

ORIGINAL ARTICLE

Soil Fertility and Crop Nutrition

Defining critical leaf- and petiole-potassium concentrations for monitoring cotton nutritional status

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Assigned to Associate Editor Lakesh
Sharma

Funding information

Arkansas Soil Test Review Board; Cotton,
Grant/Award Number: 23-660AR; Arkansas
Agricultural Experiment Station,
Grant/Award Number: Hatch Project 2800

Abstract

Plant tissue testing is an effective tool for diagnosing crop nutritional status; however, critical tissue-potassium (K) concentrations have not been established for modern cotton (*Gossypium hirsutum* L.) cultivars. We aimed to define critical leaf- and petiole-K concentrations at various growth stages for optimal cotton production. Nine fertilizer-K rate (0–187 kg K ha⁻¹) trials were conducted in a randomized complete block design on silt loam soils with very low to above optimum soil-test K in Arkansas, during 2023 and 2024. Leaf and petiole samples were collected from first square through the beginning of boll and fiber maturation, to quantify tissue-K concentrations. At maturity, cotton lint yield was measured. Lint yield was significantly affected by K fertilization ($p \leq 0.10$) in seven out of nine trials, where the unfertilized control yield was 35%–79% of the yield-maximizing fertilizer-K rates (56, 75, and 112 kg K ha⁻¹). Leaf- and petiole-K concentrations increased with increasing K availability (soil or fertilization). Tissue-K concentrations peaked at first square and declined throughout cotton reproductive development. Critical leaf- and petiole-K concentrations to maximize yield were 11.1 and 47.3 g K kg⁻¹ at first square, 10.3 and 48.0 g K kg⁻¹ at first flower, and decreased to 5.1 and 7.5 g K kg⁻¹ at eight weeks after first flower, respectively. Petiole-K concentrations had a stronger relationship with relative yield than leaf-K (R^2 range of 0.31–0.65 for petioles and 0.19–0.53 for leaves). Our results suggest petioles are more accurate for monitoring cotton K nutrition, and growth-stage-specific critical K concentrations are key for accurately assessing cotton K nutritional status.

Abbreviations: DAP, days after planting; LMCERS, Lon Mann Cotton Research Station; RRS, Rohwer Research Station; SAREC, Milo J. Shult Agricultural Research and Extension Center; SOM, soil organic matter; UAN, urea ammonium nitrate; WAFF, week(s) after first flower.

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Plain Language Summary

Potassium (K) deficiency is a common yield-limiting factor for cotton production. We defined critical tissue-K concentrations throughout cotton reproductive development for maximizing yield. Field trials were established during 2023 and 2024 on silt loam soils with varying K availability to determine cotton yield and tissue-K concentrations response to K fertilization. Leaf- and petiole-K concentrations were positively related to crop yield and increased with increasing K availability, indicating sensitivity to diagnosing K nutritional status. Critical tissue-K concentrations peaked at first square and continuously declined during cotton reproductive development. Petiole-K concentrations were almost five times greater than leaf-K concentrations. Our results suggest that both plant tissue and sampling time are important for the accurate assessment of cotton K nutrition. Tissue testing is a viable tool to help growers monitor cotton K nutritional status and guide K management decisions.

1 | INTRODUCTION

Potassium (K) deficiency is frequently reported in the US Cotton Belt and is one of the most important yield-limiting factors in Arkansas cotton (*Gossypium hirsutum* L.) production (Daniels et al., 2023; Oosterhuis et al., 2013). Modern, high-yielding, and early-maturing cotton cultivars have a higher demand for K and a greater remobilization within plant tissues early in the season compared to traditional cultivars (Dong et al., 2004; Miley & Oosterhuis, 1990). Consequently, uptake of K may occur at a faster rate than K is replenished in the soil solution (Lewis et al., 2021), reinforcing the need for adequate K fertilization for optimal cotton growth and yield potential.

Changes in plant nutrient concentrations are associated with nutrient remobilization in plant tissue during the growing season, especially during the transition from the vegetative to the reproductive stage, when K deficiency symptoms usually start appearing in plants growing on soils with below-optimum K availability (Cassman et al., 1989). Symptoms of visual K deficiency appear near the top of the plant during flowering and boll development. Severe deficiency is characterized by interveinal chlorosis, which in cotton is similar for both the top and bottom of the plant due to its indeterminate growth habit (Dong et al., 2004; McMurtrey, 1948; Reddy et al., 2000). When K deficiency symptoms are visible in the leaves, all other parts of the plant are already impacted as the leaves are less sensitive to K deficiency than stems and roots (Dong et al., 2004), and the cotton yield potential may already have been compromised (Murrell et al., 2021; Rosolem & Mikkelsen, 1991). Moreover, visually detecting nutrient deficiency can be difficult and unreliable, as it does not diagnose “hidden hunger,” a condition in which plants show no visual K deficiency symptoms, but tissue-K concentrations are low enough to negatively affect plant growth and reduce yield (Ortel et al., 2023; Stevens et al., 2002).

A proactive way of assessing crop nutritional status and avoiding yield losses is plant tissue analysis. For decades, tissue testing has served as a practical tool for monitoring in-season plant nutrient status in agricultural systems (Joham, 1951; Hsu et al., 1978; dos Santos et al., 2021; Gruener et al., 2022; Mallarino, 1996; Ortel et al., 2023; Slaton et al., 2009, 2021; Stammer & Mallarino, 2018). Tissue analysis measures the nutrient concentration in plant material, and concentrations are traditionally categorized as deficient, adequate, and excessive or toxic, based on critical nutrient concentrations or “sufficiency ranges” specific to a given plant tissue (e.g., leaves or petioles) at defined growth stages (Römheld, 2012). Nutrient levels above this range promote near-maximum yield, while levels below critical values or sufficiency ranges can lead to yield loss (Dow & Roberts, 1982; Mills, 1996). Tissue testing is well-established based on replicated field-based research trials in Arkansas for soybean [*Glycine max* (L.) Merr.; Parvej et al., 2016; Slaton et al., 2010, 2021], rice (*Oryza sativa* L.; Gruener et al., 2022; Slaton et al., 2009), and corn (*Zea mays* L.; dos Santos et al., 2021). These studies proposed growth-stage-specific critical tissue-K or nitrogen (N) concentrations by collecting tissue samples from multiple field trials and correlating the relative crop yield with tissue-nutrient concentrations. Research by Parvej et al. (2016), Slaton et al. (2021), and Gruener et al. (2022) has shown that tissue-K concentrations in soybean and rice decrease at a predictable rate across time during reproductive growth regardless of K fertilization rate. However, across the country, most research on cotton K nutrition has focused on leaf or petiole analysis conducted at early flowering or active flowering, with limited research at later reproductive development stages (Hsu et al., 1978; Kerby & Adams, 1985; Reddy et al., 2000; Sabbe & MacKenzie, 1973). Additionally, most tissue-K sufficiency ranges or critical concentrations reported in the literature were surveyed based on healthy cotton fields or conducted in greenhouse conditions, lacking calibration with

cotton yield potential (Anderson, 1971; Bassett et al., 1970; Mitchell & Baker, 1997; Sabbe & MacKenzie, 1973). Therefore, there is limited information available on critical tissue-K dynamics throughout cotton reproductive development, and a lack of up-to-date, calibrated critical tissue-K concentrations to maximize cotton yield.

Nutrient concentrations in plant tissues are dynamic and differ among various parts (e.g., leaves vs. petioles; Goodall & Gregory, 1947; Jones, 1970), crop species, growth stages, and yield potential (Adriano, 1986; Chapman, 1966; Martin-Prevel et al., 1987; Reuter & Robinson, 1997; Tyner, 1948). Sabbe and MacKenzie (1973) and Hsu et al. (1978) recommend petiole analysis for assessing cotton K nutritional status due to its sensitivity and broader range of K concentration in response to changes in K status. Similarly, Joham (1951) recommended using petioles to assess the nutritional status of cotton plants. In particular, the author identified the petioles of the uppermost expanded leaf on the main stem (third to fourth node) to be more sensitive to diagnosing K nutritional status due to soluble K accumulation. On the other hand, Oosterhuis and Morris (1979) reported that petiole testing is too variable and unrelated to yield as K concentrations decline quickly, making petiole analyses less useful at late-flowering and fruiting periods than leaf blade testing. Hall and Baker (1972) and Baker et al. (1992) investigated leaf analysis from different positions within the plant and reported varying critical K concentrations, as well as a significant difference in K concentrations between leaves sampled at the top and bottom of the cotton plant. This suggests that collecting the correct plant sample is crucial for an accurate K nutritional diagnosis. Pabuayon et al. (2020) highlighted that the smaller decline of nutrient concentrations throughout the growing season in cotton leaves compared to petioles may impact the ability to effectively detect nutrient deficiencies. Regardless of the sampling material and critical K concentration, Reddy et al. (2000) demonstrated a positive correlation between petiole-K and leaf-K concentrations. Inconsistent reports in the literature hinder the development of a reliable tissue-K monitoring program for cotton in the southern region of the United States. Additionally, making in-season fertilization decisions based on a misunderstanding of tissue analysis often results in a loss of profit (Slaton et al., 2021).

The inconsistent data in the literature regarding sampling time, plant tissues to sample, critical K concentrations, and sufficiency ranges highlight the complex dynamics of K in the soil–plant system. These unknowns emphasize the need for further research to establish effective tissue sampling protocols and critical K concentrations associated with plant yield potential, thereby allowing the monitoring of plant nutritional status in modern cotton cultivars. We hypothesize that (1) cotton leaves are a more accurate predictor of plant-K nutritional status than petioles as leaves are the main plant K storage unit and have a smaller K concentration amplitude com-

Core Ideas

- Critical leaf- and petiole-K concentrations were defined throughout cotton reproductive growth stages.
- Critical tissue-K concentrations are dynamic throughout reproductive development, making sampling time important.
- Critical petiole-K concentrations decline at a faster rate than critical leaf-K concentrations.
- Petiole testing during squaring and peak flowering is a sensitive tool for monitoring cotton K nutrition.

pared to petioles; (2) increased K availability (either soil or K fertilization) positively affects cotton leaf and petiole concentrations; however, as the growing season progresses, the tissue-K concentration in vegetative structures will decrease as K is remobilized to reproductive plant tissues; and (3) relative cotton yield is positively related with increased leaf- and petiole-K concentrations as K nutritional status improves photosynthesis efficiency and optimizes nutrient transport. Our objectives were to investigate how leaf- and petiole-K concentrations are affected by K availability (soil and K fertilization) and sampling time, define which plant tissue (leaf or petiole) is more sensitive for monitoring cotton K nutrition status, and correlate relative cotton yield with leaf- and petiole-K concentrations at individual growth stages to establish dynamic critical tissue-K concentrations, assisting with cotton K nutritional status diagnosis.

