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Effects of Nitrogen, Phosphorus and Potassium Fertilization on Cotton Yield and Fertilizer Use Efficiency in Xinjiang, China

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Abstract

Nitrogen (N), phosphorus (P), and potassium (K) are important nutrients limiting cotton yield. Although N, P, and K fertilization is an important practice for improving cotton productivity, their fertilizer use efficiencies remain insufficiently evaluated in Xinjiang, China. In this study, field experiments were conducted at 57 sites across the major cotton-growing areas of Xinjiang during 2021–2022. Four fertilization treatments, PK, NK, NP, and NPK, were established to evaluate cotton yield response, nutrient accumulation, and fertilizer use efficiencies of N, P, and K under different soil fertility conditions. The results indicated that the cotton yield in both southern and northern Xinjiang significantly increased under NPK treatment, with mean yields of 6300 and 7361 kg ha⁻¹, respectively. The use efficiencies of N, P, and K were 39.8%, 19.5%, and 51.4% in southern Xinjiang, and 40.3%, 20.2%, and 66.1% in northern Xinjiang, respectively. For every 100 kg of seed cotton produced, nutrient uptake was 4.64 kg N, 1.43 kg P₂O₅, and 3.67 kg K₂O in southern Xinjiang, and 4.74 kg N, 1.48 kg P₂O₅, and 4.58 kg K₂O in northern Xinjiang, indicating relatively high N and K requirements but lower P demand in cotton production. Cotton yield in southern Xinjiang was significantly and positively correlated with soil alkali-hydrolyzable N. In northern Xinjiang, cotton yield was significantly and positively correlated with soil organic matter, alkali-hydrolyzable N, and available K, but negatively correlated with available P. Overall, cotton yield was mainly positively affected by soil organic matter, alkali-hydrolyzable N, and available K, whereas K use efficiency was significantly and negatively correlated with N and K rates. The suitable N, P, and K rates for cotton were 285, 120, and 106 kg ha⁻¹ in southern Xinjiang, and 243, 101, and 91 kg ha⁻¹ in northern Xinjiang, respectively. Based on soil fertility classification of cotton fields, the recommended N, P, and K rates were 256–313, 96–117, and 125–153 kg ha⁻¹ in southern Xinjiang, and 219–267, 97–119, and 136–166 kg ha⁻¹ in northern Xinjiang, respectively. Accordingly, reducing N and P inputs in southern Xinjiang, maintaining N and P at appropriate levels in northern Xinjiang, and moderately increasing K are recommended to achieve coordinated improvements in yield stability and N, P, and K use efficiencies.

Keywords: fertilization rate; fertilizer contribution rate; nutrient uptake; soil fertility; yield response

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1. Introduction

Xinjiang is the largest commercial cotton-producing region in the world, where cotton cultivation occupies approximately one-third of the region's arable land [1]. In 2025, Xinjiang had a cotton sown area of 2.592×10^6 ha and produced 6.165×10^6 Mg of cotton lint, accounting for 92.8% of China's total cotton output [2]. Cotton is a pillar industry of Xinjiang agriculture, and approximately 50% of local farmers are engaged in cotton production [1]. Cotton production requires substantial inputs of N, P, and K fertilizers, with P and K rates commonly expressed as P_2O_5 and K_2O , respectively [3,4]. Inappropriate fertilization can reduce cotton yield and limit improvements in fertilizer use efficiency. Long-term experience-based fertilization has led to irrational nutrient management in mulched drip-irrigated cotton fields in Xinjiang, resulting in NPK imbalance, reduced field productivity, soil quality degradation, and lower farm income [5,6]. Therefore, systematically evaluating the effects of N, P, and K fertilization on cotton yield and fertilizer use efficiency across Xinjiang and its major cotton-growing regions is important for determining rational fertilization rates, improving yield and economic benefits, reducing nutrient losses, enhancing fertilizer use efficiency, and ensuring stable and high cotton production [3,6].

Appropriate N application can ensure sufficient N accumulation during cotton growth, optimize physiological metabolism, promote P and K uptake and utilization, and ultimately increase yield [7,8]. Rational N, P, and K management helps coordinate vegetative and reproductive growth and is essential for improving cotton yield and fiber quality [4,9]. Under medium-to-low fertilizer input conditions (N, 180–300 kg ha⁻¹, P_2O_5 , 120–150 kg ha⁻¹, and K_2O , 90–150 kg ha⁻¹), N, P, and K often exhibit synergistic effects, jointly promoting reproductive growth and yield formation in cotton [4,9]. In contrast, excessive fertilization may cause nutrient imbalance and antagonism, suppress growth and yield, and aggravate nutrient accumulation and losses through irrigation drainage, thereby increasing the risks of groundwater contamination and environmental degradation [3,10]. In cotton production systems, nitrogen use efficiency, agronomic efficiency, and partial factor productivity generally decline with increasing N application rates [8]. Maintaining K application within 90–150 kg ha⁻¹ can promote nutrient uptake and utilization across cotton organs, thereby supporting high yield and efficient nutrient use [4,11]. In cotton fields with low indigenous soil nutrient supply, appropriate increases in N, P, and K inputs remain necessary to meet crop nutrient demand and sustain yield [4,11]. However, studies on cotton fertilization in Xinjiang are mostly based on scattered field experiments conducted under specific soil, irrigation, and management conditions [4–6]. Although these studies have supported local cotton production, substantial variation in experimental designs and baseline soil fertility across studies, together with the predominance of continuous cotton monocropping without crop rotation in Xinjiang, limits their ability to represent the current status of N, P, and K fertilization and nutrient use efficiency in Xinjiang and its major cotton-producing regions [4,6,12]. Under fertigation and soil-testing-based nutrient management, systematic evidence on cotton yield, nutrient use efficiency, and region-specific optimal fertilization rates remains limited [4,6,8], thereby constraining the sustainable development of Xinjiang's cotton industry [1,8].

During 2021–2022, 57 field fertilization experiments were conducted within the Xinjiang Uygur Autonomous Region, China, covering its two major cotton-growing sub-regions: southern Xinjiang and northern Xinjiang. In this study, nutrient recovery efficiency was used to evaluate the proportion of applied nutrients taken up by cotton, whereas agronomic efficiency was used to assess the yield increase per unit of fertilizer input. This study aimed to quantify the effects of N, P, and K fertilization on cotton

yield, yield response, and aboveground nutrient accumulation; compare N, P, and K recovery efficiencies and agronomic efficiencies between the two subregions and among different soil fertility levels; and identify fertilization strategies suitable for southern and northern Xinjiang under different soil fertility conditions to improve cotton yield stability and fertilizer use efficiency.

2. Materials and Methods

2.1. Study Area

Xinjiang (34°25′–48°10′ N, 73°40′–96°18′ E) is located in northwestern China and is characterized by a temperate continental arid climate, with an annual mean temperature of 9–12 °C, annual precipitation of 164.7 mm mainly occurring from June to August, annual sunshine duration of 2550–3550 h, and a frost-free period of 180–220 d. The major soil types include gray desert soil, brown calcic soil, chestnut calcic soil, black calcic soil, saline soil, and aeolian sandy soil [13,14]. Xinjiang is one of the most important cotton-producing regions in China and worldwide. The Tianshan Mountains serve as a climatic boundary, dividing the cotton-producing region into southern and northern Xinjiang cotton-growing areas [15].

2.2. Soil Sampling and Soil Fertility Classification

Before cotton planting and the establishment of fertilization treatments, composite soil samples were collected from the 0–20 cm plow layer at each experimental site using the five-point sampling method. After air-drying, grinding, and sieving, soil pH, organic matter, alkali-hydrolyzable N, available P, and available K were determined following standard soil agrochemical analysis methods [16]. Alkali-hydrolyzable N was measured using the alkaline hydrolysis diffusion method, available P was determined using the molybdenum-antimony colorimetric method, available K was measured using flame photometry, and soil organic matter was determined using the oil-bath heating potassium dichromate oxidation method. These soil properties were used to characterize the initial soil conditions at each experimental site (Table 1).

Table 1. Basic physicochemical properties of soils at the field experimental sites.

Soil Indicator	Southern Xinjiang (<i>n</i> = 22)		Northern Xinjiang (<i>n</i> = 35)		Xinjiang as a Whole (<i>n</i> = 57)	
	Mean ± SD	CV (%)	Mean ± SD	CV (%)	Mean ± SD	CV (%)
pH	8.1 ± 0.4	5.2	8.3 ± 0.3	3.2	8.2 ± 0.4	4.2
OM (g kg ^{−1})	12.3 ± 5.8	47.3	12.2 ± 5.0	41.3	12.2 ± 5.3	43.3
AN (mg kg ^{−1})	54.5 ± 19.3	35.4	61.1 ± 20.7	33.9	58.5 ± 20.2	34.6
AP (mg kg ^{−1})	25.2 ± 13.7	54.2	20.8 ± 14.1	67.8	22.5 ± 14.0	62.1
AK (mg kg ^{−1})	149.3 ± 55.5	37.2	188.1 ± 70.7	37.6	173.1 ± 67.5	39.0

Note: *n*, sample size; SD, standard deviation; CV, coefficient of variation; OM, organic matter; AN, alkali-hydrolyzable nitrogen; AP, available phosphorus; AK, available potassium. The same applies below.

Following the nutrient grading criteria of the Second National Soil Survey of China [14], the same soil indicators were used to evaluate soil fertility. Principal component analysis (PCA) was performed using SPSS 26.0 software to determine the weights of

each indicator, and the integrated fertility index (IFI) was calculated in Microsoft Excel 2021 based on the additive-multiplicative principle of fuzzy mathematics [17]. Based on the IFI, soil fertility across the major cotton-producing regions of Xinjiang was classified into five levels (Table 2) [18]. For subsequent yield and fertilizer use efficiency analyses, the sampled cotton fields were further grouped into three fertility classes: low fertility ($IFI \leq 0.4$), medium fertility ($0.4 < IFI \leq 0.6$), and high fertility ($IFI > 0.6$).

Table 2. Soil fertility index grading standards.

Integrated Fertility Index (IFI)	Fertility Evaluation	Fertility Grade
$IFI > 0.7$	Excellent	I
$0.6 < IFI \leq 0.7$	Good	II
$0.5 < IFI \leq 0.6$	Moderate	III
$0.4 < IFI \leq 0.5$	Poor	IV
$IFI \leq 0.4$	Very poor	V

2.3. Experimental Treatment Setup and Implementation

2.3.1. Experimental Site Layout and Crop Management

The 57 experimental sites were distributed across nine prefecture-level regions in Xinjiang (Figure 1). These sites covered the northern Xinjiang cotton region, including Hami City, Tacheng Prefecture, Changji Hui Autonomous Prefecture, Bortala Mongol Autonomous Prefecture, and Turpan City, and the southern Xinjiang cotton region, including Bayingolin Mongol Autonomous Prefecture, Aksu Prefecture, Hotan Prefecture, and Kashgar Prefecture.

