

ORIGINAL ARTICLE

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Soil pH influence on cotton lint yield and quality

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Abstract

Increases in cotton (*Gossypium hirsutum* L.) production across Oklahoma due to various circumstances have led to cotton planted on soils that have been traditionally managed for differing crops, specifically winter wheat. Many of these soils are possibly acidic in nature due to natural and anthropogenic activities such as excessive ammonia-based fertilizer applications. Common wheat production practices such as banding phosphorus fertilizers with seed and planting aluminum (Al) tolerant varieties may have masked potential problems associated with crop performance in acidic soils. In response, this study was initiated to evaluate the impact of soil acidity on cotton production. This experiment was conducted in central Oklahoma in the 2019 and 2020 growing seasons. Cotton lint yield and lint quality were evaluated across a range of soil pH levels and associated potassium chloride extractable Al across a soil pH gradient of 4.0–8.0. Two cotton cultivars were planted to identify possible differences in response between genotypes. Soil acidity negatively impacted in-season growth parameters such as plant height, node count, and boll count, as well as the primary variable of lint yield. A critical threshold at a soil pH level of 5.2 was identified as detrimental to cotton lint yield, corresponding with a lint yield loss of approximately 4.5% per pH unit decrease below the critical soil pH level of 5.2. This equates to a lint yield loss of 44.5 kg ha⁻¹ per 0.1 change in soil pH, assuming 100% yield potential is approximately 989 kg ha⁻¹ of lint for this specific growing environment.

1 | INTRODUCTION

The reintroduction and expansion of cotton (*Gossypium hirsutum* L.) to areas across Oklahoma outside of its traditional production regions has led to an increased planting in fields that have been managed for other crops such as winter wheat. With this increased interest in cotton comes several management concerns that may require addressing solutions to

optimize cotton lint yield in these areas. Soil acidity is one such concern in central Oklahoma. Across Oklahoma, soil pH values can vary greatly with gradient being an expression of climatic environment and soil genesis across the state in an east-west manner. Soil pH has been heavily influenced in the region by excessive applications of ammonia-based nitrogen (N) fertilizers. These management practices combined with the ability of winter wheat producers to grow crops under acidic conditions with the additions of phosphorus (P) fertilizers in-furrow (Zhang et al., 1998), paired with the adoption of aluminum tolerant winter wheat varieties widely planted in the region that can sustain grain and biomass yields in soil pH

Abbreviations: Al_{KCl}, potassium chloride extractable Al; CVRS, Cimarron Valley Research Station; NDVI, normalized difference vegetation index; SWAFL, Soil, Water, and Forage Analytical Laboratory.

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conditions as low as 5.5 have only exasperated these issues. These practices drive concerns about potential productivity of cropping systems incorporating cotton in this region.

As mentioned, soil acidity can be of significant concern, especially for crops not adapted to these conditions. A previous study evaluating soil testing results submitted to the Soil, Water, and Forage Analytical Laboratory (SWAFL) at Oklahoma State University from across the state in the years 1985–1996 found that 30% of the 17,560 soil samples submitted had soil pH values of less than 5.5 (Zhang et al., 1998). An additional review of soil testing results from 2004 to 2008 at SWAFL found 23.6% of samples submitted had pH values of less than 6.0 (Zhang & McCray, 2008). It is assumed that many of these soils would provide suboptimal productivity in consequence of an increase in soluble Al^{3+} as is characteristic for many of the soils in the region (Zhang & Raun, 2006). Increases in soluble Al^{3+} have been documented to restrict root growth through root pruning (Kochian, 1995). This reduction in root mass is likely to result in additional crop stressors such as nutrient deficiency and water stress (Kochian et al., 2004). A similar response may result in soils high in concentration of potentially soluble manganese (Mn) resulting in root pruning and subsequent nutrient and water deficiencies, most notably iron chlorosis symptomology (Duncan, 1987). Elevated levels of soluble Al^{3+} in acidic soil conditions increase the adsorption of solubilized P, resulting in P deficiency, further inhibiting crop performance (Haynes & Mokolabate, 2001).