2 | MATERIALS AND METHODS

Field trials were established at the University of Arkansas System Division of Agriculture research stations in 2023 and 2024 to investigate cotton yield response to K fertilization and define critical leaf- and petiole-K concentrations at different growth stages. In 2023, research was conducted in Marianna, AR, at the Lon Mann Cotton Research Station (LMCRS), and in Fayetteville, AR, at the Milo J. Shult Agricultural Research and Extension Center (SAREC) on soils with very low (<61 mg K kg⁻¹) and medium (91–130 mg K kg⁻¹) soil-test K levels (Robertson et al., 2022), respectively. During the 2024 growing season, two field trials were conducted at LMCRS and one additional trial at the Rohwer Research Station (RRS) in Rohwer, AR, on soils with very low and low (61–90 mg K kg⁻¹) soil-test K levels. The site location, soil series, and agronomic information for each trial are presented in Table 1. Each trial used a randomized complete block design with four replicates. Plots were four rows wide

TABLE 1 Site-year location, soil series, and agronomic information for K fertilization trials conducted in Arkansas during the 2023 and 2024 growing seasons.

Site	Year	Trial ID	Location	GPS coordinates	Soil series ^a	Cultivar ^b	Previous crop	Row width (cm)
1	2023	LMCRS-G14A	Marianna	34.7297, −90.7363	Convent	DP 2020 B3XF	Corn	97
2	2023	SAREC-I5	Fayetteville	36.0957, −94.1787	Captina	DP 2020 B3XF	Fallow	91
3	2024	LMCRS-G14C	Marianna	34.7292, −90.7336	Convent	NG 3195 B3XF	Soybean	97
4	2024	LMCRS-G15D	Marianna	34.7236, −90.7355	Convent	PHY 411 W3FE	Corn	97
5	2024	RRS-1DS	Rohwer	33.8065, −91.2704	Hebert	PHY 411 W3FE	Corn	97
6	2024	LMCRS-1BNf ^c	Marianna	34.7289, −90.7594	Calloway	NG 3195 B3XF	Corn	97
7	2024	LMCRS-1BNcc ^d	Marianna	34.7289, −90.7594	Calloway	NG 3195 B3XF	Corn	97
8	2024	RRS-1DNf ^c	Rohwer	33.8077, −91.2704	Hebert	PHY 411 W3FE	Corn	97
9	2024	RRS-1DNcc ^d	Rohwer	33.8077, −91.2704	Hebert	PHY 411 W3FE	Corn	97

Abbreviations: LMCRS, Lon Mann Cotton Research Station; RRS, Rohwer Research Station; SAREC, Milo J. Shult Agricultural Research and Extension Center.

^aPredominant soil series. Convent silt loam (45.2%; coarse-silty, mixed, superactive, nonacid, thermic Fluvaquentic Endoaquepts), Captina silt loam (100%; fine-silty, siliceous, active, mesic Typic Fragiudults), Calloway (54%; fine-silty, mixed, active, thermic Aquic Fraglossudalfs), and Hebert (59% silt loam, fine-silty, mixed, superactive, mesic Udollic Epiaqualfs).

^bDP, Deltapine (Bayer Crop Science); NG, NexGen (Americot); PHY, PhytoGen (Corteva Agriscience).

^cLong-term trial with winter fallow.

^dLong-term trial with cereal rye (*Secale cereale* L.) and hairy vetch (*Vicia villosa* Roth.) mix as winter cover crop.

(91 or 97 cm) and 12 m long for the 2023 trials and 15 m long for the 2024 trials. High-yielding traits characterize the cultivars selected for this study and represent the cotton acreage of Arkansas and the Mid-South United States. Irrigation timing was scheduled according to the Arkansas Irrigation Scheduler, set for a 5-cm soil profile water level deficit. Weather information recorded by the nearest weather station of each research station is provided in Figure S1. All crop management practices (e.g., pest and weed control) closely followed the University of Arkansas Cooperative Extension Service recommendations.

Data were also collected in the 2024 growing season from two long-term trials established in 2017 at LMCRS and RRS to examine the effects of off-season management (winter fallow or cover crop) and fertilizer-K rate (0, 56, 112, and 168 kg K ha^{−1}) on cotton yield response in a corn–cotton–soybean rotation (Smartt et al., 2024). A brief narrative of the field and crop management in the long-term trial is presented in the following text. In the first year, corn was planted without fertilizer-K, followed by a cereal rye (*Secale cereale* L.) cover crop planted in the fall of 2017. Fertilizer treatment applications were initiated in the spring of 2018, followed by cotton in the 2018 growing season, soybean in 2019, and then main-

taining the 3-year corn–cotton–soybean rotation throughout the subsequent years. Following corn harvest in the fall 2023, cover crop treatments were established by drill seeding a 50:50 mix of cereal rye and hairy vetch (*Vicia villosa* Roth) at 40 kg ha^{−1} in half of the plots, with 15-cm row spacing, in early November. Cotton was planted after cover crop termination in the spring of 2024. Plots were four rows (97-cm row spacing) wide and extended the length of each field, approximately 67 m at RRS and 79 m at LMCRS. The experimental design of each trial consisted of three replicates, a randomized complete block with a split-plot treatment structure where cover crop (with or without) was the main plot factor and fertilizer rate was the subplot factor. This study will not assess the interaction between cover crop and fertilizer-K rates; therefore, the main effect of K fertilization will be evaluated separately for winter fallow and cover crop treatments, totaling two site-years per location (i.e., four sites in total; Table 1).

Composite soil samples (six to eight individual 2.2 cm cores) were collected from each replicate at the 0- to 15-cm depth before planting and applying the fertilizer-K rate treatments in all the trials, except in long-term trials, where two composite soil samples were collected from each plot to track

TABLE 2 Mean soil pH, Mehlich-3 extractable nutrients, and soil organic matter (SOM) in the 0- to 15-cm depth prior to fertilizer-K treatment application and planting of cotton K response trials during the 2023 and 2024 growing seasons.

Site ^a	pH ^b	Mehlich-3 extractable nutrients ^d										SOM (g kg ⁻¹) ^e
		P (mg kg ⁻¹)	K (mg kg ⁻¹) ^c	Ca (mg kg ⁻¹)	Mg (mg kg ⁻¹)	S (mg kg ⁻¹)	Fe (mg kg ⁻¹)	Mn (mg kg ⁻¹)	Zn (mg kg ⁻¹)	Cu (mg kg ⁻¹)	B (mg kg ⁻¹)	
1	7.8	31	53 (4.4)	1357	306	7.3	315	217	2.5	2.0	0.5	16
2	5.8	80	114 (17.4)	501	32	7.9	153	145	7.3	0.9	0.2	13
3	6.5	15	47 (3.1)	931	218	3.8	125	117	1.7	0.9	0.8	24
4	6.6	49	85 (10)	1516	408	4.5	149	116	2.4	1.3	0.8	21
5	6.5	17	56 (6.9)	679	120	4.7	154	87	2.6	0.7	0.9	18
6	7.4	38	48–182 ^f	1147	315	5.3	171	125	4.1	1.2	0.4	15
7	7.1	34	57–181 ^f	1196	294	5.7	169	120	3.5	1.2	0.4	18
8	6.5	38	62–211 ^f	725	115	4.9	217	101	3.0	0.7	0.7	14
9	6.5	38	46–147 ^f	765	109	5.2	247	108	3.1	0.7	0.8	16

^aTrial location and agronomic information are presented in Table 1.

^bSoil pH measured in a 1:2 (weight:volume) soil–water mixture (Sikora & Kissel, 2014).

^cMean ($\pm$ standard deviation).

^dZhang et al. (2014).

^eSoil organic matter as determined by loss on ignition (Combs & Nathan, 2015).

^fSoil-test K values regarding plot-level data are presented in Prado et al. (2025).

the long-term effects of crop and nutrient management on soil test values. After sampling, the soil was oven-dried at 55°C for 48 h, ground in a mechanical grinder (Dynacrush soil crusher, Custom Laboratory) to pass through a sieve with 2-mm openings, and stored at room temperature for subsequent chemical analyses. Oven-dried soil samples were analyzed for pH (1:2 v/v soil/water mixture; Sikora & Kissel, 2014), Mehlich-3 extractable nutrients (Zhang et al., 2014), and soil organic matter by weight loss on ignition (Combs & Nathan, 2015). The nutrient concentrations of Mehlich-3 extracts were determined using inductively coupled plasma optical emission spectrophotometry (ICP-OES; Spectro Arcos, Spectro Arcos model 160). Selected soil chemical characteristics from each location are shown in Table 2.

Fertilizer-K treatment rates were 0, 37, 75, 112, 150, and 187 kg K ha⁻¹ at single-site-year trials (Sites 1–5), and 0, 56, 112, and 168 kg K ha⁻¹ at long-term trials (Sites 6–9) and were applied as muriate of potash (500 g K kg⁻¹). This wide range of fertilizer-K rates, applied to various soil-test K values, enabled data collection on diverse soil K availabilities to assess the effect of K nutrition on cotton yield and fiber development. Treatments were broadcast applied and incorporated into the raised bed before planting for single-site-year trials and broadcast on the soil surface for long-term trials. Based on initial soil test results (Table 2), trials in 2023 received 34 kg P ha⁻¹ (triple superphosphate; 201 g P kg⁻¹) and 34 kg N ha⁻¹ and 38 kg S ha⁻¹ as ammonium sulfate (210 g N kg⁻¹; 240 g S kg⁻¹) applied before planting to provide adequate nutrient availability for plant development. Additionally, each trial received 90 kg N ha⁻¹ as urea (460 g N kg⁻¹) between first square and first flower. A foliar application of Solubor (0.6 kg

B ha⁻¹; U.S. Borax Inc.) was made on July 10 at LMCRS and on July 11 at SAREC.