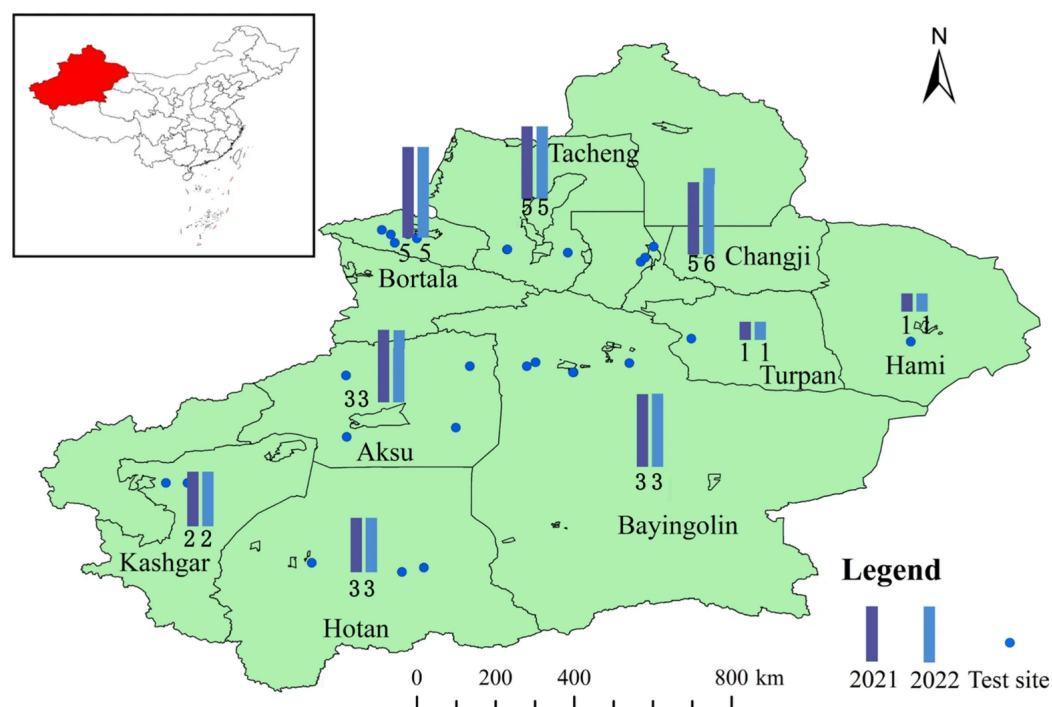


Figure 1. Distribution map of field experimental sites in Xinjiang. Blue dots (·) indicate independent experimental sites; bar charts show the distribution of experimental sites across regions in 2021 and 2022. The numbers of experimental sites in southern Xinjiang, northern Xinjiang, and Xinjiang as a whole were 22, 35, and 57, respectively.

At each of the experimental sites shown in Figure 1, a representative local cotton field was selected. Cotton was grown under a mulched drip irrigation system with a one-mulch, six-row, three-drip-tape layout, a mulch width of 2.05 m, and a wide–narrow row configuration, with wide and narrow row spacings of 66 and 10 cm, respectively. The plant spacing was 10 cm, corresponding to a sowing density of 2.63×10^5 plants ha^{-1} . Locally predominant cotton cultivars, including Xinluzhong 73, Xinluzhong 87, and Xin 84, were used. Cultivar and planting density were not included as experimental factors, and all treatments within the same experimental site used the same cultivar, planting pattern, irrigation regime, and field management practices. Fertilizer effect-related indices were calculated as the differences between the NPK treatment and the corresponding nutrient omission treatments within the same experimental site, thereby eliminating the interference caused by differences in baseline field conditions among experimental sites.

Cotton was sown in April and harvested in October. A total of 10–12 irrigations were applied throughout the growing season at 7–10 d intervals, with an irrigation volume of approximately $338\text{--}462 \text{ m}^3 \text{ ha}^{-1}$ per event and a total irrigation amount of 406–462 mm in southern Xinjiang, and $358\text{--}440 \text{ m}^3 \text{ ha}^{-1}$ per event and 430–440 mm in total in northern Xinjiang [19,20]. All other management practices followed conventional cotton farming protocols in Xinjiang.

2.3.2. Nutrient Omission Treatments and Fertilizer Application

Field nutrient omission experiments were conducted at each experimental site according to the “Technical Specification (Trial) for Estimating Fertilizer Use Efficiency of the Three Major Grain Crops Based on Field Experiments” issued by the Ministry of Agriculture and Rural Affairs of China [21]. A randomized complete block design (RCBD) was used, with four fertilization treatments: (1) PK treatment, with no N application, representing N-omission; (2) NK treatment, with no P application, representing P omission; (3) NP treatment, with no K application, representing K-omission; and (4) NPK treatment, with combined N, P, and K application, representing complete fertilization. In each nutrient omission treatment, the omitted nutrient was not applied during either basal fertilization or topdressing, whereas the remaining nutrients were applied at the same rates, timing, and methods as in the NPK treatment. Each treatment was established with three replicate plots, resulting in a total of 12 experimental plots at each experimental site. Each plot covered an area of $30\text{--}50 \text{ m}^2$, with the long side arranged parallel to the cotton planting rows, and a 2-m-wide isolation buffer zone was established between adjacent plots.

Southern Xinjiang included 264 plots ($22 \text{ sites} \times 4 \text{ treatments} \times 3 \text{ replicates}$), with 66 replicated plots for each treatment. Northern Xinjiang included 420 plots ($35 \text{ sites} \times 4 \text{ treatments} \times 3 \text{ replicates}$), with 105 replicated plots for each treatment. Across Xinjiang, a total of 684 plots were established, with 171 replicated plots for each treatment. For regional-scale analyses, the measured values from the three replicated plots of the same treatment at each experimental site were averaged and used as one independent site-level observation. The independent sample sizes for southern Xinjiang, northern Xinjiang, and Xinjiang as a whole were 22, 35, and 57, respectively.

Before fertilization, the conventional fertilizer application rates used by local large-scale cotton growers were surveyed to ensure that the N, P, and K application rates at each experimental site reflected local production practices (Figure 2 and Table 3). Urea (46% N), triple superphosphate (46% P_2O_5), and potassium sulfate (50% K_2O) were used as the N, P, and K fertilizer sources, respectively. Urea was applied as 40% basal fertilizer and 60% topdressing; triple superphosphate was applied entirely as basal fertilizer; and

potassium sulfate was applied as 60% basal fertilizer and 40% topdressing. Topdressed fertilizers were applied through the drip irrigation system at the squaring, flowering, and boll-setting stages of cotton. Topdressed N and K fertilizers were injected into irrigation water through a fertilizer tank. Except for the fertilization treatments, the experimental layout and field management practices were consistent across all treatments.

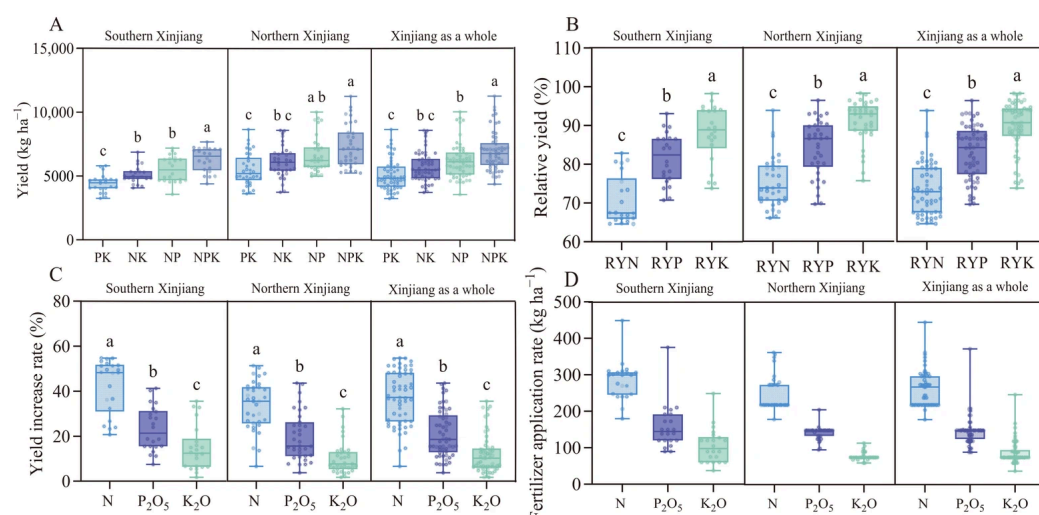


Figure 2. Fertilizer application rates and cotton yield responses in Xinjiang. **(A)** Seed cotton yield; **(B)** relative yield; **(C)** yield increase rate; **(D)** N, P₂O₅, and K₂O application rates. PK, NK, NP, and NPK, N-omission, P-omission, K-omission, and complete NPK treatments, respectively; RYN, RYP, and RYK, relative yields under N-, P-, and K-omission treatments, respectively. In the box-plots, boxes indicate the interquartile range, horizontal lines indicate medians, whiskers indicate non-outlier ranges, and circles indicate site-level observations. Different lowercase letters indicate significant differences among treatments or nutrient indices within the same region based on Tukey's HSD test ($p < 0.05$). Fertilizer application rates in panel **(D)** were preset inputs and were not statistically compared.

Table 3. Descriptive statistics of fertilizer application rates at the experimental sites.

Nutrient	Southern Xinjiang ($n = 22$)		Northern Xinjiang ($n = 35$)		Xinjiang as a Whole ($n = 57$)	
	Mean $\pm$ SD	CV (%)	Mean $\pm$ SD	CV (%)	Mean $\pm$ SD	CV (%)
N (kg ha ⁻¹)	284.2 $\pm$ 53.4	18.8	252.8 $\pm$ 46.2	18.3	264.9 $\pm$ 51.0	19.3
P ₂ O ₅ (kg ha ⁻¹)	157.2 $\pm$ 61.7	39.3	143.7 $\pm$ 18.6	12.9	148.9 $\pm$ 41.0	27.5
K ₂ O (kg ha ⁻¹)	105.6 $\pm$ 48.1	45.5	79.5 $\pm$ 10.6	13.3	89.5 $\pm$ 33.2	37.0

2.3.3. Plant Sampling and Measurements

Cotton plant sample collection and pretreatment were conducted according to the agricultural industry standard “Technical Specification for Soil Testing and Fertilizer Recommendation” to ensure consistent procedures for plant sampling, organ separation, yield determination, and nutrient analysis across all experimental sites [22]. At cotton maturity in 2021 and 2022, three representative cotton plants were selected from each replicated plot as within-plot plant subsamples, and their aboveground parts were separated into seed cotton, stems, leaves, empty bolls, and abscised residues. Meanwhile, all seed cotton in each plot was manually harvested to determine seed cotton yield. Total N,

total P, and total K contents in the aboveground organs were determined using the Kjeldahl method, molybdenum-antimony colorimetry, and flame photometry, respectively [16].

