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Subsurface banding increases ammonia emissions under rainfed cotton in Florida sandy soils

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Ammonia (NH_3) volatilization is a significant pathway for nitrogen (N) loss. The acidic, sandy soils of Florida offer ideal conditions for NH_3 losses in rainfed cotton production systems. To assess NH_3 losses under various N placement methods and rates, the experiment was conducted in 2023 and 2024 using a randomized complete block design with four replications. The study employed two placement methods: surface broadcasting and subsurface banding, and two N rates: 67.5 and 102 kg N/ha. Ammonia emissions were measured using open-chamber traps, with sampling conducted multiple times per week. Daily NH_3 emissions (g/ha/day) were averaged over each week, and cumulative emissions (g/ha) were calculated by summing weekly averages across the sampling period. These cumulative values were then used to estimate total NH_3-N losses, expressed as a percentage of the total N applied. Sampling weeks were referenced as WAF (weeks after fertilization) to standardize timing across both years. Results indicated that both daily and cumulative NH_3; emissions were significantly higher with subsurface banding compared to surface broadcasting, leading to greater N-NH_3; losses under banding. In addition, neither placement method nor N rate significantly influenced cotton lint yield. These findings suggest that, under the conditions of this study, subsurface banding increased NH_3 volatilization losses in rainfed cotton grown on sandy soils in Florida.

KEYWORDS

ammonia volatilization, nitrogen, subsurface band, surface broadcast, cotton

1 Introduction

Global agricultural production has increased over the past century, along with the increased use of nitrogen (N) fertilizers (FAO, 2020). The increased use of N fertilizers has led to higher N losses through ammonia (NH_3) volatilization, nitrate leaching, and nitrous oxide emissions, resulting in harmful environmental impacts (Stark and Richards, 2008). These losses can result in lower nitrogen use efficiency (NUE). According to Delgado

(2002), global NUE ranges between 33% and 50%, and unaccounted N can be more than $15 billion, resulting in high economic losses. Lower NUE indicates higher N losses, and NH_3 volatilization is a major concern, as more than 60% of applied N can be lost through volatilization (Rochette et al., 2013). However, N fertilizer placement can improve NUE by reducing N losses and enhancing N conservation in soil (Reiter et al., 2008; Li et al., 2018; McClanahan et al., 2020; Singh et al., 2023).

Surface application, such as broadcasting, exposes fertilizers to rapid volatilization due to greater NH_3 diffusion into the atmosphere (Götze et al., 2023). In contrast, subsurface banding is reported to reduce volatilization losses by increasing NH_4^+ retention and limiting NH_3 escape (Nkebiwe et al., 2016). Previous studies have demonstrated that banded N remains available to crops for a longer duration and enhances fertilizer use efficiency compared to broadcast applications (Canatoy et al., 2024). The field studies have reported one to nine times lower NH_3 losses under subsurface banding of fertilizer compared to surface broadcasting (Bouwman et al., 2002; Prasertsak et al., 2002). However, several studies have reported contradicting results showcasing higher NH_3 losses under subsurface band than surface broadcasting (Rochette et al., 2009a, 2009b).

Ammoniacal N fertilizers, such as urea, undergo conversion to NH_4^+ and nitrate to be available for plant uptake, a process that begins with urease enzyme-mediated hydrolysis in the soil (Wang et al., 2014, Motasim et al., 2024). The hydrolysis process is facilitated by the consumption of H^+ ions from the soil, resulting in an increase in soil pH in the vicinity of applied urea (Harty et al., 2023). Increasing soil pH can increase NH_3 concentration and, thus, increased NH_3 volatilization. However, the changes in pH depend on soil buffering capacity and concentration of NH_3 source in soil, influencing the emissions (Rochette et al., 2009a; Harty et al., 2023). The banding of a large amount of N can result in a higher soil pH and may lead to increased NH_3 volatilization, especially in soils with low buffering capacity (Rochette et al., 2009a). Therefore, the efficiency of placement methods to improve NH_3 volatilization depends on soil properties and microbial activity.

In the Florida Panhandle, sandy-textured soils combined with low pH result in a very low buffering capacity, making the soil highly susceptible to pH changes following N fertilization. Surface broadcasting of N fertilizers, a common practice among farmers in this region, often leads to substantial NH_3 volatilization losses, particularly under the humid environmental conditions prevalent in the Panhandle. Among commonly used fertilizers, urea is especially prone to such losses when left exposed on the soil surface. Given these challenges and mixed effect of subsurface band in literature, there is a critical need to evaluate subsurface banding NH_3 volatilization under these conditions as an alternative placement method. Therefore, we conducted a two-year field study to assess the effectiveness of subsurface banding compared to surface broadcasting in reducing NH_3 emissions. We hypothesized that subsurface banding would reduce the NH_3 emissions compared to surface broadcasting.