Existing literature on soil pH impact on cotton performance is limited, with much of the work primarily focused on subsoil acidity as found on many soils of the coastal plain of the Southeastern United States. For instance, work by Pearson et al. (1970) and Foy et al. (1967) observed increases in incidence of plant nutrient deficiency and drought stress in plants grown in acidic subsoil conditions. Of important note is that Foy et al. (1967) also found variability between cotton genotype performance in nonameliorated soils (pH 4.53). This work indicated that a subsoil pH of approximately 5.4 represents a critical threshold in which conditions are detrimental to crop performance; however, genetic variability in response to acidity does exist. Similar results were observed by Pearson et al. (1970) in which root elongation was inhibited by soil pH conditions less than 5.5. Additionally, Adams and Lund. (1966) determined that increasing Al^{3+} concentration correlated with decreasing root length, though different magnitudes of response were observed across different soils, highlighting the impact soil mineralogy likely has on such a response. More recent literature has corroborated these findings such as work completed by Gascho and Parker (2001) in Georgia, which found that cotton yield was positively impacted by amelioration of soil pH with agricultural lime (CaCO_3) application. More recent work in South Carolina by Johnson et al. (2002) evaluating spatial variability of soil characteristics influence

Core Ideas

- Soil pH strongly affects upland cotton performance below a critical level of 5.4.
- Soil pH effect on cotton performance was strongly correlated with increases in Al^{3+} levels.
- Amelioration of soil pH to a level above 5.5 is likely required to optimize cotton yield in soils of the southern Great Plains.

on cotton lint yield reported positive correlation between soil pH and crop performance ($r^2 = 0.46$) in which yield was increased under neutral soil pH conditions as expected.

One of the primary differences between the papers cited and this work is the relative abundance of acidic subsoil conditions in the southeastern US coastal plain where much of this work has been completed. This condition is vastly different than the acidic soil conditions of the southern plains, in which acidic conditions generally persist only in the surface soil layers (Souza et al., 2023). The surface acidity found in this region potentially allows for crops with vigorous root growth dynamics to overcome the detrimental effect of the surface soil acidity by reaching neutral pH conditions below the region of soil primarily acidified by anthropogenic causes such as excessive N fertilizer application.

While the majority of the previous work described here is in agreement that soil pH levels of approximately 5.5 or lower are detrimental to cotton lint yield and growth characteristics, information is lacking on the ability of modern cultivar performance in these soil pH conditions as well as the possibility of differing responses to the surface soil acidity as often found in Oklahoma and the surrounding region. For this purpose, this work intends to provide an estimated critical threshold in which cotton lint yield is not significantly affected by surface soil pH conditions, as well as to evaluate the relationship between potassium chloride extractable Al (Al_{KCl}) and cotton lint yield.

2 | METHODOLOGY

This study was conducted over two growing seasons consisting of 3 site-years in total. The experiment was established at the Cimarron Valley Research Station (CVRS) near Perkins, OK (2 years) and the Efaw farm located in Stillwater, OK (1 year). Site soil descriptions and locations are listed in Table 1. Both sites have been continually managed for soil pH studies and historically consisted of plots with soil pH values ranging from approximately 4.0 to 7.0. For this experiment, each site was expanded to include soil pH ranges of approximately

TABLE 1 Description of soil series at Perkins, OK and Efaw locations utilized for an experiment evaluating the influence of soil pH on cotton physiology and yield in 2019 and 2020.

Location	Coordinates	Soil series
Perkins, OK	35°59'45" N 97°02'32" W	Teller series (fine-loamy, mixed, active, thermic Udic Argiustolls) and Konawa series (fine-loamy, mixed, active, thermic Mollic Albaqualfs)
Efaw (Stillwater, OK)	36°08'05" N 97°06'11" W	Easpur series (fine-loamy, mixed, superactive, thermic Fluventic Haplustolls)

4.0–8.0 to additionally identify possible detriments of more alkaline soil conditions. Each site utilized an 8×2 factorial design in four replicates consisting of targeted pH values of 4.0, 4.5, 5.0, 5.5, 6.0, 7.0, 7.5, and 8.0 planted to two cultivars: Deltapine 1612 and Nexgen 3930. Plots measured 6 m long by 3 m wide with rows spaced at 76 cm. The experiment was planted at a seeding rate of 86,419 seeds ha^{-1} at both sites. The CVRS site included three replications while the Efaw farm location consisted of four replications. Once plants were established, stand count was recorded based on total number of plants in the two harvest rows. In-season assessment of plant health was completed using a Greenseeker (Trimble Inc.) providing NDVI (normalized difference vegetation index) output. Plant height and node count were recorded prior to boll opener application at the end of the growing season.