2.3.4. Calculation of Yield Response and Fertilizer Use Efficiency Indices

Based on the nutrient omission treatments described in Section 2.3.2, indices were calculated to quantify cotton yield response, nutrient accumulation, and fertilizer use efficiency under N, P, and K fertilization. YPK, YNK, YNP, and YNPK denote seed cotton yields (kg ha^{-1}) under the PK, NK, NP, and NPK treatments, respectively, whereas NAR, PAR, and KAR denote the application rates of N, P_2O_5 , and K_2O , respectively. Taking N as an example, the indices were calculated as follows.

The relative yield under N-omission (RYN, %) was calculated using Equation (1):

$$\text{RYN} = \frac{\text{YPK}}{\text{YNPK}} \times 100 \quad (1)$$

The yield response to N fertilization (YRN, kg ha^{-1}) was calculated using Equation (2):

$$\text{YRN} = \text{YNPK} - \text{YPK} \quad (2)$$

The agronomic efficiency of N (AEN, kg kg^{-1}) was calculated using Equation (3):

$$\text{AEN} = \frac{\text{YNPK} - \text{YPK}}{\text{NAR}} \quad (3)$$

The partial factor productivity of N (PFPN, kg kg^{-1}) was calculated using Equation (4):

$$\text{PFPN} = \frac{\text{YNPK}}{\text{NAR}} \quad (4)$$

The fertilizer contribution rate of N (FCRN, %) was calculated using Equation (5):

$$\text{FCRN} = \frac{\text{YNPK} - \text{YPK}}{\text{YNPK}} \times 100 \quad (5)$$

Total aboveground nutrient accumulation (U, kg ha^{-1}) was calculated using Equation (6):

$$U = \sum_{i=1}^n (\text{DM}_i \times C_i) \quad (6)$$

where DM_i is the dry matter of the i -th aboveground organ (kg ha^{-1}), C_i is the nutrient concentration of the corresponding organ (kg kg^{-1}), and n is the number of aboveground organs included in the calculation.

The yield increase rate (YIRN, %) was calculated using Equation (7):

$$\text{YIRN} = \frac{\text{YNPK} - \text{YPK}}{\text{YPK}} \times 100 \quad (7)$$

The N recovery efficiency (NUE, %) was calculated using Equation (8):

$$\text{NUE} = \frac{U_{\text{YNPK}} - U_{\text{YPK}}}{\text{NAR}} \times 100 \quad (8)$$

where U_{YNPK} and U_{YPK} denote the aboveground N accumulation under the complete NPK treatment and the N-omission (PK) treatment, respectively. The corresponding P-related indices (RYP, YRP, AEP, PFPP, FCRP, YIRP, and PUE) and K-related indices (RYK, YRK, AEK, PFPK, FCRK, YIRK, and KUE) were calculated analogously using their respective nutrient-omission treatments (the NK treatment for P-omission and the NP

treatment for K-omission), the corresponding nutrient application rates, and above-ground nutrient accumulation values.

2.4. Statistical Analysis

Data from the 2021 and 2022 field experiments were pooled for analysis because the experimental sites and field management practices were relatively consistent across the two years. This pooling approach was adopted to increase the representativeness of regional comparisons and to reduce potential bias caused by uneven site distribution or limited sample size within individual regions [6,23].

Statistical analyses were performed using SPSS 26.0 software (IBM Corp., Armonk, NY, USA). The experimental design was balanced within each experimental site, with four fertilization treatments and three replicates per treatment. However, because the numbers of experimental sites differed among regions and soil fertility levels, the data structure was unbalanced at the regional and soil fertility-level scales; therefore, ANOVA models based on Type III sums of squares were used. One-way ANOVA with fertilization treatment as the fixed factor was used to compare cotton yield and fertilizer use efficiency-related indices among fertilization treatments within each region, whereas differences in the same index between southern and northern Xinjiang were examined using two-way ANOVA (region $\times$ fertilization treatment). When significant differences were detected by ANOVA, Tukey's HSD post hoc test was used for multiple comparisons at $p < 0.05$. In the figure captions, significant differences among indices within the same region are indicated by different lowercase letters, whereas significant differences in the same index between southern and northern Xinjiang are indicated by different uppercase letters. The correlation matrix heatmap was generated using Origin 2024 based on Pearson correlation analysis, with *, **, and *** indicating $p < 0.05$, 0.01, and 0.001, respectively. All other figures were prepared using GraphPad Prism 10.4.

3. Results

3.1. Cotton Yield Responses and Fertilizer Use Efficiency Under N, P, and K Fertilization

3.1.1. N, P, and K Rates and Associated Cotton Yield Responses

The mean N, P, and K rates were 265, 149, and 90 kg ha⁻¹ in Xinjiang, respectively (Figure 2D). The N, P, and K rates were 284, 157, and 106 kg ha⁻¹ in southern Xinjiang, respectively. These values were 19, 8, and 16 kg ha⁻¹ higher than the Xinjiang averages and 31, 13, and 27 kg ha⁻¹ higher than the corresponding values in northern Xinjiang. In northern Xinjiang, N, P, and K application rates were 12, 5, and 11 kg ha⁻¹ lower than the Xinjiang averages, respectively. Overall, N, P, and K application rates exhibited moderate variability in Xinjiang. K application showed the greatest variability (CV = 37%), whereas N application was the most stable (CV = 19%) in Xinjiang. At the regional scale, K application in southern Xinjiang showed the largest variability (CV = 46%). N application exhibited the greatest variability (CV = 18%), whereas P application was the most stable (CV = 13%) in northern Xinjiang.

Across Xinjiang, the NPK treatment achieved the highest cotton yield (6951 kg ha⁻¹), which was significantly higher than that under PK, NK, and NP treatments (Figure 2A). Relative yields under PK, NK, and NP treatments were 73.5%, 82.6%, and 89.6% of that under NPK treatment, indicating that N was the primary yield-limiting factor, followed by P and K (Figure 2B); correspondingly, yield increases under NPK treatment ranked as N > P > K, at 36.1%, 21.0%, and 11.6%, respectively (Figure 2C). This pattern was consistent in both southern and northern Xinjiang, though yield responses were overall stronger in southern Xinjiang, where seed cotton yields under NPK treatment were 6300 and 7361 kg ha⁻¹ in southern and northern Xinjiang, respectively.

3.1.2. Yield Response and Plant Nutrient Accumulation Patterns of Cotton

Cotton yield responses to N, P, and K application in southern Xinjiang were 1861, 1188, and 754 kg ha⁻¹, respectively (Figure 3A). In northern Xinjiang, the corresponding yield responses were 1836, 1220, and 699 kg ha⁻¹, respectively. Cotton yield responses to N, P, and K application were 1845, 1208, and 720 kg ha⁻¹ in Xinjiang, respectively. Yield responses to N and to P application were greater than that to K application in Xinjiang as well as in both southern and northern Xinjiang.

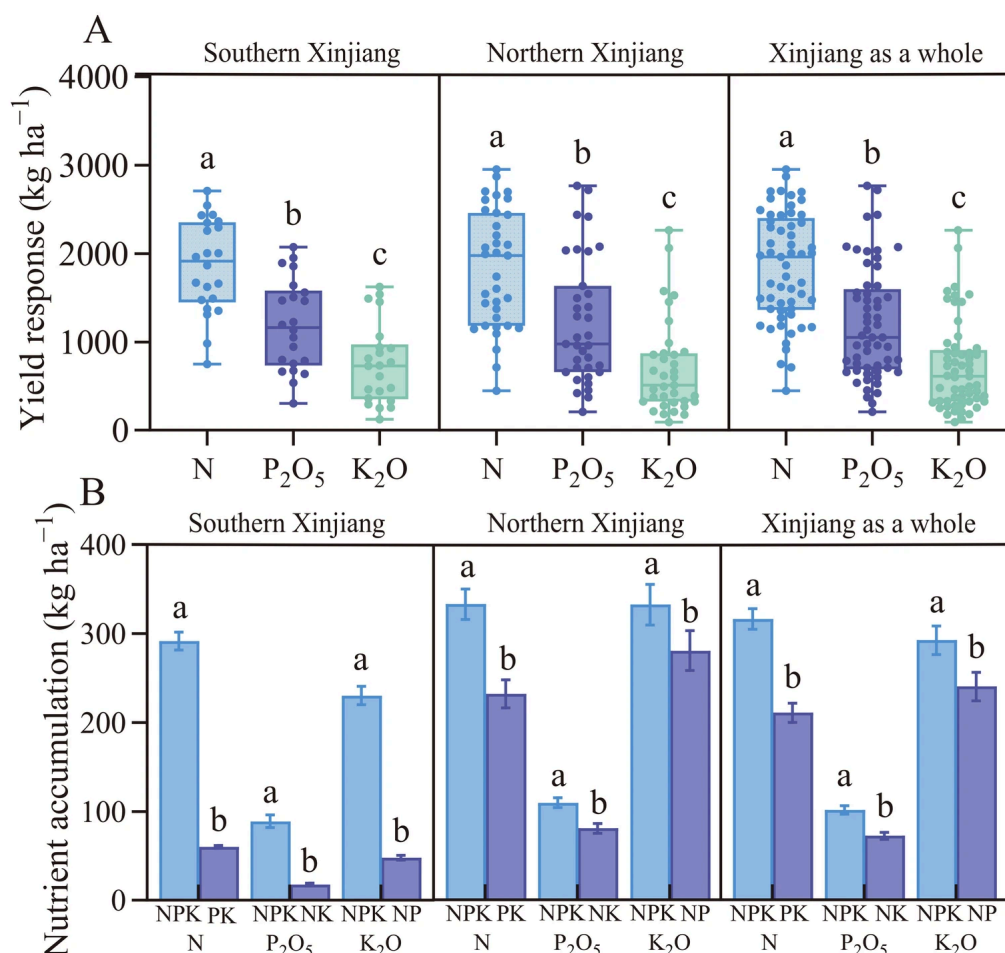


Figure 3. Cotton yield response and aboveground nutrient accumulation in Xinjiang. (A) Yield responses to N, P₂O₅, and K₂O application; (B) aboveground N, P₂O₅, and K₂O accumulation under NPK and corresponding nutrient omission treatments. PK, NK, NP, and NPK, N-omission, P-omission, K-omission, and complete NPK treatments, respectively. Boxplots in (A) show medians, interquartile ranges, non-outlier ranges, and site-level observations; bars in (B) show means $\pm$ SD. Different lowercase letters indicate significant differences within the same region according to Tukey's HSD test ($p < 0.05$).