For the 2024 growing season, single-site-year trials at LMCRS received 44 kg P ha⁻¹ (triple superphosphate; 201 g P kg⁻¹), while RRS received 34 kg P ha⁻¹ using the same fertilizer source; 34 kg N ha⁻¹ and 38 kg S ha⁻¹ as ammonium sulfate were applied prior to planting, followed by 90 kg N ha⁻¹ application as urea on July 2 (between first square and first flower) at LMCRS trials and 140 kg N ha⁻¹ as urea ammonium nitrate (UAN; 320 g N kg⁻¹) on June 28 at RRS. Additionally, Solubor (0.3 kg B ha⁻¹) foliar applications were made on July 25 at LMCRS trials and August 1 at RRS. Long-term trials received a blanket application of 23 kg P ha⁻¹ and 103 kg N ha⁻¹ as urea (LMCRS) and 135 kg N ha⁻¹ as UAN (RRS) between first square and first flower.

2.1 | Cotton tissue sampling

Cotton tissue samples consisting of 15 leaves and their petioles were collected from the two middle rows of each plot from the uppermost fully expanded leaf, normally the third or fourth node from the top of the plant. Sampling started at first square (approximately 35 days after planting [DAP]), followed by the first flower (around 60 DAP), and continued weekly (weeks after first flower [WAFF]) until early boll and fiber maturation (about 110 DAP and 8 WAFF; Table 3). At each sampling time, the leaves and petioles were separated and placed into different labeled paper bags. Samples were oven-dried at 55°C, ground to pass a sieve with 1-mm openings, and digested with concentrated HNO₃ and 30% H₂O₂

TABLE 3 Agronomic information and cotton leaf and petiole sampling dates for the nine trials conducted in Arkansas during the 2023 and 2024 growing seasons.

Cotton leaf and petiole sample collection dates											
Site ^a	Planting date	First square ^b	First flower ^c	1 WAFF ^d	2 WAFF	3 WAFF	4 WAFF	5 WAFF	6 WAFF	7 WAFF	8 WAFF
1	May 17	June 28	July 20	July 25 (6) ^e	Aug 1 (13)	Aug 9 (21)	Aug 15 (27)	Aug 22 (34)	Aug 30 (42)	Sept 7 (50)	Sept 13 (56)
2	May 8	June 27	July 13	July 20 (7)	July 27 (14)	Aug 3 (21)	Aug 10 (28)	Aug 17 (35)	Aug 24 (42)	Aug 31 (49)	Sept 7 (56)
3	May 21	July 3	July 17	July 24 (7)	July 31 (14)	Aug 7 (21)	Aug 13 (27)	Aug 21 (35)	Aug 27 (41)	- ^f	-
4	May 21	July 3	July 17	July 24 (7)	July 31 (14)	Aug 7 (21)	Aug 13 (27)	Aug 21 (35)	Aug 27 (41)	Sept 3 (48)	Sept 11 (56)
5	May 29	July 3	July 24	July 31 (7)	Aug 7 (14)	Aug 13 (20)	Aug 21 (28)	Aug 27 (34)	Sept 3 (41)	Sept 11 (49)	Sept 18 (56)
6 and 7	May 21	July 3	July 17	July 24 (7)	July 31 (14)	Aug 13 (21)	Aug 21 (27)	Aug 27 (35)	Sept 3 (41)	Sept 11 (48)	-
8 and 9	May 21	July 3	July 17	July 24 (7)	July 31 (14)	Aug 13 (21)	Aug 21 (27)	Aug 27 (35)	Sept 3 (41)	Sept 11 (48)	Sept 18 (56)

^aTrial location and more agronomic information are presented in Table 1.
^bFirst square is the stage at which 50% of plants have a visible first square.
^cFirst Flower is the stage at which at least 50% of plants have an open white flower.
^dWeek(s) after first flower.
^eNumber of days after first flower.
^fNo samples taken due to advanced plant tissue senescing.

(Jones & Case, 1990). Then, concentrations of K and other nutrients in the digests were determined by ICP-OES. All plant analyses were performed at the University of Arkansas System Division of Agriculture’s Fayetteville Agricultural Diagnostic Laboratory.

2.2 | Cotton yield

At maturity, the two center rows of each plot were harvested with a spindle-type picker or handpicked (Site 2) for yield measurement. Before harvesting, a subsample of 20 cotton bolls (representing the bottom, middle, and top of the plant across five different plants) was collected from the two middle rows in all trials and processed through a laboratory cotton saw gin to determine the weight and lint percentage (Bourland et al., 2010; Cole et al., 2016). The lint yield was calculated by multiplying each trial’s average fiber percentage per treatment by the corresponding total seedcotton yield of the treatment plots. Additionally, relative yield was calculated by dividing the yield in each plot by the highest yielding treatment in each replicate and multiplying by 100 (Pearce et al., 2022). Using relative yield for nutrient correlation and calibration research allows scientist to normalize crop yield data across sites, environments (Black, 1993; Pearce et al., 2022) and account for variability among site-years due to plant genetics and cultivar performance, field management practices (e.g., irrigation, tillage, and weed and pest control), or environmental factors (e.g., weather and soil properties).

2.3 | Statistical analysis

Single-site-year trials were a randomized complete block design with four replicates. Long-term trials were a randomized complete block design with three replicates, where the main effect of winter cover crop was not evaluated. Analysis of variance was performed by location to evaluate the effect of fertilizer-K rate on cotton lint yield using the PROC GLIMMIX procedure of SAS v. 9.4 (SAS Institute Inc., 2013) with replicate set as a random effect and fertilizer-K rates as a fixed effect, and the differences being interpreted as significant at $\alpha = 0.10$. Additionally, using the same procedure of PROC GLIMMIX, the relationship between tissue-K concentration over time for selected fertilizer-K rates (0, 56, 75, 112, and 150 kg K ha⁻¹) was evaluated, with a gamma distribution and a log transformation of leaf- and petiole-K concentrations. At specific site-year and K rate combinations where the model did not converge, a normal distribution was used instead. To define critical tissue-K concentration for near-maximum cotton production, data were analyzed in R version 4.3.2 (R Core Team, 2023) using the “soiltestcorr” package (Correndo et al., 2023). The quadratic, linear plateau, and quadratic plateau

TABLE 4 Cotton lint yield as affected by fertilizer-K rate across the nine trials conducted in Arkansas during the 2023 and 2024 growing seasons.

Site	Fertilizer rate (kg K ha ⁻¹)						<i>p</i> -value	C.V. (%)
	0	37 or 56	75	112	150 or 168	187		
	Cotton lint yield (kg ha ⁻¹)							
1	1432 c	1643 b	1818 a	1810 ab	1812 a	1869 a	0.0011	7.9
2	1371	1640	1685	1677	1612	1624	0.5240	19.3
3	370 c	650 b	753 b	1065 a	999 a	1103 a	<0.0001	29.8
4	1501 d	1628 c	1869 ab	1850 b	1860 ab	1978 a	<0.0001	4.7
5	1043 c	1309 b	1317 b	1440 ab	1458 ab	1518 a	0.0001	8.1
6	592 b	1194 a	–	1586 a	1359 a	–	<0.0001	9.4
7	1595 b	1813 a	–	1858 a	1873 a	–	0.0658	10.3
8	1402 c	2005 a	–	1855 ab	1738 b	–	0.0027	8.1
9	1663	1949	–	1751	1825	–	0.2584	9.4

Note: Means followed by the same lowercase letter within a site (row) are not different at the 0.10 probability level. CV = coefficient of variation.

models were tested to determine the relationship between relative cotton yield and tissue-K concentrations (data not shown). The linear plateau model provided a better fit (greater R^2 values, narrower confidence intervals, and lower Akaike's information criterion value) and was used to determine the critical leaf- and petiole-K concentrations for each tissue sampling time. The studentized residual (>2.5) and Cook's D (>0.16) statistics were reviewed to identify potential outliers and influential data. When necessary, outlying or influential observations were omitted, and the model was refit.

3 | RESULTS

3.1 | Cotton lint yield

Cotton lint yield was significantly affected by K fertilization ($p \leq 0.10$) in seven out of nine field trials (Table 4). Cotton yield in the no-K control ranged from 35% to 79% of the yield in the fertilizer-K treatments that maximized yield. Since the trials represent a range of soil-test K values, the fertilizer-K rate required to achieve maximum yield, as well as the magnitude of yield increase with fertilizer-K application, differed among sites. Very low and low soil-test K sites maximized lint yield with fertilizer-K applications of 75 or 112 kg K ha⁻¹, with yield increase ranging from 218 to 695 kg lint ha⁻¹ compared to the no-fertilizer-K control. The single-year Site 2 (medium soil-test K) and the long-term Site 9 did not show significant yield response to K fertilization ($p = 0.5240$ and 0.2584, respectively); only a numerical yield increase of 269 and 286 kg ha⁻¹, respectively, was observed with the lowest fertilizer-K rate. Overall, the maximum cotton yield in plots with K fertilization ranged from 1103 to 2005 kg lint ha⁻¹, with an overall mean of 1729 kg lint ha⁻¹.

3.2 | Tissue-K concentration as affected by potassium fertilization after first flower

Leaf- and petiole-K concentrations decreased linearly or quadratically over the days following the first flower growth stage across all nine trials (Figures 1 and 2). The intercepts for each trial varied among K rates and increased as the fertilizer-K rate increased (Tables 5 and 6). Overall, leaf-K concentrations decreased at a predictable rate as captured by the model fit. In the very low and low soil-test K trials (Figure 1a,c–e), leaf-K concentrations ranged from 8.81 to 3.21 g K kg⁻¹ in the no-K control from first flower to 8 WAFF, 9.74 to 4.18 g K kg⁻¹ at 75 kg K ha⁻¹, and 11.9 to 4.54 g K kg⁻¹ at 150 kg K ha⁻¹. Notably, the medium soil-test K trial (Figure 1b) showed a K concentration of 11.2 g K kg⁻¹ at first flower under the no fertilizer-K control, which was similar to the values observed with the 150 kg K ha⁻¹ application in the very low and low soil-test K trials. Additionally, the values for 75 and 150 kg K ha⁻¹ applications were similar for this location (Figure 1b), as this site already had greater soil K availability than the other single-site-year trials (Table 2). In general, the linear or quadratic data fit is supported by the R^2 values, which ranged from 0.65 to 0.92 across all single-site-year trials and 0.26 to 0.89 at the long-term trials (Figure 1f–i). The variation and slightly lower R^2 values observed in the long-term trials are likely associated with the overall large size of the trial, with greater soil-test K variability.