To determine product application rates, soil samples were taken at 15 cm depth by plot to measure soil pH as well as additional fertility characteristics using a 2.54-cm diameter soil probe. The samples were air dried and ground to pass through a 2-mm sieve. The samples were then analyzed for pH and buffer index using a 1:1 soil:water suspension and glass electrode, as well as the Sikora buffer method (Sims, 1996; Sikora, 2006). Hydrated lime ($\text{Ca}(\text{OH})_2$) and aluminum sulfate ($\text{Al}_2(\text{SO}_4)_3$) application rates to reach target soil pHs were determined based upon a previous laboratory experiment as reported by Butchee et al. (2012) and Sutradhar et al. (2014). The use of aluminum sulfate has been shown to not impact soil Al^{3+} concentration significantly in work done by Kinraide and Parker (1987) and Cameron et al. (1986). This is important to note given the impact of phytotoxic forms of Al on crops in previous studies.

Soil samples were taken postharvest to determine soil pH for analysis of plant growth and yield parameters. These samples were additionally analyzed for Al_{KCl} using the Bertsch and Bloom (1996) method and was quantified using inductively coupled plasma spectrometry (Soltanpour et al., 1996).

Cotton was harvested with a two-row cotton stripper, harvesting the middle two rows of each four-row plot and weighed using a hanging scale system. Approximately 3 kg subsamples were taken from each plot sample for ginning and further lint analysis. Bur cotton was processed through a lint cleaner and ginned with a laboratory gin. Lint samples were then submitted to the Fiber and Biopolymer Research Institute

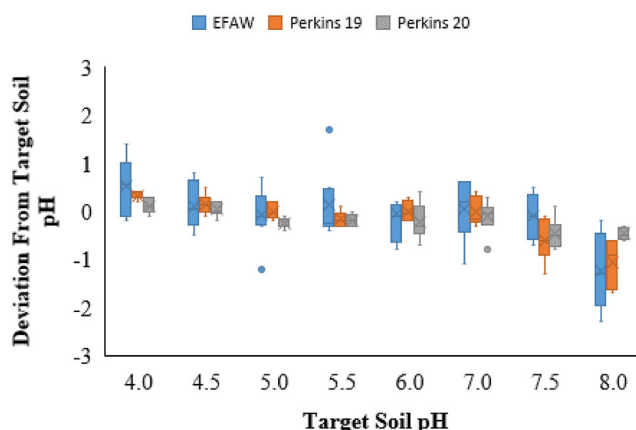


FIGURE 1 Deviation from target soil pH values across plots at each experimental site.

at Texas Tech University (Lubbock, TX) for further analysis. Statistical analysis was completed utilizing nonlinear regression and quadratic least squares regression in SAS software version 9.4 (SAS Institute Inc., Cary, NC).

3 | RESULTS

Soil pH values after treatment ranged from 4.2 to 8.0 (Figure 1) with the highest targeted pH level (8.0) only achieved in two plots at the Perkins 2020 site and one plot at the Efaw site. Mean absolute deviation from target soil pH measured ± 0.36 and ± 0.27 at the Perkins 2019 and 2020 sites, respectively. The Efaw location deviated on average ± 0.57 from the target soil pH level. This likely is a mechanism of the soils buffering ability at these sites as native pH values generally range from neutral to slightly acidic in central Oklahoma.

Soil pH level influenced all measured crop components. Soil pH significantly impacted seedling emergence at 2 of 3 site-years (Table 2), both being from the 2020 cropping season. Plant stand at the Perkins 2019 location was not significant due to elevated precipitation experienced 2 days after planting, leading to an erosion event impacting seedling emergence in some plots. Further investigation into cultivar effect on emergence as influenced by soil pH provided no additional insight as the only significant differences by cultivar were confined to the Perkins 2019 location in which cultivar

TABLE 2 Results from quadratic least squares regression and nonlinear regression on initial plant stand relative to soil pH level.