Balanced N, P, and K fertilization significantly increased aboveground accumulation of N, P, and K in cotton plants (Figure 3B). In southern Xinjiang, mean aboveground N, P, and K accumulations under NPK treatment were 292, 89, and 230 kg ha⁻¹, representing increases of 64%, 51%, and 30% relative to the corresponding omission treatments (PK, NK, and NP), respectively. In northern Xinjiang, mean aboveground N, P, and K accumulations under NPK treatment were 335, 110, and 334 kg ha⁻¹, which were 43%, 36%, and 18% higher than those under the corresponding omission treatments. Nutrient requirements per 100 kg of seed cotton differed markedly between southern and northern

Xinjiang. In southern Xinjiang, producing 100 kg of seed cotton required 4.64 kg N, 1.43 kg P_2O_5 , and 3.67 kg K_2O , whereas in northern Xinjiang the corresponding requirements were 4.74 kg N, 1.48 kg P_2O_5 , and 4.58 kg K_2O . Across Xinjiang, the corresponding requirements were 4.70 kg N, 1.46 kg P_2O_5 , and 4.23 kg K_2O per 100 kg seed cotton. Overall, cotton showed the greatest uptake demand for N, followed by K_2O , whereas P_2O_5 demand was the lowest.

3.1.3. Fertilizer Use Efficiency of Cotton

The N, P, and K use efficiencies of cotton across Xinjiang were 40.1%, 19.9%, and 60.4%, respectively (Figure 4A). Mean N and P use efficiencies were 39.8% and 19.5% in southern Xinjiang and 40.3% and 20.2% in northern Xinjiang, respectively; however, the regional differences were not significant. In contrast, mean KUE was significantly higher in northern Xinjiang than in southern Xinjiang (66.1% vs. 51.4%). This suggests that K utilization from soil application to plant uptake was more strongly constrained in southern Xinjiang.

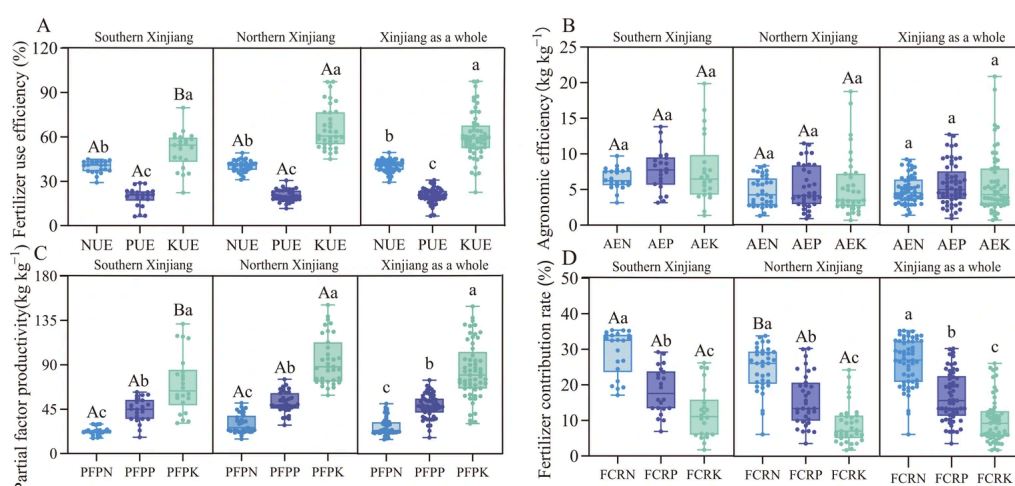


Figure 4. Fertilizer use efficiency-related indices of cotton in Xinjiang. (A) Fertilizer recovery efficiency; (B) agronomic efficiency; (C) partial factor productivity; (D) fertilizer contribution rate. NUE, PUE, and KUE, recovery efficiencies of N, P, and K, respectively; AEN, AEP, and AEK, agronomic efficiencies of N, P, and K, respectively; PFPN, PFPP, and PFPK, partial factor productivity of N, P, and K, respectively; FCRN, FCRP, and FCRK, fertilizer contribution rates of N, P, and K, respectively. Boxplots show medians, interquartile ranges, non-outlier ranges, and site-level observations. Different lowercase letters indicate significant differences among nutrient indices within the same region, and different uppercase letters indicate significant differences in the same index between southern and northern Xinjiang according to Tukey's HSD test ($p < 0.05$).

Agronomic efficiencies (AE) of N, P, and K were 7.2, 8.3, and 8.4 kg seed cotton per kg nutrient in Xinjiang, respectively (Figure 4B). Among the three nutrients, AE was highest for K, followed by P and N. In northern Xinjiang, AE values were 7.6 (N), 8.6 (P), and 8.9 (K) $kg\ kg^{-1}$, which were 15.8%, 10.7%, and 14.5% higher than those in southern Xinjiang, respectively. AE in southern Xinjiang tended to be lower than that in northern Xinjiang; however, the regional differences were not statistically significant.

The partial factor productivity (PFP) values for N, P, and K were 27.3, 48.6, and 85.0 kg seed cotton per kg nutrient, respectively, in Xinjiang (Figure 4C). PFPK was 74.8% higher than PFPP and 211.4% higher than PFPN. In southern Xinjiang, PFP values were 22.6 (N), 44.0 (P), and 70.6 (K) $kg\ kg^{-1}$. In northern Xinjiang, the corresponding values were 30.3 (N), 51.5 (P), and 94.0 (K) $kg\ kg^{-1}$. PFPK was significantly lower in southern

than in northern Xinjiang. Although PFPN and PFPP were also lower in southern Xinjiang, regional differences were not significant. This indicates that the yield output per unit K input was more limited in southern Xinjiang.

Fertilizer contribution rates of N, P, and K were 26.5%, 16.9%, and 10.2% in Xinjiang, respectively (Figure 4D). In southern Xinjiang, fertilizer contribution rates of N, P, and K were 29.3%, 18.4%, and 12.1%, respectively, whereas in northern Xinjiang they were 24.7%, 15.9%, and 9.0%, respectively. The N fertilizer contribution rate was significantly higher in southern than in northern Xinjiang, indicating a stronger yield dependence on N fertilization in southern Xinjiang. Although P and K fertilizer contribution rates were also higher in southern Xinjiang, regional differences were not significant.

3.2. Effects of Soil Fertility on Cotton Yield and Fertilizer Use Efficiency

3.2.1. Cotton Yield and Fertilizer Input Rates Across Fertility Classes

Low-Fertility Cotton Fields

In low-fertility cotton fields, the NPK treatment significantly increased cotton yield across Xinjiang, with an average yield of 6579 kg ha⁻¹ (Figure 5A). Compared with the PK, NK, and NP treatments, NPK increased yield by 37.8%, 21.4%, and 11.2%, respectively, indicating that N was the primary yield-limiting nutrient in low-fertility cotton fields, followed by P and K. Cotton yield under all treatments was significantly higher in northern Xinjiang than in southern Xinjiang, with NPK yields of 6873 and 6137 kg ha⁻¹, respectively. Although K input and total NPK input were higher in southern Xinjiang than in northern Xinjiang, the yield response to K was relatively weak, suggesting a potential risk of excessive K fertilization (Figure 5B). For every 100 kg of seed cotton produced, nutrient uptake was 4.71 kg N, 1.47 kg P₂O₅, and 3.72 kg K₂O in southern Xinjiang, and 5.06 kg N, 1.44 kg P₂O₅, and 4.69 kg K₂O in northern Xinjiang.

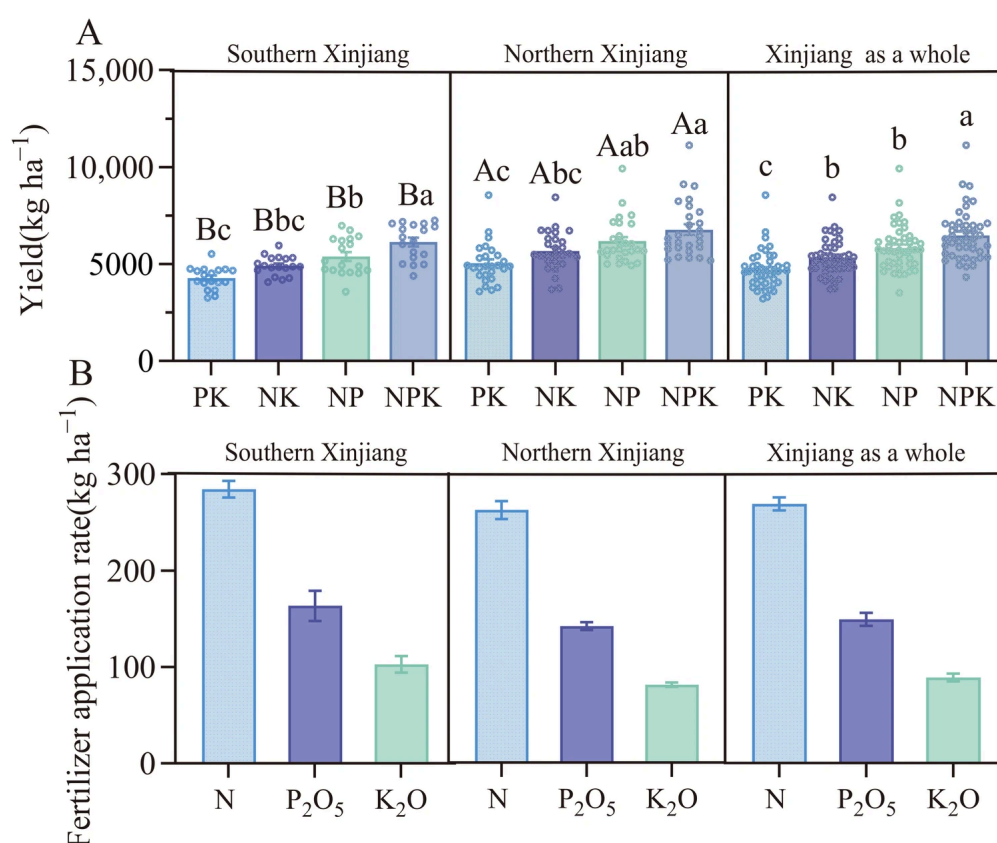


Figure 5. Cotton yield and fertilizer application rates in low-fertility cotton fields. (A) Seed cotton

yield under nutrient omission and complete NPK treatments; **(B)** N, P₂O₅, and K₂O application rates. PK, NK, NP, and NPK, N-omission, P-omission, K-omission, and complete NPK treatments, respectively. Bars show means $\pm$ SD, and points indicate site-level observations. Different lower-case letters indicate significant differences among treatments within the same region, and different uppercase letters indicate significant differences in the same treatment between southern and northern Xinjiang according to Tukey's HSD test ($p < 0.05$). Fertilizer rates in **(B)** were preset inputs and were not statistically compared.