Abbreviations: N, Nitrogen; NH_3, Ammonia; WAF, Weeks after fertilization.

2 Materials and methods

2.1 Experiment site and materials

Field experiments were conducted in 2023 and 2024 at the University of Florida/IFAS West Florida Research and Extension Center, Jay, FL (30°46′34.5″N, 87°08′15.9″W). Although both trials were conducted at the same research station, they were established in different fields each year to accommodate spatial variability and maintain consistent rotation practices across the station. Soil at the experimental site was a Red Bay fine sandy loam (fine-loamy, kaolinitic, thermic Rhodic Kandiudults) with 0 to 2% slope. The soil properties for both study years are listed in Table 1. For 2023, soil pH was 6.4 and CEC was 7.5 cmol/kg, and for 2024, soil pH was 6.3 and CEC was 8.8 cmol/kg. The minor differences in initial soil pH and CEC between years reflect this inherent variability across field locations within the research station. Weather data during the study were collected from stations operated by the Florida Automated Weather Network, located within 1 km of the experimental site. The field was disked, leveled with a field cultivator, and strip-tilled before planting. Cotton was planted at a seed rate of 89,700 seeds/ha with 91 cm row spacing in 7.62 m × 3.65 m plots using Monosem planter (Monosem NG Plus, A.T.I. Inc., Kansas). Pre-plant soil samples (0–0.30 m depth) were taken in March for both years and were sent to Waters Lab, Camilla, GA, for analysis using Mehlich 3 method (Ziadi and Tran, 2007). Basal fertilizers were applied using Waters lab recommendation, excluding N.

2.2 Experimental design and treatments

The experiment followed a randomized complete block design with a 2 × 2 factorial arrangement and four replications. The treatments consisted of two N application rates (67.5 kg N/ha and 102 kg N/ha) and two N placement methods (surface broadcast and subsurface banding). Urea (46-0-0) (Nutrien Ag., Loveland, CO) was applied in two splits: 33.3% at emergence (3 weeks after planting) and 66.6% before the pinhead growth stage (6–7 weeks after planting). Urea was applied using a Gandy spreader (Gandy Company, Owatonna, MN) for broadcast treatments and a band applicator (First Products, Tifton, GA) for subsurface banding (at >5 cm depth). The depth below 5 cm represents the subsurface banding practice adapted at our research site to ensure soil coverage of fertilizer. Other than that, literature highlights depths above 5 cm as the optimum depth to decrease the diffusion of NH_3 into the atmosphere (Canatoy et al., 2024). Ammonia traps were deployed before each fertilizer application.

2.3 Ammonia measurement

Ammonia sampling was conducted using open-chamber traps as described by Jantalia et al. (2012). These traps, placed between the second and third rows of cotton, consisted of cotton wicks soaked in sulfuric acid to capture NH_3. The wicks and containers were replaced at each sampling to ensure accurate measurements. To protect the traps from rainfall and maintain sampling

TABLE 1 Soil properties across 0-30 cm depth in 2023 and 2024 at the study site.

Year	pH	CEC	P	K	Mg	Ca	S	B	Zn	Mn	Fe	Cu
			mg/kg									
2023	6.4	7.5	42.69	54.50	119.25	784.19	7.19	0.35	1.91	37.00	81.63	0.83
2024	6.3	8.8	75.12	120.43	176.56	829.12	6.18	0.22	2.06	97.56	76.18	0.8

consistency, each trap was covered by attaching the bottom half of a plastic bottle over the top of the chamber (Supplementary Figure 1). Following rainfall events, any wet traps were promptly replaced with dry ones to minimize sampling bias and ensure data reliability. Each collected sample was analyzed for NH_3 concentration using a phenol-hypochlorite assay, which measured absorbance at 630 nm using a spectrometer (Thermo Fisher Scientific, Waltham, MA). A standard curve was generated using predetermined concentrations of NH_3-N ranging from 0 to 8 mM, and absorbance values were plotted against millimolar concentrations of NH_3-N. The relationship between absorbance (y) and NH_3-N concentration in millimolar (x) was described by the linear regression Equation 1:

$$y = 0.1854x + 0.0646 \tag{1}$$

This equation was used to convert absorbance values to NH_3-N concentration (mM) which was converted to milligrams (mg). The trap area (0.01008 m^2) was used to calculate the amount of fertilizer (mg) applied in that specific area.

