·hm<sup>-2</sup> in Siza 3, highlighting the necessity of balancing soil B availability with cultivar-specific demand to optimize yield and resource efficiency. The observed rate discrepancies between Yancheng and Xinghua further demonstrate how edaphic and climatic factors mediate B efficacy. Available B content, organic matter, pH, and texture are key determinants of soil properties affecting B fertilizer use efficiency. The yield-enhancing effect of B application response inversely correlates with native B levels, peaking under deficiency (Cordeiro et al. 2022). Organic matter exhibits parabolic efficiency relationships, with moderate concentrations optimizing B availability (Atique-ur-Rehman et al. 2018). Fine-textured soils enhance B retention, while coarse-textured soils increase leaching risk (Cordeiro et al. 2024). Bioavailability peaks in acidic-neutral soils, declining sharply under alkalinity. Thermal (25–30 °C optimum) and hydrological regimes further

modulate B utilization. Suboptimal temperatures (< 25 °C) limited root function, while B mitigates heat stress (> 30 °C) via antioxidant activation (Dusenge et al. 2019; Yeates et al. 2010). These findings reinforce the imperative for soil-specific B management strategies to maximize cotton productivity (Liu et al. 2024).

Column-planting trials for CCRI 425 in Nanjing (2.25 kg·hm<sup>-2</sup> of B) verified the theoretical optima while revealing significant location-dependent variations in cultivar response (Fig. 4). Column-planting trials revealed vertical canopy partitioning of B responses, with the middle (FB5–8; 48.22% yield contribution) and upper (FB9+) canopies showing greater sensitivity than lower strata (FB1–4) (Table 2). This gradient may reflect restricted B phloem mobility limiting redistribution; upper canopy deficits arise from B's phloem immobility, preventing redistribution from lower strata (Landi et al. 2019; Oikonomou et al. 2019). Further investigation is warranted to elucidate the physiological mechanisms underlying this stratification.

Our findings indicate that B supplementation is an important measure to alleviate soil B deficiency, including cotton yield, boll abscission rate, boll number, and boll size. This is of great significance for understanding the promotional effect of B on cotton. However, we are also aware of certain limitations. First, this was a short-term field trial (2020–2021), and climatic factors significantly influenced the effects of B application, potentially leading to large interannual variability. Additionally, site representation, though covering major cotton areas in Jiangsu, requires expansion to national growing regions. Future research should: (1) implement precise soil B diagnostics across China's three primary cotton zones; (2) evaluate alternative application methods (e.g., foliar fertilizer, controlled-release formulations) to overcome soil-mediated limitations; and (3) investigate cellular/hormonal mechanisms governing B-modulated abscission.