Site	Analysis	DF	MSE	F	Prob F	r ²
Perkins 19	Quadratic	2	13.6550	0.48	0.6224	0.02
Perkins 20	Quadratic	2	7.5111	15.78	<0.0001	0.41
Efaw	Quadratic	2	4.8162	40.82	<0.0001	0.57
Site	Analysis	Joint	Plateau	F	Prob F	r ²
Perkins 19	Nonlinear	—	—	—	—	—
Perkins 20	Nonlinear	4.6	8.79	31.22	<0.0001	0.58
Efaw	Nonlinear	5.4	11.68	47.68	<0.0001	0.61

TABLE 3 Confidence intervals obtained from nonlinear regression analysis of cultivar emergence in response to soil pH level at individual sites.

Site	Variety	Joint	95% CI
Efaw 2020	Deltapine 1612	5.5	5.173, 5.793
Efaw 2020	Nexgen 3930	5.3	4.959, 5.660
Perkins 2020	Deltapine 1612	4.9	4.561, 5.312
Perkins 2020	Nexgen 3930	4.8	2.470, 7.035
Perkins 2019	Deltapine 1612	4.6	4.424, 4.776
Perkins 2019	Nexgen 3930	6.5	4.960, 8.111

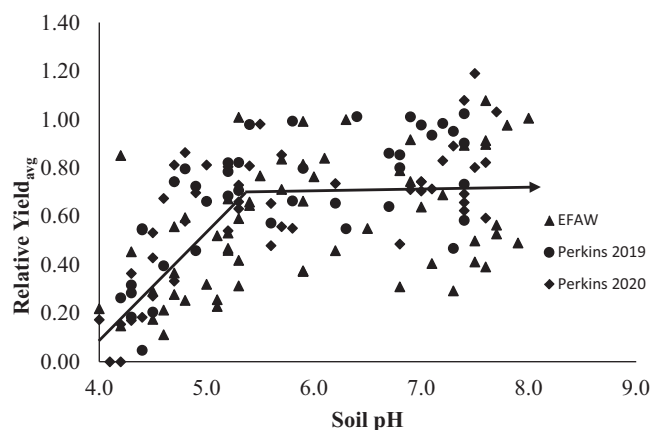
Abbreviation: CI, confidence interval.

was a significant factor influencing seedling emergence due to erosion that was largely isolated to only the Nexgen 3930 planted area of the experiment due to experimental design (Table 3).

Plant height was positively influenced by soil pH and was significant across all site-years (Table 4) as was node count (Table 5) when evaluated with quadratic least squares regression. When plant height was evaluated using nonlinear regression (Linear Plateau), inflection points were observed at soil pH levels of 5.2, 5.1, and 5.4 for the Perkins 2019, Perkins 2020, and Efaw 2020 locations, respectively. Nonlinear regression of node count yielded a positive relationship between soil pH and node count existed with inflection points observed at soil pH levels of 4.8, 4.7, and 5.2 for the Perkins 2019, Perkins 2020, and Efaw 2020 locations, respectively. All analysis provided significant evidence that soil pH level is strongly correlated with plant performance.

The relationship between NDVI at squaring and soil pH was also evaluated using quadratic least squares regression and nonlinear regression (Table 6). Positive relationships were significant at all sites with *p* values for all locations less than 0.0001. Inflection points were observed at all sites at soil pH levels of 5.3, 5.4, and 5.1 for the Perkins 2019, Perkins 2020, and Efaw 2020 locations, respectively.

Cotton lint yield ranged from 0 to 1439 kg ha⁻¹ across this experiment. Relationships between in-season growth mea-

**FIGURE 2** Linear plateau chart of relative lint yield in relation to soil pH as evaluated using nonlinear regression across all sites combined.