Sampling was done over multiple days in a week, and daily NH_3 emissions (g/ha/day) were averaged over weeks. Averaging daily values helped reduce variability caused by day-to-day fluctuations in weather conditions, thereby improving data interpretability and allowing for clearer comparisons across treatments. However, this conservative approach may have limited the detection of short-term emission peaks that could occur immediately following fertilization or rainfall events. Despite this limitation, the method aligned with our primary objective of assessing broader emission trends under different N management practices.

Daily NH_3 emissions over weeks were summed to calculate cumulative NH_3 emissions (g/ha). These cumulative NH_3 emissions were used to determine total NH_3-N losses (%) as percentage loss of total applied N. In this study, "NH_3 emissions" represents the emission loss on a weekly basis from the treatments, whereas "NH_3-N loss" represents the percentage of N applied which was lost as NH_3.

In 2023, samples were taken at 1, 2, 3, 4, and 5 weeks after fertilization (WAF). In 2024, samples were collected at 1, 2, 3, 4, 5, 6, 7, 8, and 9 WAF. The WAF represents weeks after the first application. Sampling was continued after the second application in both years. In 2023, the second application was done at 3 WAF, whereas, in 2024, it was done at 4 WAF.

2.4 Lint yield estimation

Seed cotton yield was estimated by harvesting two non-border rows with a two-row John Deere cotton picker (John Deere, Moline, IL). Seed cotton subsample (300 g) was ginned using a micro-gin to determine lint turnout (%), which was then used to estimate lint yield.

2.5 Data analysis

Data was analyzed using the *lmer* (Nagle, 2018), *agricolae* (Kozak, 2020), and *doebioresearch* packages in R Studio (v 4.2.2) (R Core Team, 2021). A generalized linear mixed-effects model was employed, incorporating blocks and years as random effects and N placement methods and rates and their interaction as fixed effects. The data was assessed for constant variance using the Levene test and normality using the Shapiro-Wilk test, with log transformations applied when assumptions were violated. Treatment means were separated using the Tukey test at 95% significance level ($p \leq 0.05$). Graphs were designed using the *ggplot2* package in R studio (Wickham and Sievert, 2009).

3 Result and discussion

3.1 Daily and cumulative ammonia emissions, and total N-NH_3 loss (%)

For 2023, there was no significant difference in daily NH_3 emissions between the treatments at any time point (Figure 1A) ($p = 0.81$). The highest emissions were observed after the application of second fertilizer split (at 3 WAF) for all the treatments (Figure 1A). In 2023, fertilizer application was followed by heavy rainfall at both, which might have resulted in leaching down of N and resulted in no significant differences (Figure 2). However, in 2024, there was a significant effect of placement method on emissions (Figure 1B). Daily emissions were significantly higher under subsurface banding at 1 WAF (772 g/day/ha) as compared to surface broadcast (392 g/day/ha) ($p = 0.028$). However, there was no difference between daily emissions at any other time point. At 1 WAF, the first split was followed by a small amount of rain and dry period, which might have helped in the accumulation of NH_3 emissions. However, the second application was followed by constant rain, which might have resulted in leaching of N (Figure 2).

In 2023, a significant effect of the placement method on cumulative NH_3 emissions was observed (Figure 1C) ($p = 0.01$). The subsurface band resulted in significantly higher cumulative emissions (932 g/ha) compared to surface broadcast (860 g/ha) across both rates. In 2024, the interaction effect was observed on cumulative NH_3 emissions (Figure 1D) ($p = 0.001$). At 67.5 kg N/ha,