Similar to the leaf-K concentrations, regardless of fertilizer-K rate, there was a strong relationship between petiole-K concentration and days after first flower (R^2 values ranging from 0.66 to 0.96 for the single-site-year trials, and 0.29 to 0.90 for the long-term trials; Figure 2; Table 6). However, in contrast to the overall gradual decline observed in leaf-K concentrations, petiole-K concentrations decreased rapidly after first flower across all trials (Figure 2). Consid-

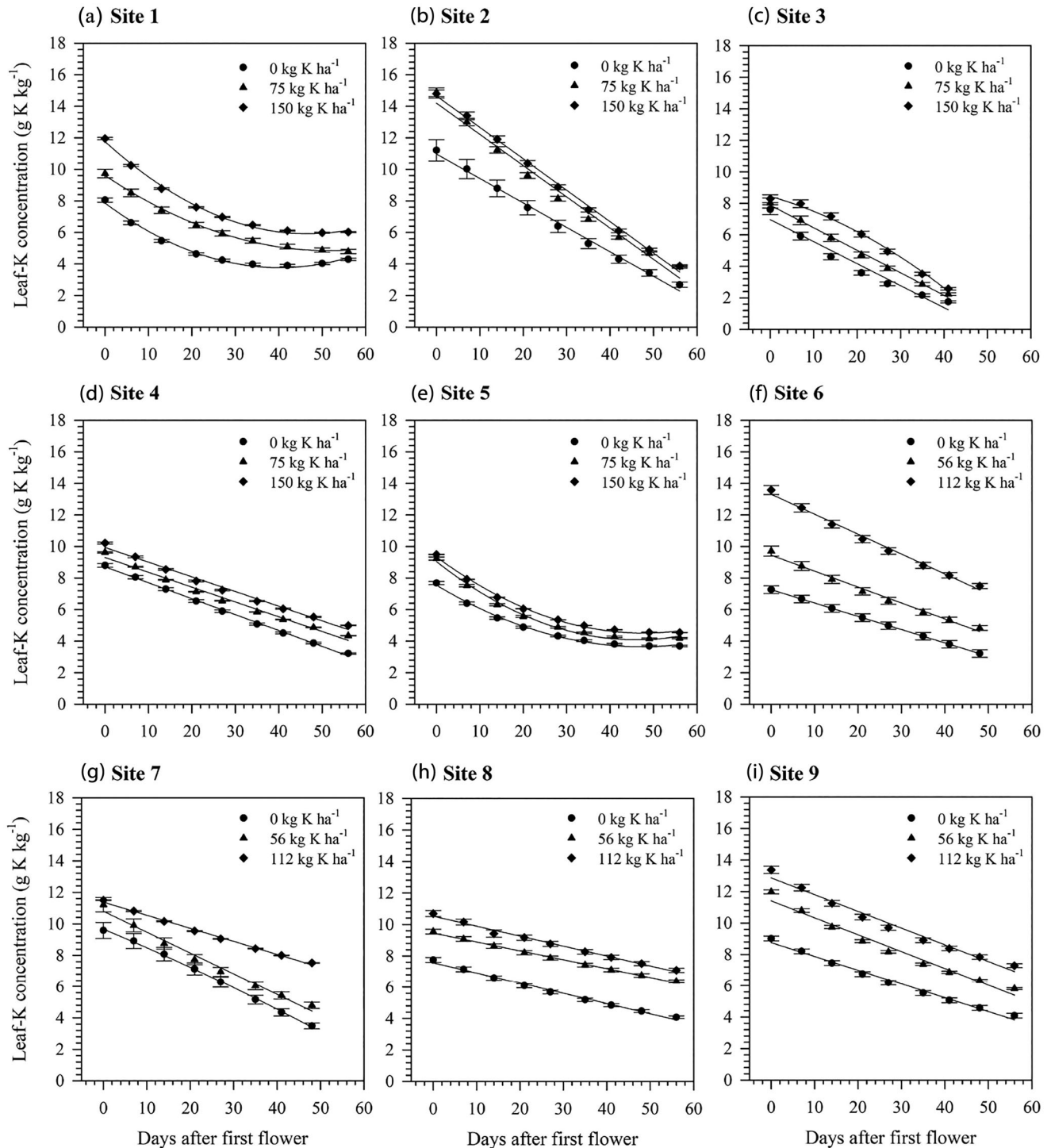


FIGURE 1 Predicted cotton leaf-K concentration after the first flower growth stage as affected by different fertilizer-K rates in five single-site-year trials (Sites 1–5) conducted during the 2023 and 2024 growing seasons and four long-term trials (Sites 6–9; established in 2017) during the 2024 growing season. All trials were conducted at the University of Arkansas System Division of Agriculture research properties (Table 1). Regression coefficients for each site and fertilizer-K rate are listed in Table 5.

ering that the petiole acts like a pathway for the nutrient, the increased K availability present at the medium soil-test K trial (Figure 2b) did not appear to influence the petiole-K concentrations at first flower, as observed for the leaf-K

concentrations when compared to the other single-site-year trials with lower soil-test K values. A great range of petiole-K concentration was observed among trials and sampling times, with values fluctuating from 62.3 to 3.63 g K kg⁻¹ from first

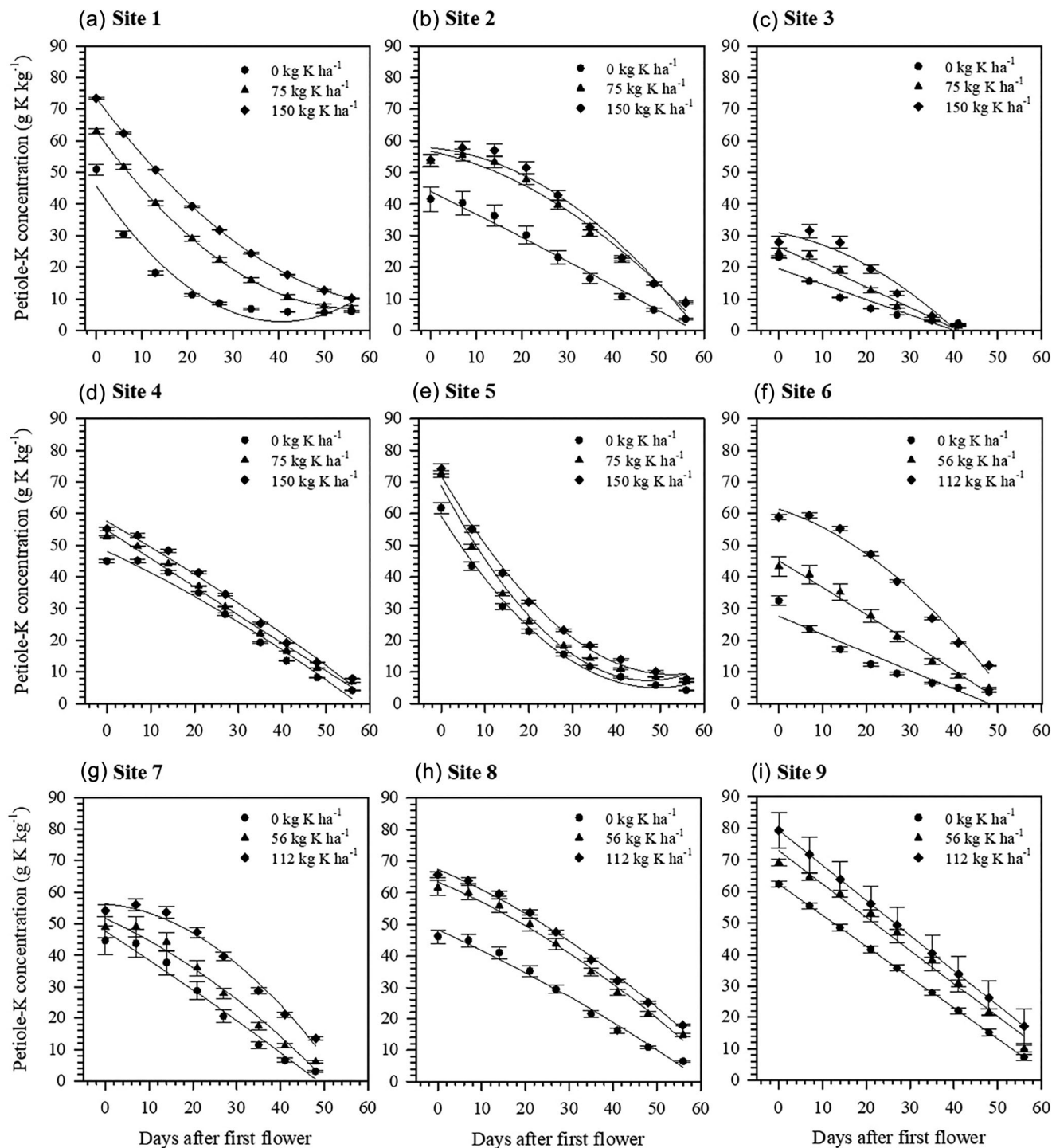


FIGURE 2 Predicted cotton petiole-K concentration after the first flower growth stage as affected by different fertilizer-K rates across five single-site-year trials (Sites 1–5) conducted during the 2023 and 2024 growing seasons and four long-term trials (Sites 6–9; established in 2017) during the 2024 growing season. All trials were conducted at the University of Arkansas System Division of Agriculture research properties (Table 1). Regression coefficients for each site and fertilizer-K rate are listed in Table 6.

TABLE 5 Regression coefficients and standard errors (SE) for predicting cotton leaf-K concentrations during reproductive stages (days after first flower) as affected by fertilizer-K rate for nine trials conducted in Arkansas during the 2023 and 2024 growing seasons.