surements and soil pH level were indicative of the influence acidic soil conditions have on cotton lint yield as all in-season growth components measured exhibited a significant relationship ($p < 0.0001$) with soil pH level (Table 7). The relationship between soil pH and relative yield was evaluated using nonlinear regression to identify soil pH critical thresholds for each site-year (Table 8) and cultivar (Table 9). Relative yields were positively correlated with increases in soil pH up to the plateau identified. Relative lint yield reached critical thresholds at soil pH levels of 5.1, 4.8, and 5.7 for the Perkins 2019, Perkins 2020, and Efaw 2020 locations, respectively (Table 8). Relative yield for all site-years combined was also evaluated, indicating a soil pH critical threshold of 5.2 (Table 8 and Figure 2). The associated linear regression for data points at or below the critical threshold of pH 5.2 identified a slope of 0.45 or 45%. The relationship between relative yield and soil pH for individual cultivars was also evaluated in the same manner with a soil pH critical threshold observed at a level of 6.1 and 5.2 for Deltapine 1612 and Nexgen 3930, respectively (Figure 3). Critical threshold levels were not significantly different between cultivars at $\alpha = 0.05$ based upon confidence intervals obtained from nonlinear analysis listed in Table 9.

TABLE 4 Results of quadratic least squares regression and nonlinear regression of plant height in response to soil pH levels.

Site	Analysis	DF	MSE	F	Prob F	r ²
Perkins 19	Quadratic	2	52.3168	51.51	<0.0001	0.70
Perkins 20	Quadratic	2	93.3016	40.72	<0.0001	0.64
Efaw	Quadratic	2	208.3045	39.82	<0.0001	0.57
Site	Analysis	Joint	Plateau	F	Prob F	r ²
Perkins 19	Nonlinear	5.2	42.43	68.77	<0.0001	0.75
Perkins 20	Nonlinear	5.1	46.99	53.05	<0.0001	0.70
Efaw	Nonlinear	5.4	72.62	47.13	<0.0001	0.60

TABLE 5 Results of quadratic least squares regression and nonlinear regression of plant node count in response to soil pH levels.

Site	Analysis	DF	MSE	F	Prob F	r ²
Perkins 19	Quadratic	2	2.6906	22.25	<0.0001	0.50
Perkins 20	Quadratic	2	6.9957	27.96	<0.0001	0.55
Efaw	Quadratic	2	9.9321	19.31	<0.0001	0.39
Site	Analysis	Joint	Plateau	F	Prob F	r ²
Perkins 19	Nonlinear	4.8	8.18	37.02	<0.0001	0.62
Perkins 20	Nonlinear	4.7	11.26	66.46	<0.0001	0.75
Efaw	Nonlinear	5.2	13.51	25.56	<0.0001	0.46

TABLE 6 Results of quadratic least squares regression and nonlinear regression of normalized difference vegetation index (NDVI) in response to soil pH levels.

Site	Analysis	DF	MSE	F	Prob F	r ²
Perkins 19	Quadratic	2	0.0149	14.78	<0.0001	0.40
Perkins 20	Quadratic	2	0.0122	43.09	<0.0001	0.66
Efaw	Quadratic	2	0.0125	25.48	<0.0001	0.46
Site	Analysis	Joint	Plateau	F	Prob F	r ²
Perkins 19	Nonlinear	5.3	0.51	17.70	<0.0001	0.44
Perkins 20	Nonlinear	5.4	0.70	54.03	<0.0001	0.71
Efaw	Nonlinear	5.1	0.86	40.07	<0.0001	0.57

TABLE 7 Results of quadratic least squares regression analysis of in-season growth components measured relative to soil pH level across all site-years combined.

Growth component	DF	MSE	F	Prob F	r ²
Height	1	79786	23.91	<0.0001	0.13
Node count	1	77378	29.57	<0.0001	0.16
NDVI	1	65955	45.83	<0.0001	0.23

Abbreviation: NDVI, normalized difference vegetation index.

Relationships between soil pH level and lint quality parameters evaluated with quadratic least squares regression in the study were inconsistent across all sites (Table 10). No site provided a significant relationship for all four parameters

TABLE 8 Results of nonlinear regression analysis of relative cotton lint yield in response to soil pH level.