Medium-Fertility Cotton Fields

Under medium-fertility conditions, the NPK treatment produced the highest mean yield in Xinjiang (8935 kg ha⁻¹), but it did not differ significantly from the PK, NK, or NP treatments (Figure 6A). At the regional scale, the NPK treatment in southern Xinjiang produced a yield of 6651 kg ha⁻¹, with no significant difference from the other treatments. In contrast, the NPK treatment in northern Xinjiang significantly increased yield to 10,077 kg ha⁻¹, which was significantly higher than that under the PK, NK, and NP treatments (7438, 7939, and 9412 kg ha⁻¹, respectively). Under the same fertilization treatments, cotton yield was significantly higher in northern Xinjiang than in southern Xinjiang. However, the mean N, P, K, and total NPK inputs were numerically comparable between the two regions, indicating that the higher yield in northern Xinjiang was not caused by greater fertilizer input (Figure 6B). For every 100 kg of seed cotton produced, nutrient uptake was 4.21 kg N, 1.17 kg P₂O₅, and 3.40 kg K₂O in southern Xinjiang, and 3.37 kg N, 1.45 kg P₂O₅, and 4.67 kg K₂O in northern Xinjiang.

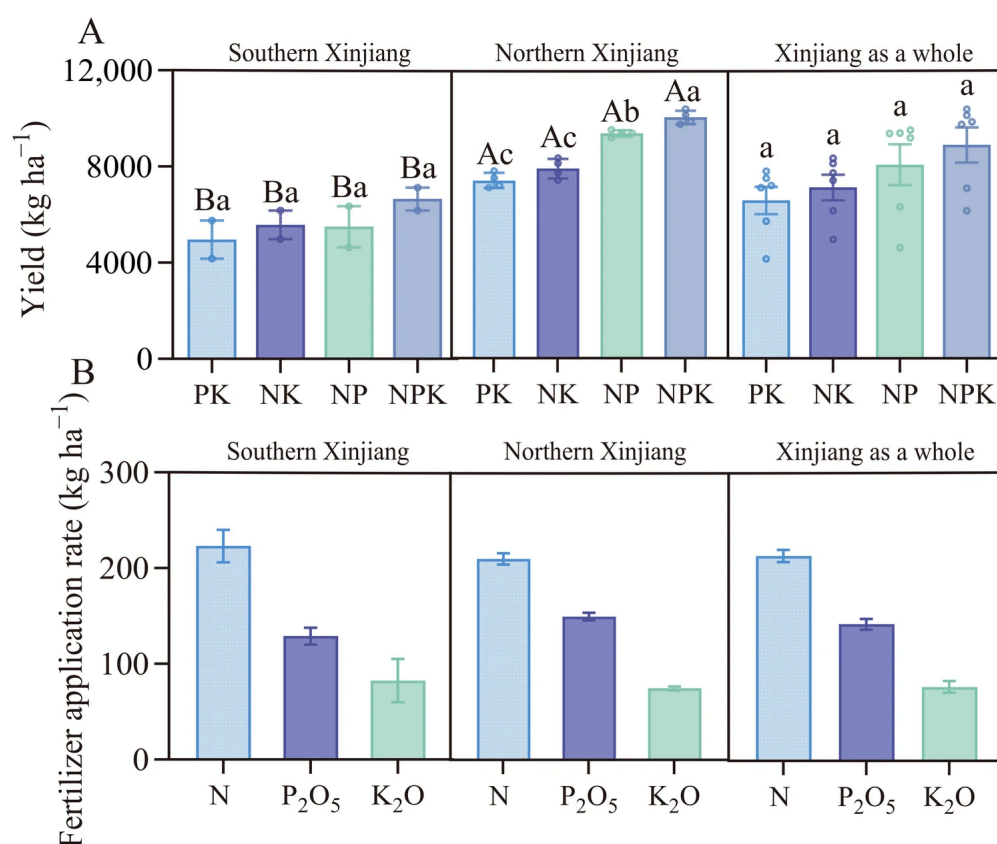


Figure 6. Cotton yield and fertilizer application rates in medium-fertility cotton fields. **(A)** Seed cotton yield under nutrient omission and complete NPK treatments; **(B)** N, P₂O₅, and K₂O application rates. PK, NK, NP, and NPK, N-omission, P-omission, K-omission, and complete NPK treatments, respectively. Bars show means $\pm$ SD, and points indicate site-level observations. Different

lowercase letters indicate significant differences among treatments within the same region, and different uppercase letters indicate significant differences in the same treatment between southern and northern Xinjiang according to Tukey's HSD test ($p < 0.05$). Fertilizer rates in (B) were preset inputs and were not statistically compared.

High-Fertility Cotton Fields

In high-fertility fields, at the Xinjiang scale, the NPK treatment increased cotton yield compared with the PK treatment, but did not differ significantly from NK and NP treatments (Figure 7A). This indicates the yield advantage of combined N, P, and K fertilization was weakened under high soil fertility conditions. Regional differences in yield were generally small, and the yield under NPK treatment in northern Xinjiang was only numerically higher than that in southern Xinjiang (7939 vs. 7415 kg ha⁻¹). In high-fertility cotton fields, N and K inputs in southern Xinjiang were relatively high and highly variable, suggesting possible excessive fertilization in some fields (Figure 7B). For every 100 kg of seed cotton produced, nutrient uptake was 4.41 kg N, 1.30 kg P₂O₅, and 3.48 kg K₂O in southern Xinjiang, compared with 3.90 kg N, 1.77 kg P₂O₅, and 3.71 kg K₂O in northern Xinjiang.

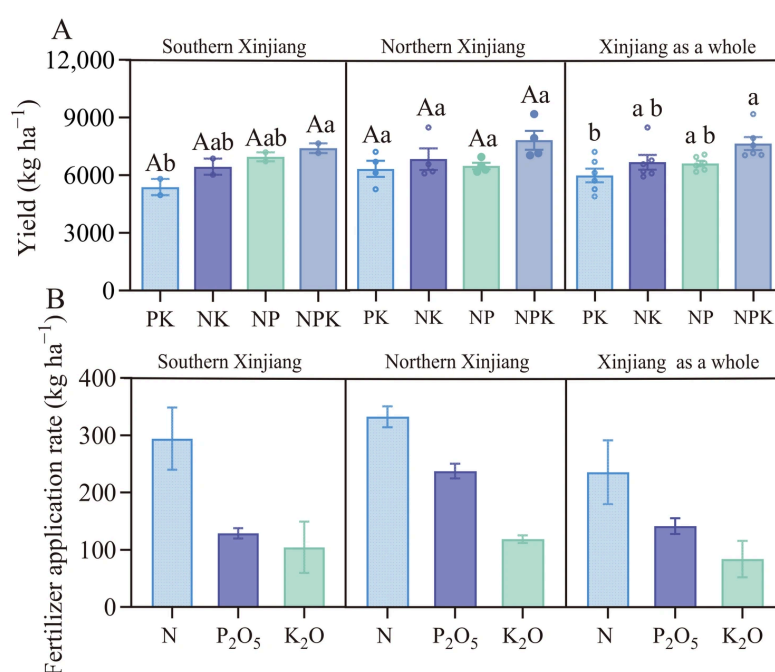


Figure 7. Cotton yield and fertilizer application rates in high-fertility cotton fields. (A) Seed cotton yield under nutrient omission and complete NPK treatments; (B) N, P₂O₅, and K₂O application rates. PK, NK, NP, and NPK, N-omission, P-omission, K-omission, and complete NPK treatments, respectively. Bars show means $\pm$ SD, and points indicate site-level observations. Different lowercase letters indicate significant differences among treatments within the same region, and different uppercase letters indicate significant differences in the same treatment between southern and northern Xinjiang according to Tukey's HSD test ($p < 0.05$). Fertilizer rates in (B) were preset inputs and were not statistically compared.

3.2.2. Fertilizer Use Efficiency

Low-Fertility Cotton Fields

In low-fertility cotton fields, KUE was the highest, followed by N and P use efficiencies, with values of 60.2%, 40.1%, and 20.2%, respectively (Figure 8A). In contrast, the agronomic efficiencies of N, P, and K were similar, ranging from 6.8 to 7.9 kg kg⁻¹, with

no significant differences among them (Figure 8B). Regional comparisons showed that N and P use efficiencies did not differ significantly between southern and northern Xinjiang, whereas K use efficiency was significantly higher in northern Xinjiang than in southern Xinjiang (64.5% vs. 53.8%). No significant regional differences were observed in the agronomic efficiencies of N, P, and K. These results indicate that regional differences in low-fertility cotton fields were mainly reflected in KUE, whereas the agronomic efficiencies of N, P, and K were generally consistent between the two regions.

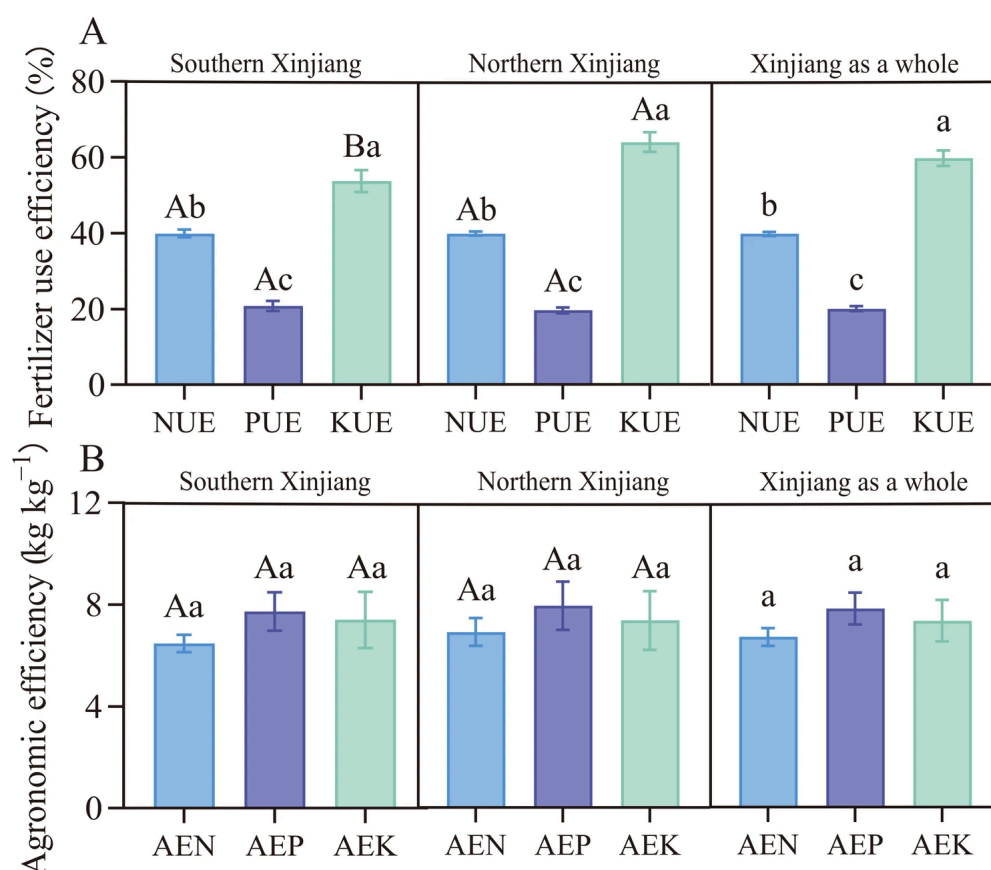


Figure 8. Fertilizer recovery efficiency and agronomic efficiency in low-fertility cotton fields. (A) Recovery efficiencies of N, P, and K; (B) agronomic efficiencies of N, P, and K. NUE, PUE, and KUE, recovery efficiencies of N, P, and K, respectively; AEN, AEP, and AEK, agronomic efficiencies of N, P, and K, respectively. Bars show means $\pm$ SD, and points indicate site-level observations. Different lowercase letters indicate significant differences among nutrient indices within the same region, and different uppercase letters indicate significant differences in the same index between southern and northern Xinjiang according to Tukey's HSD test ($p < 0.05$).