Site ^a	K rate (kg K ha ⁻¹)	Intercept ^b	SE	Linear	SE	Quadratic	SE	R ²
1	0	2.0847	0.07456	-0.03538	0.005254	0.000431	0.00009	0.73
	75	2.2712	0.08317	-0.02356	0.004704	0.000195	0.000081	0.89
	150	2.4812	0.0492	-0.02713	0.003878	0.000266	0.000067	0.83
2	0	2.3936	0.1523	-0.01462	0.006497	-0.00019	0.000112	0.84
	75	2.6993	0.07617	-0.01875	0.005247	ns ^d	—	0.87
	150	2.6922	0.08671	-0.0126	0.006215	-0.0002	0.000107	0.78
3	0	2.0192	0.1029	-0.03578	0.002200	ns	—	0.92
	75	2.0729	0.116	-0.019	0.008316	ns	—	0.90
	150	2.1101	0.1001	-0.00091	0.008318 ^c	-0.00067	0.000194	0.82
4	0	2.1743	0.07301	-0.01184	0.005388	ns	—	0.83
	75	2.2651	0.05644	-0.01425	0.001633	ns	—	0.79
	150	2.3251	0.05311	-0.01281	0.001492	ns	—	0.72
5	0	2.0385	0.08859	-0.0281	0.006741	0.000267	0.000116	0.65
	75	2.2231	0.07394	-0.03158	0.005649	0.000311	0.000097	0.76
	150	2.2515	0.0716	-0.02774	0.00601	0.00026	0.000103	0.70
6	0	7.2651 ^c	0.2481	-0.08456	0.0101	ns	—	0.53
	56	2.2688	0.08927	-0.01454	0.0019	ns	—	0.87
	112	2.6074	0.07545	-0.01239	0.001977	ns	—	0.70
7	0	2.2487	0.1197	-0.00857	0.005514	-0.00026	0.00011	0.89
	56	2.4097	0.1114	-0.01773	0.002222	ns	—	0.85
	112	2.4424	0.05733	-0.00887	0.001930	ns	—	0.51
8	0	2.0447	0.08185	-0.01148	0.001949	ns	—	0.60
	56	2.2555	0.07333	-0.00722	0.001851	ns	—	0.77
	112	2.3683	0.05523	-0.00736	0.001825	ns	—	0.26
9	0	8.7584 ^c	0.4113	-0.08819	0.01395	ns	—	0.54
	56	2.4627	0.08187	-0.01292	0.002264	ns	—	0.78
	112	2.5745	0.06363	-0.0108	0.002117	ns	—	0.45

^aTrial location and agronomic information are presented in Table 1.

^bCoefficients were obtained from PROC GLIMMIX using a gamma distribution and log transformation of data. Equations included linear and/or quadratic terms as appropriate. Predicted values were calculated as $y = \exp(ax^2 + bx + c)$, omitting nonsignificant terms. Terms are as follows: x = days after first flower, a = quadratic coefficient, b = linear coefficient, c = intercept, and $\exp$ = the natural exponential function.

^cWhen models did not converge, a normal distribution was used, assuming normally distributed residuals.

^dQuadratic coefficients were not significant ($p \geq 0.10$) in the model.

flower to 8 WAFF at the no-K control, 72.6 to 6.78 g K kg⁻¹ at 75 kg K ha⁻¹, and 79.4 to 7.80 g K kg⁻¹ at 150 kg K ha⁻¹ application.

3.3 | Critical leaf- and petiole-K concentrations throughout cotton development stages

The nine field trials provided a wide range of soil-test K values and cotton yield response to K fertilization (Figures 3 and 4; Tables 2 and 4). The total number of tissue sam-

ples collected from multiple sampling timings and site-years totaled over 1500 datapoints for leaf- and petiole-K concentrations, providing a robust database for the overall goal of establishing critical tissue-K concentrations throughout cotton development stages.

There was a significant and positive relationship between leaf-K concentration and relative cotton yield at various growth stages (Figure 3; Table 7). Regardless of tissue sampling time, relative cotton yield increased with increasing leaf-K concentrations until reaching a plateau, indicating no yield benefit with additional K availability beyond this point. The linear plateau model showed a moderate to strong

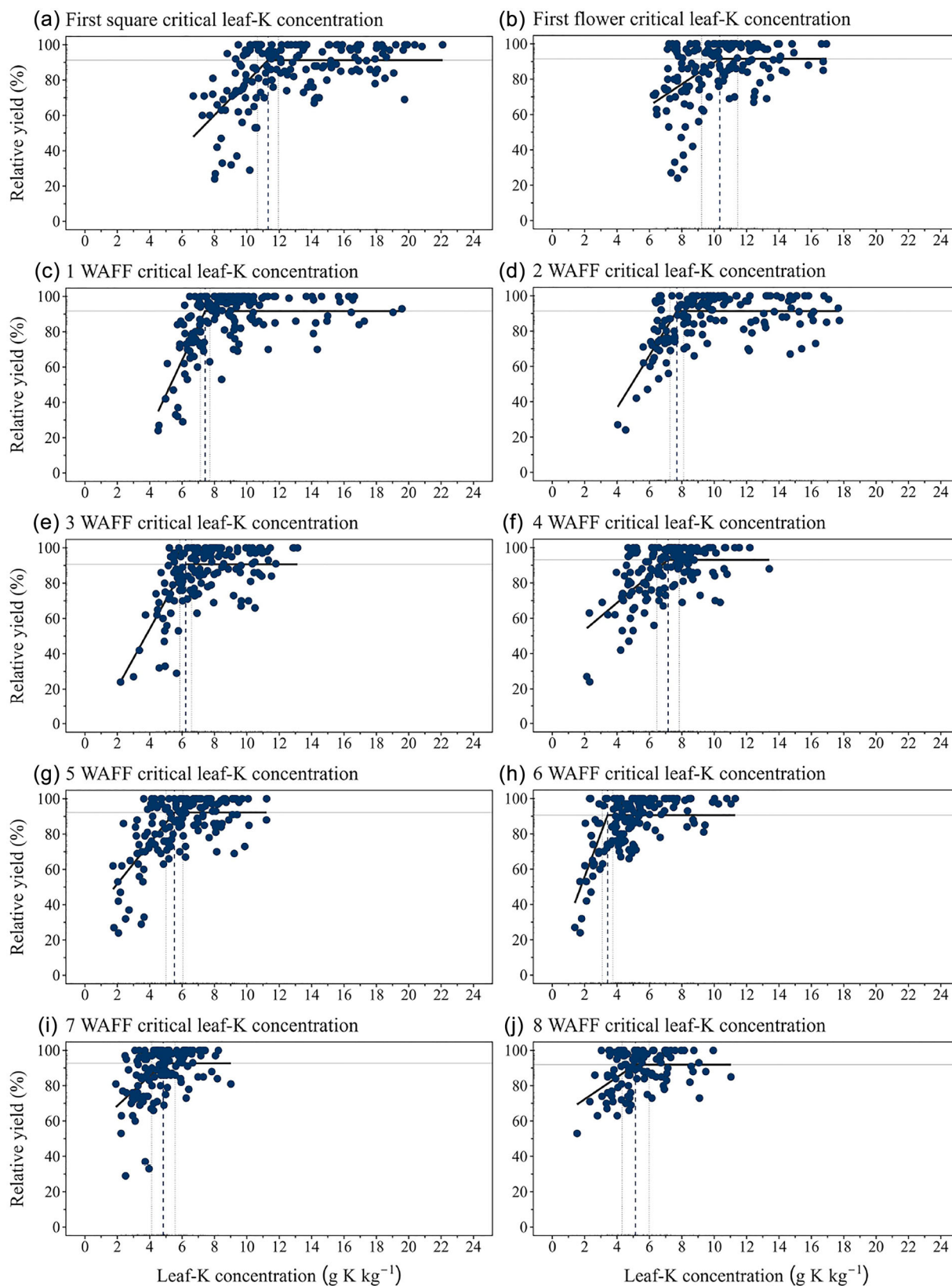


FIGURE 3 Cotton critical leaf-K concentrations across different growth stages (first square, first flower, and weekly beginning at first flower and extending until early boll and fiber maturity, i.e., 8 weeks after first flower [WAFF]). The dataset encompasses nine field trials conducted at the University of Arkansas System Division of Agriculture's properties during 2023 and 2024, utilizing three modern cotton cultivars. Dashed lines indicate the critical leaf-K concentration to produce maximum yield, along with confidence intervals. Model coefficients, critical concentration, and confidence interval are listed in Table 7.