Site	Joint	Plateau	F	Prob F	r ²
Perkins 19	5.1	0.63	28.5034	<0.0001	0.60
Perkins 20	4.8	0.74	41.0032	<0.0001	0.65
Efaw	5.7	0.68	17.1895	<0.0001	0.36
All locations	5.2	0.73	49.6379	<0.0001	0.39

evaluated ($\alpha = 0.05$) as indicated in Table 10. A significant quadratic relationship between micronaire and soil pH was identified at the Perkins 2019 site only ($p = 0.0159$). At the Perkins 2020 site, length, uniformity, and strength were all significantly correlated with soil pH when evaluated with

TABLE 9 Results of nonlinear regression analysis of relative cotton lint yield in response to soil pH level for individual cotton cultivar across all sites combined.

Cultivar	Joint	Plateau	F	Prob F	r^2	95% CI
DP 1612	6.1	0.76	25.43	<0.0001	0.40	5.4947, 6.7370
NG 3930	5.2	0.72	17.77	<0.0001	0.32	4.7466, 5.5795

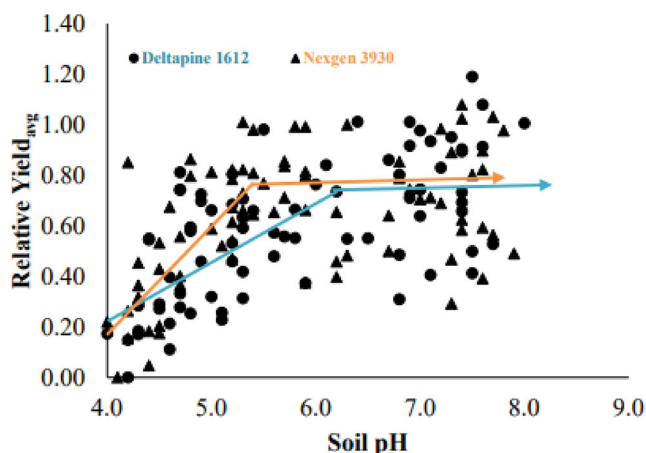


FIGURE 3 Linear plateau chart of relative lint yield in relation to soil pH as evaluated using nonlinear regression separated by cultivar across all sites combined.

TABLE 10 Results of quadratic least squares regression on cotton lint quality parameters and the relationship to soil pH level at individual sites.

Perkins 19	df	MSE	F	Prob F	r^2
Micronaire	2	0.1157	4.55	0.0159	0.17
Length	2	0.0010	1.80	0.1764	0.07
Uniformity	2	0.7968	0.16	0.8488	0.01
Strength	2	1.6127	0.26	0.7703	0.01
Perkins 20					
Micronaire	2	0.1108	2.09	0.1359	0.09
Length	2	0.0008	4.32	0.0193	0.16
Uniformity	2	1.1704	6.74	0.0028	0.23
Strength	2	2.011	4.63	0.0150	0.17
Efaw					
Micronaire	2	0.0357	2.09	0.1320	0.06
Length	2	0.0011	0.79	0.4566	0.03
Uniformity	2	1.6637	0.90	0.4116	0.03
Strength	2	3.433	1.15	0.3246	0.04

quadratic least squares regression with p values of 0.0193, 0.0028, and 0.0150, respectively. No significant relationships between lint quality parameters and soil pH were identified at the Efaw site ($\alpha = 0.05$).

TABLE 11 Results of quadratic least squares regression on cotton lint quality parameters and the relationship to soil pH level for individual cultivars at sites indicated to be significant.

Site/measure/ cultivar	Relationship	DF	MSE	F	Prob F	r^2
Perkins 19						
Micronaire						
DP 1612	Linear	1	0.0766	12.56	0.0018	0.36
NG 3930	NS	—	—	—	—	—
Perkins 20						
Length						
DP 1612	Quadratic	2	0.0004	5.44	0.0125	0.34
NG 3930	NS	—	—	—	—	—
Uniformity						
DP 1612	NS	—	—	—	—	—
NG 3930	Quadratic	2	0.9761	6.37	0.0072	0.39
Strength						
DP 1612	Quadratic	2	1.4891	3.90	0.0364	0.27
NG 3930	Quadratic	2	1.1615	4.44	0.0254	0.31

Abbreviation: NS, not significant.