Medium-Fertility Cotton Fields

In medium-fertility cotton fields, KUE was the highest (65.8%), whereas PUE was the lowest (20.4%) (Figure 9A). At the regional scale, KUE was significantly higher in northern Xinjiang than in southern Xinjiang (76.6% vs. 44.3%), indicating greater K fertilizer use efficiency in northern Xinjiang. The agronomic efficiency of P was significantly higher in northern Xinjiang than in southern Xinjiang (14.3 vs. 8.3 kg kg⁻¹), suggesting a greater yield gain per unit P input in northern Xinjiang (Figure 9B). No significant regional differences were observed for NUE, PUE, agronomic efficiency of N, or agronomic efficiency of K.

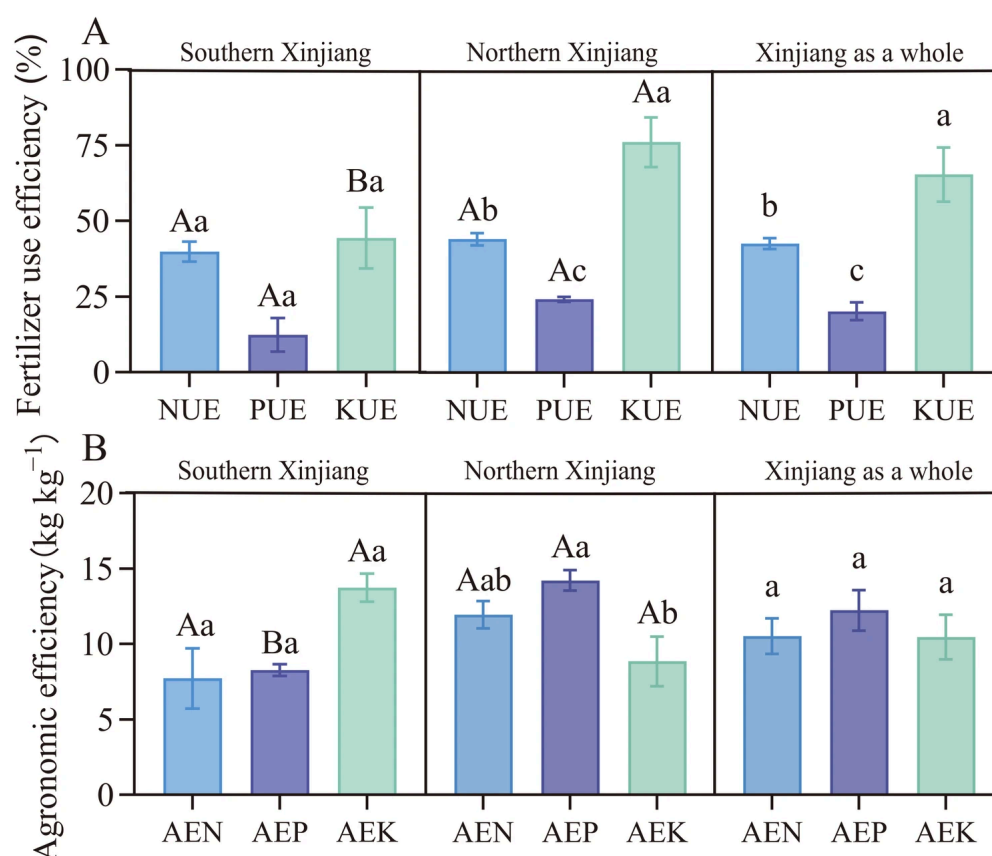


Figure 9. Fertilizer recovery efficiency and agronomic efficiency in medium-fertility cotton fields. (A) Recovery efficiencies of N, P, and K; (B) agronomic efficiencies of N, P, and K. NUE, PUE, and KUE, recovery efficiencies of N, P, and K, respectively; AEN, AEP, and AEK, agronomic efficiencies of N, P, and K, respectively. Bars show means $\pm$ SD, and points indicate site-level observations. Different lowercase letters indicate significant differences among nutrient indices within the same region, and different uppercase letters indicate significant differences in the same index between southern and northern Xinjiang according to Tukey's HSD test ($p < 0.05$).

High-Fertility Cotton Fields

In high-fertility cotton fields, NUE did not differ significantly between southern and northern Xinjiang (Figure 10A). The mean PUE was higher in northern Xinjiang than in southern Xinjiang (19.2% vs. 14.1%), but the difference was relatively small. In contrast, KUE was significantly higher in northern Xinjiang than in southern Xinjiang (66.3% vs. 37.3%), and K agronomic efficiency was also significantly higher in northern Xinjiang than in southern Xinjiang (18.2 vs. 4.7 kg kg⁻¹). However, regional differences in N and P agronomic efficiencies were not significant (Figure 10B). Regional differences in fertilizer efficiency in high-fertility cotton fields were mainly reflected in KUE and the agronomic efficiency of K, whereas N- and P-related efficiencies were relatively consistent. These results indicate that the yield-promoting and efficiency-improving effects of N and P fertilization were relatively weakened under high-fertility conditions.

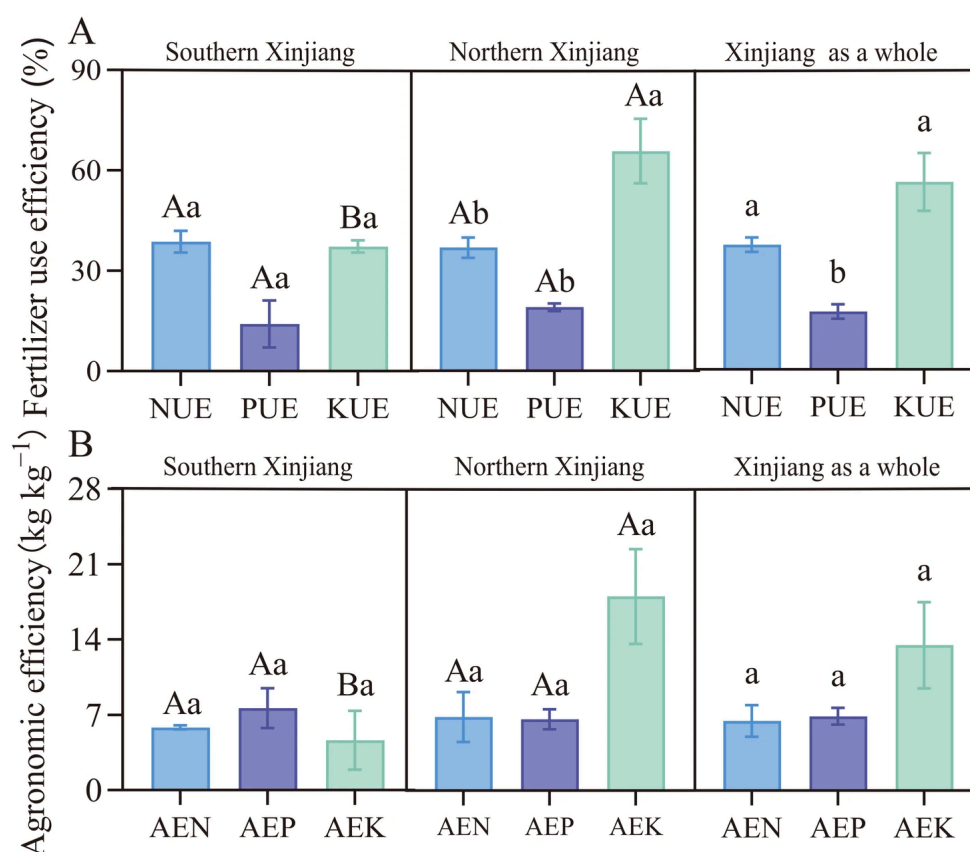


Figure 10. Fertilizer recovery efficiency and agronomic efficiency in high-fertility cotton fields. **(A)** Recovery efficiencies of N, P, and K; **(B)** agronomic efficiencies of N, P, and K. NUE, PUE, and KUE, recovery efficiencies of N, P, and K, respectively; AEN, AEP, and AEK, agronomic efficiencies of N, P, and K, respectively. Bars show means $\pm$ SD, and points indicate site-level observations. Different lowercase letters indicate significant differences among nutrient indices within the same region, and different uppercase letters indicate significant differences in the same index between southern and northern Xinjiang according to Tukey's HSD test ($p < 0.05$).

3.3. Factors Influencing Cotton Yield and Fertilizer Use Efficiency in Xinjiang

3.3.1. Factors Associated with Cotton Yield

In southern Xinjiang, cotton yields under NPK, PK, and NK treatments were significantly positively correlated with soil alkali-hydrolyzable N, whereas yields under NP treatment exhibited a significant positive correlation with soil alkali-hydrolyzable N and nitrogen application rate (Figure 11A). Nitrogen availability therefore represents a major determinant of cotton productivity in southern Xinjiang, and appropriate nitrogen fertilization enhances yield formation. Cotton yield was negatively correlated with soil pH, suggesting that soil salinization and alkalization may be limiting factors for cotton production in this region.