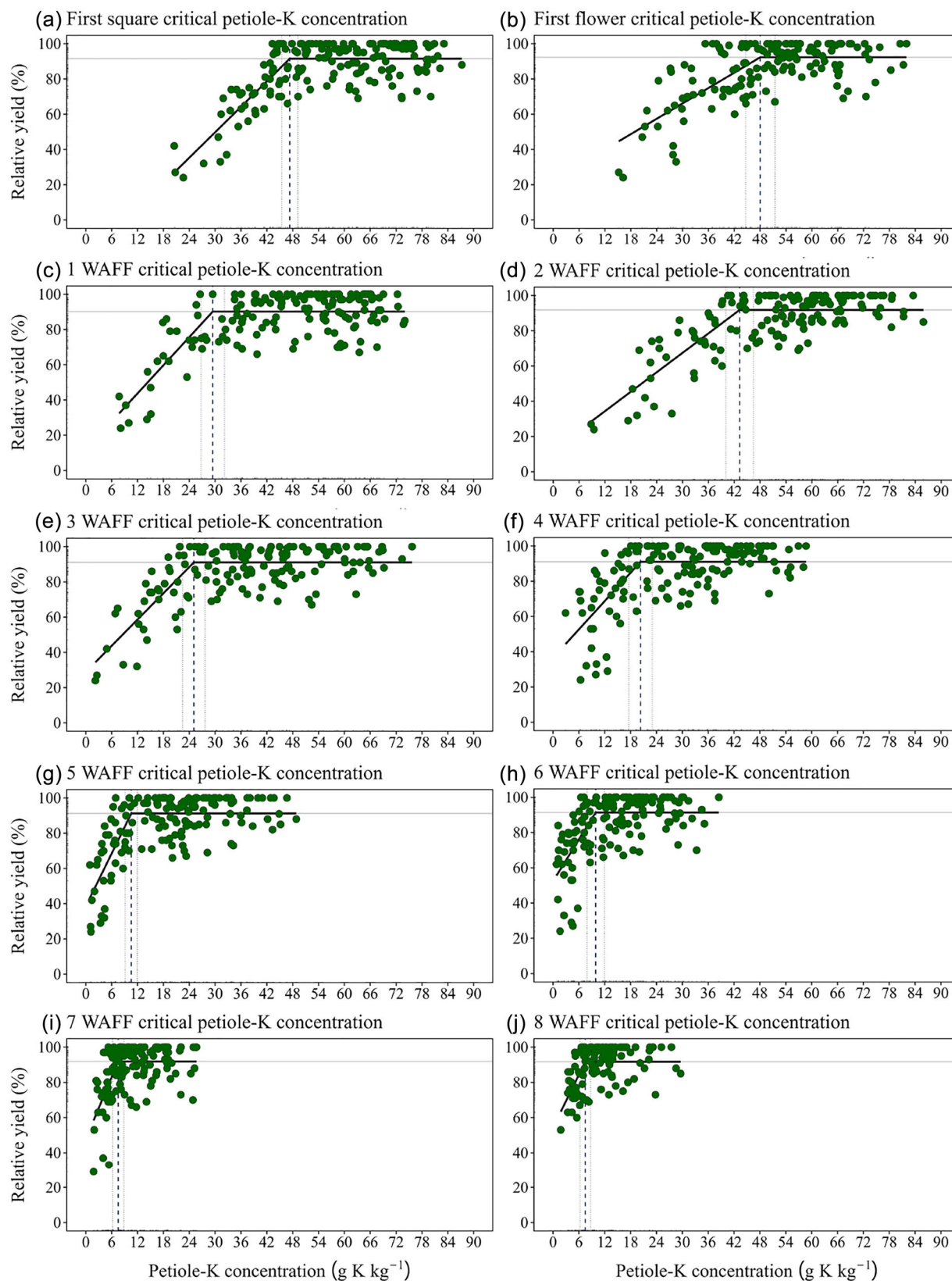


FIGURE 4 Cotton critical petiole-K concentrations across different cotton growth stages (first square, first flower, and weekly beginning at first flower and extending until early boll and fiber maturity, i.e., 8 weeks after first flower [WAFF]). The dataset encompasses nine field trials conducted at the University of Arkansas System Division of Agriculture's properties during 2023 and 2024, utilizing three modern cotton cultivars. Dashed lines indicate the critical petiole-K concentration to produce maximum yield, along with the 95% confidence intervals. Model coefficients, critical concentration, and confidence interval are listed in Table 8.

TABLE 6 Regression coefficients and standard errors (SE) for predicting cotton petiole-K concentrations during reproductive stages (days after first flower) as affected by fertilizer-K rate for nine trials conducted in Arkansas during the 2023 and 2024 growing seasons.

Site ^a	K rate (kg K ha ⁻¹)	Intercept ^b	SE	Linear	SE	Quadratic	SE	R ²
1	0	3.9245	0.1813	−0.09191	0.01353	0.00096	0.000232	0.71
	75	63.0143 ^c	2.8773	−1.9823	0.1915	0.01754	0.003287	0.95
	150	73.480 ^c	1.9970	−1.9268	0.1582	0.01423	0.002715	0.96
2	0	3.6685	0.2381	0.00173	0.009804	−0.00081	0.000168	0.82
	75	3.9748	0.1145	0.01006	0.007212	−0.00074	0.000124	0.91
	150	3.981	0.09718	0.01585	0.004852	−0.00086	0.000083	0.94
3	0	3.1431	0.2127	−0.05740	0.008169	ns ^d	ns	0.66
	75	3.1881	0.2056	−0.00196	0.01821	−0.00196	0.000424	0.77
	150	3.3020	0.2458	0.03385	0.02056	−0.00244	0.000479	0.74
4	0	3.8056	0.1244	0.00632	0.009802	−0.00087	0.000169	0.87
	75	3.9669	0.1227	−0.00497	0.01032	−0.00057	0.000178	0.81
	150	4.0096	0.1151	−0.00111	0.009108	−0.00060	0.000157	0.82
5	0	4.1171	0.1526	−0.05060	0.01111	0.000046	0.000191	0.72
	75	4.2835	0.1272	−0.05635	0.009884	0.00025	0.00017	0.78
	150	4.3037	0.1146	−0.04266	0.008435	0.000044	0.000145	0.85
6	0	3.4730	0.1340	−0.04593	0.005210	ns	ns	0.70
	56	3.7463	0.1905	−0.00197	0.01154	−0.00091	0.000231	0.90
	112	4.0765	0.1159	0.00702	0.01060	−0.00084	0.000212	0.88
7	0	3.76	0.2472	0.00593	0.01328	−0.00129	0.000266	0.78
	56	3.8725	0.1788	0.00787	0.01081	−0.00107	0.000216	0.89
	112	3.9865	0.09547	0.01104	0.006329	−0.00083	0.000127	0.89
8	0	3.8229	0.1764	0.00048	0.01147	−0.00064	0.000198	0.79
	56	4.1149	0.1169	−0.00068	0.007043	−0.00044	0.000122	0.90
	112	4.1849	0.09567	−0.00144	0.008305	−0.00039	0.000143	0.76
9	0	62.3131 ^c	3.2453	−0.9839	0.109	ns	ns	0.73
	56	72.8858 ^c	2.8473	−1.0530	0.09687	ns	ns	0.82
	112	79.3839 ^c	2.7119	−1.1116	0.09755	ns	ns	0.29

^aTrial location and agronomic information are presented in Table 1.

^bCoefficients were obtained from PROC GLIMMIX using a gamma distribution and log transformation of data. Equations included linear and/or quadratic terms as appropriate. Predicted values were calculated as $y = \exp(ax^2 + bx + c)$, omitting nonsignificant terms. Terms are as follows: x = days after first flower, a = quadratic coefficient, b = linear coefficient, c = intercept, and $\exp$ = the natural exponential function.

^cWhen models did not converge, a normal distribution was used, assuming normally distributed residuals.

^dQuadratic coefficients were not significant ($p \geq 0.10$) in the model.

relationship between leaf-K concentration and relative cotton yield, predicting maximum relative yield at 11.31 and 10.34 g K kg⁻¹ at first square and first flower, respectively. Thereafter, aside from some fluctuations among sampling times, there was an overall trend of decreasing critical leaf-K concentrations throughout reproductive cotton development. Moreover, the linear plateau model presented greater R^2 values and narrower confidence intervals at 1 WAFF and 2 WAFF ($R^2 = 0.53$ and 0.48 , respectively) than later in the season at 5 WAFF and 6 WAFF ($R^2 = 0.47$ and 0.46 , respectively), indicating greater sensitivity in predicting cotton nutritional status (Figure 3c,d,g,h; Table 7). At the last two sampling times (7 WAFF and 8 WAFF; Figure 3i,j),

the R^2 values were lower ($R^2 = 0.23$ and 0.19 , respectively; Table 7), and the leaf-K concentration fluctuated among sampling times. Overall, the maximum relative cotton yield predicted by the linear plateau model ranged from 90.7% to 93.1%.

Critical petiole-K concentrations showed a similar trend to the critical leaf-K concentrations, with a significant positive relationship between petiole-K concentration and relative cotton yield at different growth stages, but with notably greater K concentrations (Figure 4; Table 8). Regardless of tissue sampling time, relative cotton yield increased with increasing petiole-K concentration until reaching a plateau, which indicates no further yield benefit beyond this point. The lin-

TABLE 7 Regression coefficients and standard errors (SE) for predicting relative cotton yield (RY) with leaf-K concentrations starting at first square and continuing throughout the growing season for nine trials conducted in Arkansas during the 2023 and 2024 growing seasons.

Sampling time ^a	<i>n</i>	<i>R</i> ²	Regression coefficients ^b				Plateau ^d		
			Intercept	SE	Linear	SE	Leaf-K (g K kg ⁻¹)	CI ^c	RY (%)
First square	174	0.37	−15.13	13.9	9.413	1.4	11.31	10.7–12.0	91.3
First flower	156	0.22	28.21	11.9	6.124	1.4	10.34	9.2–11.5	91.5
1 WAFF	152	0.53	−53.71	15.1	19.589	2.3	7.42	7.1–7.7	91.7
2 WAFF	154	0.48	−40.41	15.7	17.207	2.4	7.65	7.3–8.1	91.4
3 WAFF	153	0.44	−12.01	11.5	16.508	2.2	6.22	5.9–6.6	90.7
4 WAFF	152	0.39	37.93	6.3	7.711	1.1	7.15	6.5–7.8	93.1
5 WAFF	155	0.47	28.91	6.1	11.470	1.5	5.52	5.0–6.0	92.2
6 WAFF	151	0.46	6.68	10.0	24.562	3.8	3.42	3.1–3.7	90.6
7 WAFF	133	0.23	51.75	7.4	8.466	1.9	4.84	4.1–5.6	92.7
8 WAFF	109	0.19	59.89	7.2	6.237	1.7	5.14	4.3–6.0	92.0

Abbreviation: WAFF, week(s) after first flower.

^aTrial location and agronomic information are presented in Table 1.

^bLinear ($y = a + bx$) model where y = relative yield (%), x = leaf-K concentration expressed as (g K kg⁻¹), a = intercept coefficient, and b = linear slope coefficient.

^cConfidence interval (95%).

^dCritical leaf-K and relative yield plateau calculated by the model.

TABLE 8 Regression coefficients and standard errors (SE) for predicting relative cotton yield (RY) with petiole-K concentrations starting at first square and continuing throughout the growing season for nine trials conducted in Arkansas during the 2023 and 2024 growing seasons.