All locations at which a significant relationship between lint quality parameters and soil pH was identified were further analyzed based on cultivar (Table 11). Micronaire at the Perkins 2019 location was only significant for the Deltapine 1612 cultivar when evaluated with linear regression ($p = 0.0018$), whereas no relationship was present among the Nexgen 3930 cultivar planted treatments. This same pattern existed for fiber length at the Perkins 2020 site where Deltapine 1612 provided a significant quadratic response to soil pH ($p = 0.0125$) while Nexgen 3930 did not. An inverse of this pattern existed for the uniformity parameter at the Perkins 2020 site as Nexgen 3930 was significant ($p = 0.0072$), whereas Deltapine 1612 was not. Strength was significant for all treatments with p values of 0.0364 and 0.0254 and similar r^2 values of 0.27 and 0.31, respectively, for Deltapine 1612 and Nexgen 3930 when evaluated using quadratic least squares regression.

In the southern and central plains region, soil pH causes problems primarily in the form of increased levels of soluble Al. In response, this experiment also evaluated cotton lint yield as a function of Al_{KCl} . The Al_{KCl} level was negatively related to soil pH level (Figure 4) with strong coefficient of determination values of 0.78, 0.73, and 0.87 per Perkins 2019, 2020, and Efaw locations, respectively. Relative cotton lint yield responded inversely to Al_{KCl} concentration at a rate of 0.0024% per 1 mg kg⁻¹ increase in Al across all sites (Figure 5). All locations indicated a strong relationship between relative lint yield and Al_{KCl} (Table 12). Soil pH level, however, did provide a stronger coefficient of determination when comparing values when all locations were combined.

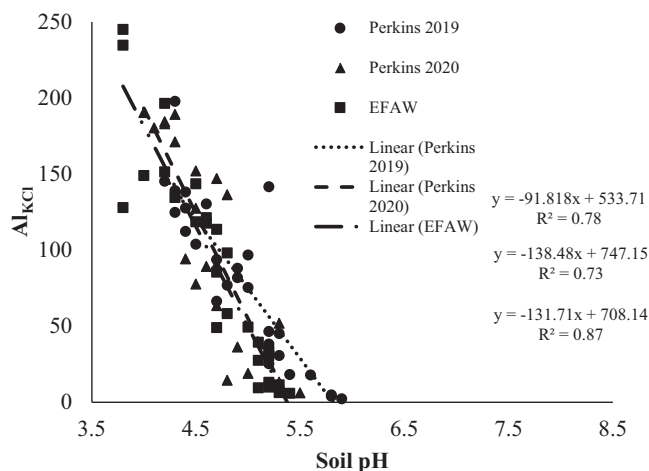


FIGURE 4 Linear regression of Al_{KCl} (potassium chloride extractable Al) concentration ($mg\ kg^{-1}$) relative to soil pH levels across each site.

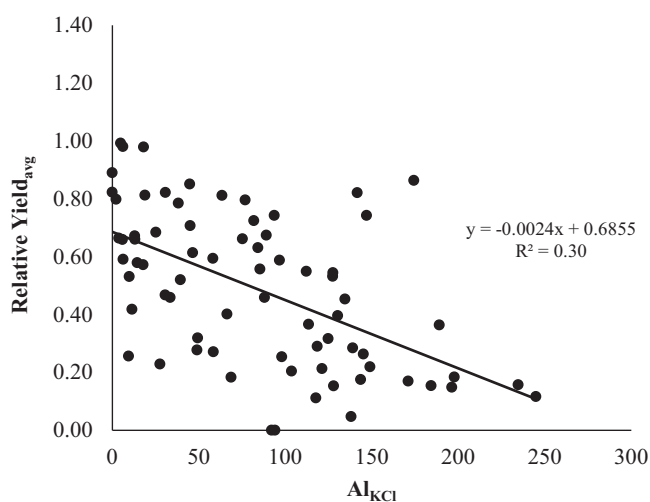


FIGURE 5 Linear regression relative cotton lint yield and Al_{KCl} (potassium chloride extractable Al) concentration ($mg\ kg^{-1}$).

TABLE 12 Results of quadratic least squares regression analysis of relationship between cotton lint yield and Al_{KCl} (potassium chloride extractable Al) concentration.