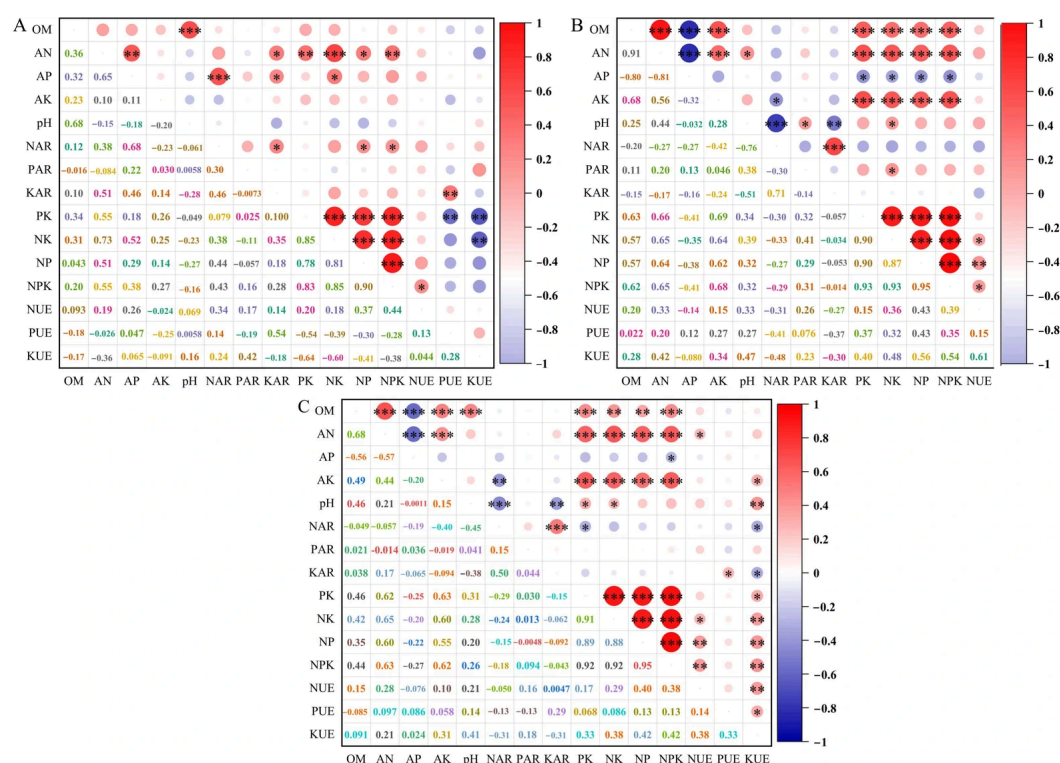


Figure 11. Pearson correlation matrices for cotton yield, fertilizer recovery efficiency, fertilizer application rates, and soil properties in southern Xinjiang ((A); $n = 22$), northern Xinjiang ((B); $n = 35$), and Xinjiang as a whole ((C); $n = 57$). The lower triangle shows Pearson correlation coefficients, and the upper triangle shows correlation direction and strength using circles. Red and blue indicate positive and negative correlations, respectively; circle size and color intensity indicate the absolute correlation coefficient. Significance levels are indicated as * $p < 0.05$, ** $p < 0.01$, and *** $p < 0.001$. Abbreviations: OM, soil organic matter; AN, alkali-hydrolyzable nitrogen; AP, available phosphorus; AK, available potassium; NAR, PAR, and KAR, application rates of N, P_2O_5 , and K_2O , respectively; PK, NK, NP, and NPK, cotton yield under N-omission, P-omission, K-omission, and complete NPK treatments, respectively; NUE, PUE, and KUE, recovery efficiencies of N, P, and K, respectively.

In northern Xinjiang, cotton yields were significantly positively correlated with soil organic matter, alkali-hydrolyzable N, and available K, whereas significant negative correlations were observed with soil available P (Figure 11B). Under NPK treatment, cotton yield was not increased by additional nitrogen and potassium inputs, demonstrating that balanced fertilization management is essential in northern Xinjiang cotton fields.

Across Xinjiang, cotton yields were significantly positively correlated with soil organic matter, alkali-hydrolyzable N, and available K, highlighting the important roles of these soil fertility indicators in regulating cotton productivity (Figure 11C). In contrast, cotton yield was significantly negatively correlated with soil available P. Cotton yield was significantly negatively correlated with soil available P. When soil available P exceeds 19 mg kg^{-1} , excessive phosphorus interferes with the allocation of assimilates from vegetative tissues to reproductive organs in cotton plants [24]. Yield rankings among the PK, NK, NP, and NPK treatments were consistent. Under NPK treatment, cotton yield displayed negative correlations with nitrogen and potassium rates, whereas no significant relationship was detected with phosphorus rate.

3.3.2. Factors Associated with Fertilizer Use Efficiency

In southern Xinjiang, NUE exhibited a negative correlation with soil available K and a significant positive correlation with cotton yield under NPK treatment (Figure 11A). PUE exhibited a significant positive correlation with K rate, and negative correlations with P rate and cotton yield under PK treatment. In low-K cotton fields of southern Xinjiang, appropriate K application contributes to improved PUE. KUE exhibited significant negative correlations with cotton yield under PK and NP treatments. Soil available P maintained significant positive correlations with soil alkali-hydrolyzable N and N rates.

In northern Xinjiang, soil pH exhibited highly significant negative correlations with N and K application rates (Figure 11B). Soil available P exhibited highly significant negative correlations with soil organic matter and alkali-hydrolyzable N. Available K maintained highly significant positive correlations with soil organic matter and alkali-hydrolyzable N, but a significant negative correlation with N rate. NUE exhibited significant positive correlations with cotton yield under NPK, NK, and NP treatments. PUE exhibited significant negative correlations with N and K application rates, implying that excessive N and K inputs constrain P uptake in cotton in northern Xinjiang. PUE exhibited significant positive correlations with cotton yield under NPK, PK, and NP treatments. KUE exhibited significant positive correlations with soil alkali-hydrolyzable N and available K, but a highly significant negative correlation with N application rate. KUE exhibited highly significant positive correlations with cotton yield under NPK, NK, and NP treatments and with NUE, and a significant positive correlation with PUE.

Across Xinjiang, soil pH exhibited highly significant negative correlations with N and K rates (Figure 11C). Soil available P exhibited highly significant negative correlations with soil organic matter and alkali-hydrolyzable N. Available K maintained highly significant positive correlations with soil organic matter and alkali-hydrolyzable N, but a significant negative correlation with N rate. NUE exhibited a significant positive correlation with soil alkali-hydrolyzable N and highly significant positive correlations with cotton yield under NPK, NK, and NP treatments, demonstrating that greater soil alkali-hydrolyzable N availability enhances N uptake by cotton plants. PUE exhibited a significant positive correlation with K rate, and appropriate K fertilization enhances P uptake in cotton. KUE exhibited highly significant positive correlations with cotton yield under the NPK, PK, NK, and NP treatments and with NUE. KUE exhibited a significant positive correlation with soil available K, but significant negative correlations with N and K rates, demonstrating that this may indicate nutrient imbalance or excessive potassium input at some experimental sites.

4. Discussion

4.1. Yield Responses and Fertilizer Use Efficiency in Xinjiang Cotton Fields

This study found that nitrogen was the primary yield-limiting nutrient in Xinjiang cotton fields. Analysis of 57 experimental sites across Xinjiang showed that the NPK treatment produced the highest yield, whereas the relative yields under N-, P-, and K-omission treatments were 73.5%, 82.6%, and 89.6% of that under the NPK treatment, respectively, indicating that cotton yield responses to N, P, and K fertilization followed the order $N > P > K$. Although the application rates of N, P_2O_5 , and K_2O were generally higher in southern Xinjiang than in northern Xinjiang, the higher fertilizer inputs did not translate into higher cotton yield and were accompanied by lower K use efficiency, as evidenced by lower K recovery efficiency and K partial factor productivity than those in northern Xinjiang. This regional difference suggests that the current limitation to cotton

production may not be insufficient total fertilizer input, but rather a mismatch between nutrient inputs and crop nutrient demand under different soil fertility conditions, which may be associated with the long-standing imbalance in N, P, and K input structure in Xinjiang cotton production [5,6]. Without adequately accounting for crop nutrient demand and soil fertility conditions, simply increasing fertilizer inputs is unlikely to sustainably improve cotton yield and fertilizer use efficiency [3].

Compared with fertilizer application rates reported from the 2005–2011 soil testing and formulated fertilization program in Xinjiang [6], the average N and P fertilizer application rates in the present study decreased slightly, whereas K fertilizer application increased markedly. This suggests that fertilization in Xinjiang cotton fields is gradually shifting from a system dominated by N and P inputs toward a more balanced N, P, and K fertilization pattern. At the regional scale, N, P_2O_5 , and K_2O inputs in southern Xinjiang were generally higher than the Xinjiang average, whereas those in northern Xinjiang were relatively lower, consistent with previous surveys of fertilization practices in Xinjiang cotton fields [25]. Compared with previous reports from the Yellow River and Yangtze River cotton-growing regions, Xinjiang cotton fields still show relatively high P fertilizer input and relatively insufficient K fertilizer input [26,27]. Meanwhile, excessive P application may increase soil P surplus and reduce P use efficiency [28], whereas appropriate K management plays an important role in improving cotton yield, nutrient accumulation, and regionally efficient production [11,29]. Therefore, imbalanced nutrient input remains an important factor limiting the efficient use of fertilizers in Xinjiang cotton production [3,6].

Balanced N, P, and K fertilization significantly increased cotton yield and nutrient accumulation in Xinjiang cotton fields. The average yield under the NPK treatment was not only higher than previously reported levels in southern Xinjiang, but also exceeded those reported for the Yellow River and Yangtze River cotton-growing regions [25–27]. Compared with earlier studies on nutrient-limiting factors in Xinjiang cotton fields, the agronomic efficiencies of N, P, and K fertilizers were all improved in the present study [30]. The P recovery efficiency was within the reasonable national range, while the N and K recovery efficiencies were higher than the national averages [31]. In addition, the P and K recovery efficiencies were also higher than those reported in previous studies on fertilizer reduction and efficiency improvement in Xinjiang [32]. These improvements may be associated with the implementation of soil testing and formulated fertilization, the widespread adoption of mulched drip irrigation, and advances in scientific fertilizer management [3,6,33]. Although the N recovery efficiency of Xinjiang cotton fields was within the appropriate range [34], there remains an improvement potential of approximately 7% compared with highly efficient water and fertilizer management systems [3,35]. Previous studies have shown that optimized water and fertilizer management under drip irrigation can improve cotton yield and the uptake and utilization efficiencies of N, P, and K [3,35]. In contrast, excessive P input and inappropriate K management may reduce fertilizer use efficiency and constrain further yield improvement [28,29].

4.2. Effects of Soil Physicochemical Properties and Fertility on Cotton Yield and Fertilizer Use Efficiency

4.2.1. Factors Associated with Cotton Yield and Fertilizer Use Efficiency in Southern Xinjiang

Cotton yield under NPK and NP treatments was significantly positively correlated with soil alkali-hydrolyzable N and significantly positively correlated with N rate, indicating that soil N supply capacity and N input level are important factors affecting cotton yield in southern Xinjiang. Previous studies have shown irrigation and N manage-

ment under the mulched drip irrigation system in southern Xinjiang significantly affect cotton yield and nitrogen use efficiency, and appropriate water–N regulation promotes cotton growth and yield formation [20,23,33]. Given that cotton fields in southern Xinjiang are located in a typical arid irrigation agriculture environment; future research should integrate soil salinity and water–salt transport processes to further elucidate the role of coordinated water–salt–fertilizer regulation in maintaining stable cotton production and improving fertilizer use efficiency [5, 36, 37].