Sampling time ^a	<i>n</i>	<i>R</i> ²	Regression coefficients ^b				Plateau ^d		
			Intercept	SE	Linear	SE	Petiole-K (g K kg ⁻¹)	CI ^c	RY (%)
First square	171	0.64	−22.60	7.9	2.411	0.2	47.3	45.4–49.2	91.5
First flower	152	0.51	22.53	6.1	1.452	0.2	48.0	44.6–51.4	92.3
1 WAFF	148	0.58	11.80	6.5	2.660	0.3	29.5	26.7–32.2	90.2
2 WAFF	149	0.65	12.32	5.6	1.838	0.2	43.2	40.1–46.4	91.8
3 WAFF	151	0.57	28.84	5.0	2.481	0.3	25.1	22.2–27.6	91.0
4 WAFF	151	0.44	36.56	5.7	2.681	0.4	20.3	17.6–23.0	90.9
5 WAFF	152	0.56	38.57	4.1	4.985	0.6	10.6	9.2–12.0	91.2
6 WAFF	147	0.42	52.41	4.1	3.940	0.7	9.9	7.9–11.9	91.4
7 WAFF	133	0.36	47.82	6.5	5.858	1.3	7.5	6.2–8.8	91.9
8 WAFF	108	0.31	54.38	6.4	4.987	1.1	7.5	6.3–8.7	91.7

Abbreviation: WAFF, week(s) after first flower.

^aTrial location and agronomic information are presented in Table 1.

^bLinear ($y = a + bx$) model, where y = relative yield (%), x = leaf-K concentration expressed as (g K kg⁻¹), a = intercept coefficient, and b = linear slope coefficient.

^cConfidence interval (95%).

^dCritical petiole-K and relative yield plateau calculated by the model.

ear plateau model demonstrated good strength and predicted a maximum relative cotton yield of 91.5% with 47.3 g K kg⁻¹ petiole-K concentration at the first square. Similarly, the first flower sampling time showed a predicted 92.3% maximum relative cotton yield and a minor increase in the critical petiole-K concentration (i.e., 48.0 g K kg⁻¹). Following the first flower sampling time, there was a fluctuation of critical petiole-K concentrations at 1 WAFF and 2 WAFF sampling times (29.5 and 43.2 g K kg⁻¹, respectively); thereafter, there

was a continuous decrease of critical petiole-K concentrations to maximize cotton yield throughout the growing season, with the lowest value occurring at 7 WAFF and 8 WAFF (i.e., 7.5 g K kg⁻¹).

The linear plateau model showed a moderate to strong relationship between petiole-K concentrations and relative cotton yield (Figure 4; Table 8). The linear plateau model had the greatest *R*² value at 2 WAFF (*R*² = 0.65; Figure 4d; Table 8), with *R*² values decreasing at the following sampling times

(R^2 values ranging from 0.57 to 0.42 between 3 WAFF and 6 WAFF; Figure 4e–h; Table 8), but still indicating moderate sensitivity in predicting cotton K nutritional status. Analogous to the leaf, at later sampling times (i.e., 7 WAFF and 8 WAFF), both critical petiole-K concentrations and relative yield prediction accuracy decreased (Figure 4i,j; Table 8). Overall, the R^2 values across all the sampling times were greater for petiole-K than for leaf-K concentrations (Tables 7 and 8).

4 | DISCUSSION

4.1 | Cotton lint yield

The state average lint yield in Arkansas for the 2023 and 2024 growing seasons was 1452 and 1472 kg ha⁻¹, respectively (USDA-NASS, 2025). In comparison, the maximum yield observed across the nine field trials in this study exceeded the state average by 3%–38%, indicating that crop management practices were adequate for both growing seasons and supported high yield potential. Additionally, the range of soil-test K across the single-site-year trials reflects what is commonly observed in Arkansas furrow-irrigated cotton hectare (DeLong et al., 2024). Overall, the reported increase in yield with K fertilization (126–767 kg lint ha⁻¹; Table 4) highlights the importance of proper K management, as maximizing cotton yield without K fertilization is unattainable on soils with suboptimal K availability. The yield response trend to K fertilization observed in our study, with soils with very low and low soil test-K showing high yield response frequency and magnitude to K fertilization, and the site with medium soil test-K only showing a numerical yield increase, aligns with current recommendations (Robertson et al., 2022) and suggest that there is no need to increase fertilizer-K rates to maximize cotton yield. The main effects of K fertilization on cotton lint yield and quality are discussed in detail by Prado et al. (2025). The current study focuses on defining critical tissue-K concentrations for maximum cotton yield, and relative yield data are presented for context.

4.2 | Tissue-K concentration as affected by potassium fertilization after first flower

Tissue-K concentration increased as K availability increased and decreased continuously with cotton development (Figures 1 and 2). This trend highlights the sensitivity of tissue testing to diagnosing plant internal K dynamics, such as greater K uptake or K remobilization from vegetative to

reproductive plant tissues. These results are consistent with findings by Hsu et al. (1978), who suggested that a predicted decline in cotton tissue-K concentration can be determined to adjust critical values across growth stages. This approach is well-established for soybean (Parvej et al., 2016; Slaton et al., 2021) and rice (Gruener et al., 2022), where tissue-K concentrations decrease at a predictable rate across time during reproductive growth, regardless of K fertilization rate. Our findings establish the foundation for defining critical tissue-K concentrations for cotton, serving as a first step toward modeling a dynamic critical tissue-K curve similar to those developed for other crops (Gruener et al., 2022; Slaton et al., 2021).

Hsu et al. (1978) reported that K concentration decreased in leaves and petioles as the plant developed and matured, with a larger rate of decline noted in petiole-K concentrations compared to leaf-K concentrations. Our results align with these findings. Additionally, K fertilization positively affected tissue-K concentrations, with a greater magnitude of increase observed at the beginning of reproductive growth. The decrease in tissue-K concentration with increasing DAFF may be influenced by the dynamics of the cotton root system (i.e., decay of older roots and new root formation and development) with an overall reduction in basal root system activity and K uptake at the beginning of flowering (Brouder & Cassman, 1990; Oosterhuis, 2002). Regardless of K rate, the decline in tissue-K concentrations is less pronounced toward the end of the season, suggesting that the sensitivity of tissue testing for K nutritional status diagnosis decreases as crop development progresses.

According to Pabuyon et al. (2020), new cultivars have enhanced efficiency in translocating resources from source to sink, which may influence K dynamics compared to studies with older cultivars. Therefore, research with modern, high-yielding cotton cultivars may result in different critical tissue-K concentrations compared to critical concentrations published several decades before. This is important as the timing and magnitude of K uptake can vary significantly. For instance, K uptake from the soil by cotton peaks when the plant reaches its maximum daily K uptake, between 63 and 77 DAP, which is usually from the beginning of flower to the boll fill stage, but may vary between soils, years, and cultivars (Mullins & Burmester, 1990). The 2-week period following the onset of flowering is critical for cotton, during which time approximately one-third of all the K is taken up by the plant (Halevy, 1976; Oosterhuis, 2002). Approximately 50%–65% of all K is used for forming plant reproductive structures (Mullins & Burmester, 1990; Pabuyon et al., 2020; Rimón, 1989), which reinforces the importance of K for optimal cotton production and the need for effective tools to monitor cotton K nutritional status.

4.3 | Critical leaf- and petiole-K concentrations throughout cotton development stages

Early studies in Arkansas by Harris (1962) reported that critical K concentrations for the uppermost leaf declined from 18.2 g K kg⁻¹ at beginning of flower to 12.6 g K kg⁻¹ at 2 WAFF and 6.9 g K kg⁻¹ at peak flowering (i.e., around 3 WAFF). Our study, despite slightly different critical leaf-K concentration magnitudes (i.e., 10.3 g K kg⁻¹ at first flower, 7.7 g K kg⁻¹ at 2 WAFF, and 6.2 g K kg⁻¹ at 3 WAFF), showed a similar trend of decreasing critical tissue-K concentrations across reproductive cotton development (Figure 3; Table 7). This behavior is associated with the K redistribution within the plant (Figure 1), where K is remobilized from leaves to developing bolls, fiber, and seeds during reproductive development (Rochester et al., 2012). Additionally, the difference in our critical leaf-K values compared to research by Harris (1962) is expected due to changes in cultivars (i.e., current shorter cycle and high-yielding cultivars), as well as differences in sampling timing and sampling methods (e.g., separating leaves from petioles at sampling vs. before drying).

Chapman (1966), Kenworthy (1969), and Jones et al. (1971) propose that, for nutrient analysis to be meaningful, cotton should be sampled when the first squares appear or prior to first flower. Kerby and Adams (1985) emphasized that visual symptoms of K deficiencies are difficult to identify early in the season. Our proposed critical leaf-K concentration at first square (11.3 g K kg⁻¹) is similar to the critical concentration of 12.5 g K kg⁻¹ reported by Hsu et al. (1978) for the same sampling time. Hsu et al. (1978) also reported a 1.8 g K kg⁻¹ decrease in the critical leaf-K concentration at early flowering (10.7 g K kg⁻¹), followed by another decrease of 2.9 g K kg⁻¹ in half-grown cotton bolls (7.8 g K kg⁻¹). Late-season plant tissue testing can help assess the effectiveness of K fertilizer management and predict yield potential; however, if a deficiency is detected at that stage, it may be too late to correct it with in-season fertilization, as yield may already be compromised (Murrell et al., 2021). Additionally, our results reveal some inconsistency in the critical leaf-K values near the end of the season, suggesting that early reproductive stages are more sensitive to diagnosing plant nutritional status. Similar results were reported by Singh et al. (1992), who highlighted that cotton should be sampled at the peak flowering stage, and proposed a critical leaf-K value of 6.9 g K kg⁻¹ (young, fully mature leaf from the top of the plant) for this sampling time. Mullins and Burmester (1990) reported a high critical leaf-K concentration of 16.3 g kg⁻¹ before harvest, likely because their tissue sampling protocol consisted of leaves from the entire plant canopy, rather than the uppermost mature leaf, as in most other studies. The inconsistency of critical leaf-K values across studies highlights the challenges of developing a reliable dynamic critical concentration for cotton.