Site	DF	MSE	F	Prob F	r^2
Perkins 19	1	0.0318	25.02	<0.0001	0.50
Perkins 20	1	0.0262	46.38	<0.0001	0.68
Efaw	1	0.0311	19.48	0.0002	0.47
All locations	1	0.0498	31.06	<0.0001	0.30

4 | DISCUSSION

While evaluating the relationship between relative lint yield and soil pH, nonlinear analysis (linear plateau) generally provided greater coefficient of determination values relative to quadratic least squares regression. The nonlinear regression

also allows for clear identification of a specific critical threshold at which cotton lint yield is likely to decrease due to acidic soil conditions, this being imperative to the applied nature of the experiment. Critical soil pH levels were identified at all sites (Table 9), although across a wide range of soil pH levels from 5.7 at the Efaw 2020 site to 4.8 at Perkins 2020. The variability exhibited across the experiment suggests that the growing environment likely influenced crop response relative to soil pH level. This response could be attributed to a change in early season vigor and thus rooting depth, which may allow the plant to perform better by reaching the neutral subsoil earlier in the growing season. Rooting characteristics were not examined due to limitations of the study. Similar responses have been described in studies conducted by Butchee et al. (2012) and Sutradhar et al. (2014) evaluating soil pH influence on sorghum and sunflower performance.

When all sites were combined, a critical threshold of 5.2 was observed for the relationship between relative cotton lint yield and soil pH level. This would suggest that cotton possesses similar tolerance to soil acidity and its related toxicities as other crops such as wheat (Zhang & Raun, 2006). In addition, when analyzed using linear regression utilizing points at the critical soil pH level or lower, an estimated lint yield loss per soil pH unit (0.1) is calculated at approximately 4.5%. When soil pH critical threshold was evaluated for the individual cultivars based on relative yield, there was no significant difference at $\alpha = 0.05$. However, confidence intervals indicate that identifying critical thresholds for individual cultivars is likely attainable and may provide additional value to germplasm selection for acidic soil tolerant cultivars, considering the wide range of soil pH conditions in which cotton is grown. Increases of Al_{KCl} negatively impacted yield. Strong correlation between soil pH and Al_{KCl} provides ample evidence of the key driver in yield loss in acidic soil conditions. However, under the circumstances of this experiment, soil pH level provided the greatest coefficient of determination for lint yield losses expected under acidic soil conditions.

Variability between soil pH critical threshold levels across location and measurement for in-season growth parameters was not as great as relative yield. All in-season growth parameters were significantly related with soil pH ($\alpha = 0.05$). All significant critical threshold levels fell in between a soil pH range of 4.6–5.4. These measurements were indicative of in-season stress experienced by the crop even if not directly equated with observed lint yield loss as exemplified by the slightly lower critical threshold levels contrast to relative lint yield.

5 | CONCLUSION

Cotton performance is strongly influenced by soil pH level as expressed throughout this work. Amelioration of acidic

conditions is likely required to optimize production in fields with soil pH levels lower than 5.5. This result is similar to the current amelioration recommendations for other crops in Oklahoma (Zhang et al., 1998). As demonstrated by this experiment, soil pH levels below 5.5 negatively impacted cotton lint yield with losses occurring at a rate of 386 kg ha⁻¹ per 0.1 change in soil pH, assuming 100% yield level at approximately 989 kg ha⁻¹ of lint. Early indications of negative impacts of acidic conditions were prevalent as in-season growth measurements were correlated inversely with soil pH levels. All of the in-season growth measurement also indicated similar critical threshold soil pH levels to analysis of relative lint yield.

As such, it is important for growers to identify and ameliorate these problem soils preemptively to avoid yield loss and possible decrease in use efficiency of nutrients and water. These soil conditions are prevalent throughout central Oklahoma as presented by soil analysis data summarized by Zhang et al. (1998) and Zhang and McCray (2008), highlighting the need for amelioration to optimize production on many of the soils in the region.

AUTHOR CONTRIBUTIONS

R. L. Sharry: Data curation; formal analysis; investigation; project administration; writing—original draft; writing—review and editing. **M. Smith:** Investigation; writing—review and editing. **H. Moulay:** Writing—review and editing. **J. Souza:** Data curation; writing—review and editing. **S. Sharma:** Writing—review and editing. **D. B. Arnall:** Conceptualization; data curation; funding acquisition; investigation; methodology; writing—review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

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