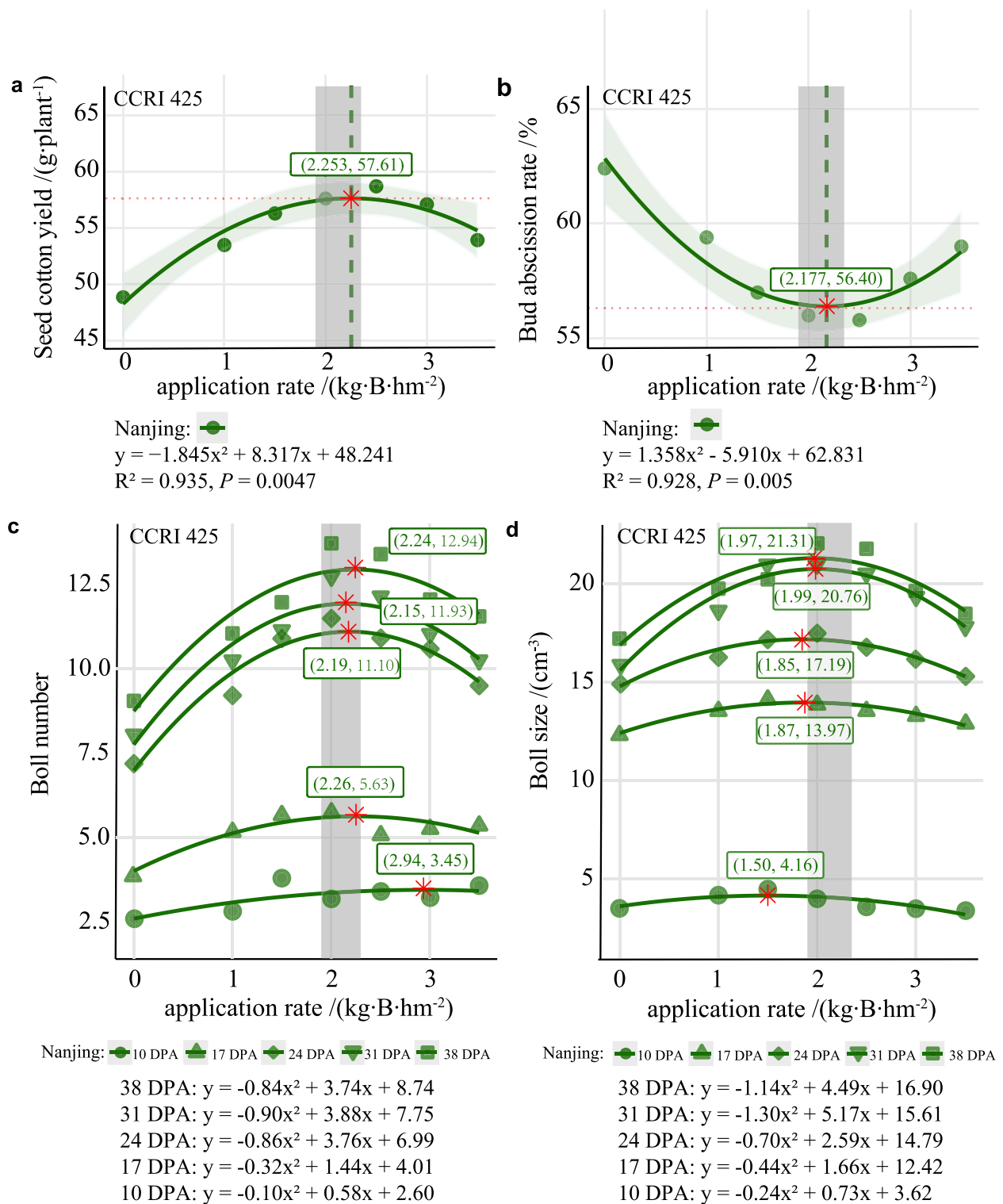


**Fig. 4** Validation of optimal B rates for CCRI 425 in column trials (Nanjing). Quadratic relationships between B application rate and seed cotton yield (**a**), and bud abscission rate (**b**), and boll number (**c**), and boll size (**d**) for CCRI 425 at Nanjing. Asterisks denote yield, boll number and boll size maxima, and bud abscission rate minimum. Gray shading indicates optimal B ranges

## Conclusion

Supplemental B fertilizer significantly enhances seed yield (14.7%–25.8%) through optimized modulation of yield components, particularly boll number. Q modeling established cultivar-specific optimal B application rates as 1.90–2.36 kg·hm<sup>-2</sup> of B for CCRI 425 and 2.05–2.36 kg·hm<sup>-2</sup> of B for Siza 3. Within these thresholds, critical agronomic traits, including boll number, boll abscission rate, and boll size, achieved physiological optima. Vertical canopy analysis revealed the middle canopy (FB5–8) contributed 48.22% of the total yield and responded most significantly to B fertilization. These findings underscore the necessity of implementing location-specific and cultivar-tailored B management strategies to simultaneously maximize yield potential in intensive cotton production systems.

## Supplementary Information

The online version contains supplementary material available at <https://doi.org/10.1186/s42397-026-00257-1>.

Supplementary Material 1: Table S1. Basic soil nutrient contents in the 0–20 cm depth before starting experiment. Figure S1. Meteorological data of the experimental sites. Daily maximum air temperature, minimum air temperature and mean air temperature as well as precipitation during cotton growth seasons in 2020 in Yancheng (a), Xinghua (b) and in 2021 in Nanjing (c). Table S2. Shapiro-Wilk and Levene's test results.

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## Authors' contributions

Conceptualization: Hu W; Data collection: Wang SS, Wang C, Zhang YT, and Liang XJ; Formal analysis: Wang SS and Hu W; Funding acquisition: Hu W; Investigation: Wang SS, Wang C, Zhang YT, and Liang XJ; Methodology: Wang SS and Wang C; Writing—original draft: Wang SS, Wang C, and Zhang YT; Writing—review and editing: Wang SS, Wang C, and Hu W. All authors have read and agreed to the final version of the manuscript.

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## Data availability

All relevant data are within this article.

## Declarations

### Ethics approval and consent to participate

Not applicable.

### Consent for publication

Not applicable.

### Competing interests

The authors declare that they have no conflict of interest. Authors Zhou ZG and Hu W are members of the Editorial Board of *Journal of Cotton Research*. Authors Zhou ZG and Hu W were not involved in the journal's review of, or decision related to this manuscript.

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