Bednarz and Oosterhuis (1999) reported critical leaf-K concentrations close to first square to be around 9.5 g K kg⁻¹ in greenhouse experiments. Measurements were collected from the third uppermost leaf from the main stem before and during first square, when the leaves were still expanding. The authors observed significant variation in K concentrations for measurements taken during this growth stage, with no changes in physiological growth stage observed across the sampling period (i.e., before first square), leading them to conclude that luxury consumption may have occurred. Our results also show wide variation in leaf-K concentrations at first square as reported by Bednarz and Oosterhuis (1999). Additionally, these differences may be attributed to variations in soil moisture and the initiation of crop irrigation in some trials. We observed greater data dispersion and a low goodness of fit ($R^2 = 0.22$) at first square compared to samples taken after first flower (Figure 3). Moreover, during squaring, the plant is preparing to shift from K storage to sink-driven demand. Lewis et al. (2021) reported leaf-K concentrations ranging from 10.4 to 16.2 g K kg⁻¹ in samples collected 4 WAFF on optimum soil-test K soils in Arkansas. Additionally, a positive relationship between cotton lint yield and leaf-K concentration was observed across site-years (Lewis et al., 2021), evidence that leaf-K concentration is an adequate predictor of cotton K nutritional status and yield potential. Our findings align with those reported by Lewis et al. (2021), confirming a moderate correlation between leaf-K concentrations and relative cotton yield, while also extending the evidence base through a larger set of plot-level observations. However, the critical leaf-K concentrations found in our study were overall lower than those reported in previous research from across the US Cotton Belt (Mitchell & Baker, 1997), suggesting that cotton yield in current modern cultivars may be maximized with lower leaf-K concentrations than those reported two decades ago. Changes in plant genetics (e.g., maturity, yield potential, insect and herbicide resistance, and quality traits) can also affect nutrient uptake and remobilization processes (Bender et al., 2013; Pabuayon et al., 2020). The fact that we observed lower critical tissue-K concentrations than previous literature suggests that while the demand for K in modern cotton cultivars has increased due to shorter maturity and greater yield potential compared to traditional cultivars, there has likely been an increase in K remobilization from cotton leaf to reproductive structures.

Similar to the critical leaf-K concentrations, the reported critical petiole-K concentrations vary among different studies over the past decades. Greenhouse studies by Joham (1951) highlighted that petioles from the third to fourth uppermost node of the main stem are sensitive to diagnose K nutritional status and reported K concentration values of 60, 41, and 30 g K kg⁻¹ for petiole samples at 60, 90, and 145 DAP (approximately first flower, 4 WAFF, and maturity). Although the author proposed fresh weight critical petiole-K concen-

trations with the greenhouse study, the limited number of observations collected in a later field experiment hindered an accurate comparison with yield. Our study addressed this limitation by correlating and calibrating critical petiole-K concentrations with relative cotton yield across reproductive development stages. Other studies proposed critical petiole-K concentrations and documented a decline in the tissue-K values throughout the growing season. Bednarz and Oosterhuis (1999), in a greenhouse study, reported critical petiole-K concentrations of 8.8 and 4.6 g K kg⁻¹ near first square, based on photosynthesis and chlorophyll responses using petioles from the top third of the main stem. Additionally, Halevy (1976) showed a continuous decrease in the critical petiole-K concentrations, with greater values, ranging from 45 g K kg⁻¹ at first square, 30 g K kg⁻¹ at peak flowering, and 15 g K kg⁻¹ at maturity.

Bassett et al. (1970) and Sabbe and MacKenzie (1973) developed survey-based studies examining healthy cotton fields and reported K concentrations in petioles to be sufficient when concentrations were above 40 g K kg⁻¹ at first flower, 30 g K kg⁻¹ during peak flower, and 20 g K kg⁻¹ by first open boll. Field studies by Hsu et al. (1978) proposed critical petiole-K concentrations based on the relationship between petiole-K and soil-test K, with values ranging from 25.5 to 10.6 g K kg⁻¹ from early flowering to early half-grown bolls (5 WAFF). Our proposed critical petiole-K concentration at first flower (48 g K kg⁻¹) aligns more with research by Bassett et al. (1970) and Sabbe and MacKenzie (1973). However, the critical petiole-K concentration observed at the first square sampling time in our study (47.3 g K kg⁻¹) is greater than that reported by Bednarz and Oosterhuis (1999) for greenhouse conditions, while the critical K value of 7.5 g K kg⁻¹ we observed at open boll (7 WAFF and 8 WAFF) is lower than that reported by Hsu et al. (1978). Additionally, the critical petiole-K concentration at 5 WAFF in our study corroborates the concentration previously reported by Hsu et al. (1978) for the half-grown boll stage.

Singh et al. (1992) determined critical petiole-K concentrations from the third uppermost leaf (young, fully mature leaf) of 32.6 g K kg⁻¹ at first flower, 26.0 g K kg⁻¹ at the peak flowering, and 6.8 g K kg⁻¹ at the boll opening stage, which closely aligns with our results at peak flowering (i.e., 25.1 g K kg⁻¹ at 3 WAFF; Figure 4e; Table 8). Interestingly, a substantial decrease in critical petiole-K concentrations was observed at the 1 WAFF sampling time compared to first flower, which coincides with the critical 2-week period (Halevy, 1976; Oosterhuis, 2002) described earlier. Similarly, Harris (1962) reported critical petiole-K values of 19.5 g K kg⁻¹ at the beginning of flowering, followed by a slight increase to 19.9 g K kg⁻¹ at 2 WAFF, and a decrease to 17.2 g K kg⁻¹ at 3 WAFF. Research defining critical petiole-nitrate concentrations for cotton in Arkansas also reported similar behavior, with changes linked to a decreased root N uptake

and increased N demand for reproductive plant tissues (Gerik et al., 1998).

The novel aspect of our research is the definition of critical leaf- and petiole-K concentrations across various plant growth stages associated with relative cotton yield. This approach is different and more informative for growers than studies considering sufficient ranges based on surveys (Bassett et al., 1970; Anderson, 1971; Mitchell & Baker, 1997; Sabbe & MacKenzie, 1973), plant physiological responses (Bednarz & Oosterhuis, 1999), or soil-test K (Hsu et al., 1978). Regarding which plant tissue is more accurate for assessing cotton nutritional status, our results demonstrate that both leaf- and petiole-K concentrations are sensitive to diagnosing K nutritional status, supporting previous findings for soybean (Parvej et al., 2016; Slaton et al., 2021). However, contrary to the initial hypothesis and previous report by Oosterhuis and Morris (1979), petiole analysis showed a better correlation of tissue-K concentrations with relative cotton yield than the leaf, suggesting that, despite the wide range of petiole-K concentrations across the season, it may better reflect the K dynamics during reproductive cotton development. These results agree with Sabbe and MacKenzie (1973), who recommend cotton K nutritional status assessment through petiole analysis. The wider range of K concentration in petioles, which reflects greater changes in K status over time, may offer an advantage in determining critical K levels compared to the smaller amplitude of change observed in the leaves (Hsu et al., 1978; Pabuayon et al., 2020). Additionally, petiole analysis showed a greater sensitivity in diagnosing K nutrition and predicting relative yield for samples collected between first square and 3 WAFF; thereafter, R^2 values fluctuated and tended to decrease across sampling time.

5 | CONCLUSIONS

Our research highlights the importance of effective K management for achieving optimal cotton production and the potential application of tissue testing as a tool to diagnose K-deficient cotton and guide corrective K fertilization. Fertilizer-K rates significantly affected cotton lint yield on soils with suboptimal K availability, highlighting the importance of effective K management to maximize cotton yield. Cotton leaf and petiole analyses are sensitive for diagnosing the K nutritional status of the plant, as tissue-K concentrations are responsive to changes in K availability (soil or K fertilization) and consistently decrease throughout the growing season in response to increased plant biomass and K remobilization to reproductive tissues. Critical leaf- and petiole-K concentrations to maximize cotton yield potential were 11.1 and 47.3 g K kg⁻¹ at first square, 10.3 and 48.0 g K kg⁻¹ at first flower, and decreased to 5.1 and 7.5 g K kg⁻¹ at eight WAFF, respectively. Petiole-K concentrations had a stronger relationship

with relative yield than leaf-K throughout the growing season (R^2 range of 0.31–0.65 for petioles and 0.19–0.53 for leaves).

We proposed season-long (i.e., from first square to early boll and fiber maturity [8 WAFF]) critical leaf- and petiole-K concentrations to monitor cotton K nutritional status, but late-season critical leaf and petiole-K analyses are less sensitive to predict cotton yield potential, as tissue-K concentrations vary less, regardless of fertilizer-K rate or soil-K availability. The rapid change in tissue-K concentration suggests that growth stage-specific critical concentrations are key for effective nutritional status interpretation. Our proposed season-long critical tissue-K concentrations enable growers and scientists to monitor cotton K nutritional status and adjust fertilizer management practices to maximize cotton yield, allowing for overall increased fertilizer use efficiency and farming profitability. Further research is needed to validate the proposed critical tissue-K concentrations and define the window of opportunity to correct K-deficient cotton with in-season K fertilization.

AUTHOR CONTRIBUTIONS

Maria Paula R. Prado: Data curation; formal analysis; investigation; methodology; validation; visualization; writing—original draft; writing—review and editing. **Gerson L. Drescher:** Conceptualization; funding acquisition; investigation; methodology; project administration; resources; supervision; validation; visualization; writing—original draft; writing—review and editing. **Trenton L. Roberts:** Conceptualization; funding acquisition; investigation; methodology; resources; supervision; writing—review and editing. **Nathan A. Slaton:** Conceptualization; investigation; methodology; resources; validation; visualization; writing—review and editing. **Fred M. Bourland:** Conceptualization; investigation; methodology; resources; validation; visualization; writing—review and editing. **Qamar Sarfaraz:** Data curation; investigation; methodology; resources; visualization; writing—review and editing. **Gabriela A. L. Menezes:** Data curation; investigation; methodology; visualization; writing—review and editing. **Katie S. French:** Investigation; methodology; visualization; writing—review and editing.

ACKNOWLEDGMENTS

The funding for this project was provided by Cotton Incorporated, administered by the Arkansas State Cotton Support Group, Fertilizer Tonnage Fees administered by the Arkansas Soil Test Review Board, and the University of Arkansas System Division of Agriculture. The authors extend sincere appreciation to the Arkansas Agricultural Experiment Station staff for their continued help and cooperation, without which this project would not have been possible. This work was supported by the USDA National Institute of Food and Agriculture, Hatch Project 2800.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

How to cite this article: Prado, M. P. R., Drescher, G. L., Roberts, T. L., Slaton, N. A., Bourland, F. M., Sarfaraz, Q., Mengez, G. A. L., & French, K. S. (2026). Defining critical leaf- and petiole-potassium concentrations for monitoring cotton nutritional status. *Agronomy Journal*, 118, e70273. <https://doi.org/10.1002/agg2.70273>