Nitrogen use efficiency showed no significant correlation with soil available K, but was significantly positively correlated with cotton yield under NPK treatment, indicating that higher yields favor improved nitrogen use efficiency. Optimized water–fertilizer management and enhanced coordination between nutrient uptake and yield formation can increase the absorption and utilization efficiency of N, P, and K in cotton [5,23,35]. Phosphorus use efficiency was significantly positively correlated with K application rate, suggesting that K application may enhance P uptake and utilization by promoting root activity, demonstrating a synergistic interaction between P and K acquisition [3,11]. Phosphorus use efficiency showed a non-significant negative correlation with P application rate, indicating that P input in some fields may have reached or exceeded the critical requirement, leading to diminished marginal yield response and an increased risk of P surplus [24,28,38]. Potassium use efficiency showed non-significant negative correlations with both K application rate and soil available K, indicating that increased K input did not generate corresponding yield gains, reducing the yield return per unit of K input; potassium use efficiency may decline as K rates increase or soil K availability rises [29,39].

4.2.2. Factors Associated with Cotton Yield and Fertilizer Use Efficiency in Northern Xinjiang

In northern Xinjiang, cotton yields under all treatments exhibited strong positive correlations with soil organic matter and available K, highlighting soil fertility as a key determinant of high cotton productivity. Enhancing soil quality and implementing site-specific K management contribute to stable and increased yields [29,37]. Cotton yields under all treatments exhibited strong negative correlations with soil available P, as high soil available P at certain sites reduced responsiveness to P fertilization. Continued P application in these fields did not increase yield, causing phosphorus accumulation and decreased P use efficiency, which constrained crop growth and yield formation. Excessive P application and low phosphorus use efficiency are common in northern Xinjiang, emphasizing the need for optimized P management strategies to control P surplus [3,24,28].

Soil pH exhibited strong negative correlations with N and K application rates and positive correlations with N and K use efficiencies. The negative correlations between initial soil pH and N and K application rates may reflect differences in baseline soil conditions and regional fertilization practices rather than a direct acidification effect of fertilizer inputs [37,40]. Nitrogen use efficiency correlated positively with cotton yields under NPK, NK, and NP treatments. Phosphorus use efficiency correlated negatively with N and K application rates and positively with yields under NPK, PK, and NP treatments. Increases in N and P use efficiencies primarily resulted from yield responses per unit N or P input. High N or K inputs without corresponding yield increases reduced N and P use efficiencies due to imbalanced nutrient ratios or diminished marginal yield responses [8,39,41]. Excessive soil P accumulation should be avoided in production, and water-fertilizer management optimized to enhance phosphorus use efficiency [24,28]. Potassium use efficiency correlated positively with soil alkali-hydrolyzable N and avail-

able K, negatively with N rate, and positively with cotton yields and N and P use efficiencies across treatments [11,29,39].

4.2.3. Factors Associated with Cotton Yield and Fertilizer Use Efficiency in Xinjiang

Cotton yields under all treatments had highly significant positive correlations with soil organic matter, alkali-hydrolyzable N, and available K. The basic soil fertility level and the effective supply of nitrogen and potassium remain critical determinants of high cotton productivity, and improved nutrient availability can further enhance yield [29,37].

Nitrogen use efficiency had significant positive correlations with soil alkali-hydrolyzable N and with cotton yield under NPK and NP treatments. Adequate soil nitrogen availability supports yield formation and promotes higher nitrogen use efficiency under high-yield conditions. Optimization of the temporal and spatial coordination between irrigation and fertilization under drip irrigation systems strengthens the coupling between yield formation and nitrogen uptake [3,23,35]. Phosphorus use efficiency had a significant positive correlation with the potassium rate. K enhances root physiological activity and facilitates the conversion of soil P into plant-available forms [11,38]. Potassium use efficiency had a significant positive correlation with soil available K. Appropriate K fertilization increases soil available K, stimulates plant metabolic enzymes, and enhances agronomic and physiological potassium use efficiency [37,41]. Potassium use efficiency had a significant negative correlation with N rate. Synergistic interactions between N and K enhance nutrient uptake [41]; however, excessive N input accelerates plant growth and may induce relative potassium deficiency, which reduces potassium use efficiency [39,41]. Potassium use efficiency also had a significant negative correlation with the K rate, implying that continued potassium input in soils with relatively high K availability may reduce potassium use efficiency [29,39]. Nitrogen use efficiency was significantly positively correlated with soil alkali-hydrolyzable N. Under appropriate N rates, cotton plants can more efficiently absorb and utilize nitrogen, thereby promoting growth and improving nitrogen use efficiency [42,43].

4.3. Optimization of Nitrogen, Phosphorus, and Potassium Application Rates for Cotton in Xinjiang

This study showed that soil fertility significantly affected cotton responses to N, P, and K. The NUE and AEN in low-fertility cotton fields were higher than those in high-fertility fields, indicating that crops responded more strongly to external N input under low-fertility conditions. As soil fertility increased, the marginal yield gain per unit fertilizer input decreased, and PFPN and agronomic efficiency also tended to decline. Consistent with previous reports, these trends indicate that excessive fertilization is unlikely to sustain yield improvement and may instead result in nutrient waste and reduced fertilizer use efficiency [3,8,44]. The yield under the NPK treatment in high-fertility cotton fields was lower than that in medium-fertility fields, and the yield benefit of N fertilization weakened with increasing soil fertility. This indicates that, under high-fertility conditions, yield limitation may shift from nutrient supply to non-nutrient factors, such as root-zone water and salinity conditions, irrigation management, and canopy structure [35,36,45].

Across Xinjiang, the recovery efficiencies of N and P followed the order medium-fertility > low-fertility > high-fertility fields. Nutrient supply and crop demand may be better coordinated in medium-fertility fields, resulting in higher fertilizer recovery efficiency. In contrast, nutrient surplus in high-fertility fields may reduce nutrient uptake and assimilation efficiency, whereas insufficient nutrient supply and limited root uptake capacity in low-fertility fields may constrain recovery efficiency [25,46]. Therefore, opti-

mization of N, P, and K inputs should fully consider soil fertility status rather than simply increasing fertilizer application rates.

Fertilization priorities should differ among soil fertility levels. In low-fertility cotton fields, the yield response followed the order $N > P > K$, indicating that N was the primary limiting nutrient, whereas the marginal response to K was relatively weak [23,30]. Therefore, effective N supply should be prioritized in low-fertility fields, while K input should be regulated according to soil available K and plant diagnostic indicators [11,29,47]. In medium-fertility cotton fields, the relatively low P recovery efficiency and P agronomic efficiency in southern Xinjiang indicated that P input was not fully matched with crop demand. Continuous high P input may increase soil P surplus and reduce fertilizer efficiency [24,28]. In high-fertility cotton fields, the yield- and efficiency-promoting effects of additional N and P inputs were markedly weakened, and further increases in K fertilization were unlikely to significantly improve yield; instead, they may increase redundant inputs and production costs [39,43,47]. Therefore, ineffective high fertilizer inputs should be reduced in high-fertility fields, and K supplementation should be guided by root-zone K diagnosis [29,47]. Cotton fertilization in Xinjiang should shift from high-input management to soil fertility-based balanced nutrient management to maintain high yield and improve fertilizer use efficiency.

Balanced N, P, and K fertilization produced significant yield benefits in Xinjiang cotton fields; however, current fertilization practices still tend to emphasize N and P inputs relative to K. In this study, the fertilizer contribution rates followed the order $N > P > K$, which was consistent with the previously reported pattern of nutrient limitation in Xinjiang cotton fields [30]. Based on the yield responses and nutrient uptake characteristics observed in this study, and using the recommended fertilization system approach [48], suitable N, P, and K application rates for cotton in Xinjiang were estimated. The recommended N, P, and K application rates were 256–313, 96–117, and 125–153 kg ha⁻¹ in southern Xinjiang, and 219–267, 97–119, and 136–166 kg ha⁻¹ in northern Xinjiang, respectively. The recommended rates varied among soil fertility levels, indicating that fertilizer management in Xinjiang cotton production should be optimized according to regional differences and soil fertility classes [17,18]. Across Xinjiang, the recommended N application rate was 232–283 kg ha⁻¹, which was close to the current mean N input of 265 kg ha⁻¹. The recommended P application rate was 97–118 kg ha⁻¹, markedly lower than the current mean P input of 149 kg ha⁻¹, suggesting that P input may be excessive in Xinjiang cotton production. Previous research in Xinjiang cotton fields suggested that P fertilizer input should be controlled within 100–124 kg ha⁻¹ to improve soil P availability [24]. In contrast, the recommended K application rate was 108–132 kg ha⁻¹, higher than the current mean K input of 90 kg ha⁻¹. Although soil K is generally abundant in Xinjiang, clear regional differences exist. Therefore, excessive P input should be reduced, and K fertilization should be moderately increased according to regional soil K supply to promote stable, high cotton yield and efficient fertilizer use in Xinjiang.

Given the potential influence of the absence of unfertilized controls and interannual meteorological variability on fertilizer response assessment, future research should include unfertilized control treatments, perform year-specific independent analyses, and incorporate meteorological factors such as precipitation and temperature to improve evaluation accuracy and provide a scientific basis for precision fertilization and fertilizer reduction in cotton in Xinjiang.

5. Conclusions

The results of the two-year field experiments show that cotton yield and fertilizer use efficiency in Xinjiang were jointly regulated by nutrient supply, regional conditions,

and soil fertility. Balanced N, P, and K fertilization significantly increased seed cotton yield, and the yield response followed the order $N > P > K$, indicating that N was the primary limiting nutrient. As soil fertility increased, the marginal yield benefit of NPK fertilization decreased, suggesting that fertilization should be optimized according to soil fertility rather than simply increasing fertilizer inputs. Cotton yield was mainly associated with soil organic matter, alkali-hydrolyzable N, and available K. In southern Xinjiang, fertilizer inputs were relatively high, but K recovery efficiency was low; therefore, improving K use efficiency and controlling excessive N and P inputs should be prioritized.

Regional and soil-fertility-based fertilization management is recommended for cotton production in Xinjiang. The recommended application rates of cotton fields are 256–313 kg N ha⁻¹, 96–117 kg P₂O₅ ha⁻¹, and 125–153 kg K₂O ha⁻¹ for southern Xinjiang, and 219–267 kg N ha⁻¹, 97–119 kg P₂O₅ ha⁻¹, and 136–166 kg K₂O ha⁻¹ for northern Xinjiang. Overall, N and P inputs should be controlled, and K fertilization should be moderately increased according to soil K supply to improve cotton yield stability and fertilizer use efficiency.

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