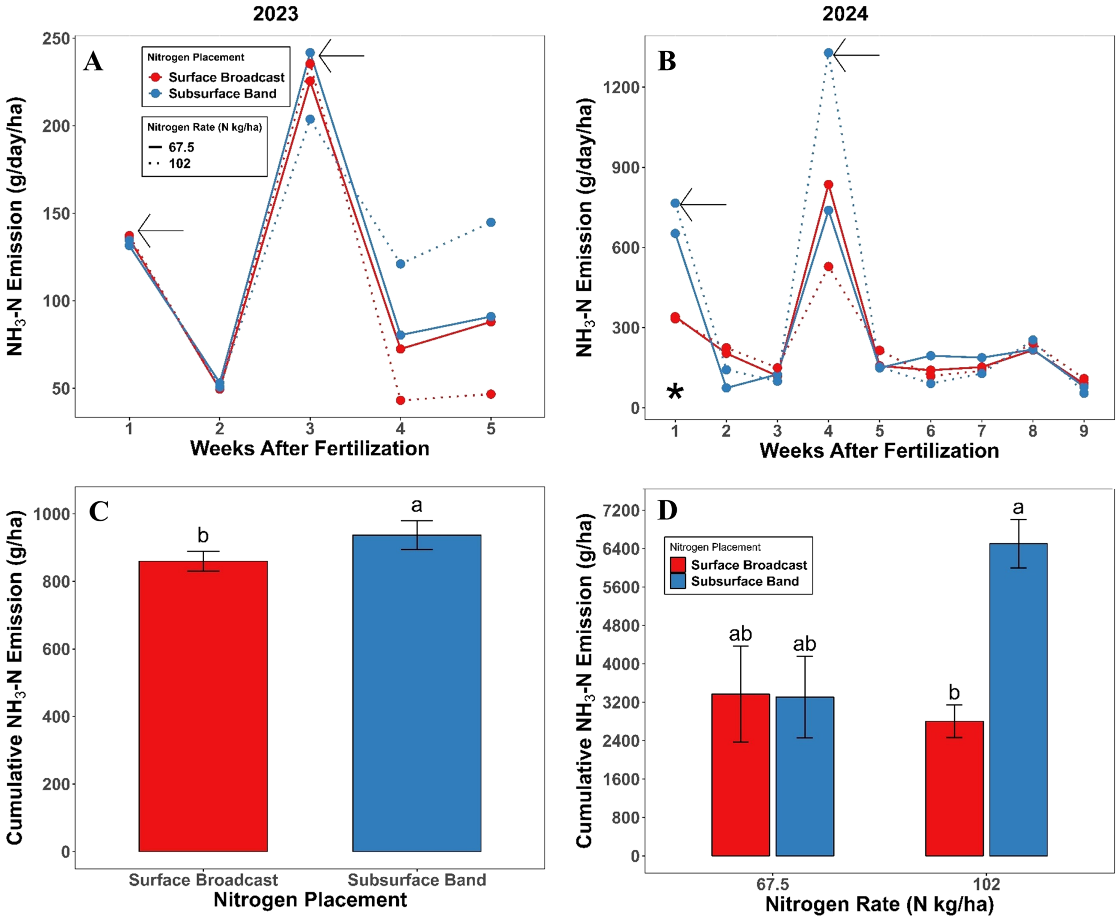

FIGURE 1
(A) Daily ammonia emissions from surface broadcast and subsurface band placement of urea at the rate of 67.5 and 102 kg N/ha in 2023. The arrow at 1 week after fertilization (WAF) represents the first split (33.33% of total nitrogen) application and arrow at 3 WAF indicates the second split (66.66% of total nitrogen) of fertilization. **(B)** Daily ammonia emissions from surface broadcast and subsurface band placement of urea at the rate of 67.5 and 102 kg N/ha in 2024. The arrows in B at 1 and 4 WAF represent first and second split of fertilization, respectively. **(C)** effect of placement method on cumulative ammonia emissions in 2023. **(D)** Interaction effect of placement method and nitrogen rates on cumulative ammonia emissions in 2024. Means followed by different letters in C and D represents significant differences between treatments at $p < 0.05$. The asterisk "*" sign in B indicate that the ammonia emissions were significantly different at that time point.

there was no difference between the placement methods; however, surface broadcast resulted in reduced cumulative NH_3 emissions (2802 g/ha) at higher N rate (102 kg N/ha) than subsurface band (6502 g/ha).

Results from the current study indicate that the subsurface band was unable to reduce daily NH_3; emissions and cumulative NH_3; emissions compared to surface broadcast, which is contradictory to previous findings by Huijsmans et al. (2001); Bittman et al. (2005), and Pfluke et al. (2011). These studies reported that the subsurface band can reduce diffusion of NH_3 into the atmosphere by creating resistance or by reducing the surface area exposed to the atmosphere in surface band. However, NH_3 volatilization is influenced by the complex interactions among soil properties, the urease enzyme, placement method, and N rates. Surface broadcasting distributes fertilizer across a wider soil area, leading to lower localized concentrations. In contrast, subsurface banding concentrates urea in a narrow zone, resulting in higher N concentration and more intense pH increases in the surrounding soil (Rochette et al., 2009b; Tewolde et al., 2023). As mentioned earlier, the low buffering capacity of sandy soil can lead to higher soil pH under the subsurface band, resulting in higher NH_3 emissions and higher N-NH_3 losses. Under the sandy loam texture of acidic soils at research site, this localized pH spike can intensify NH_3; volatilization. This effect appeared more prominent at the higher N rate (102 kg N/ha), where subsurface banding resulted in 132% increase in NH_3; emissions compared to surface broadcast (Figure 1D). This interaction observed between placement and rate may therefore be attributed to the compounded effect of high N concentration and limited pH buffering in the band zone, amplifying NH_3; losses under banded applications at higher rates (Figure 3).

A significant effect of the placement methods was observed for total N-NH_3 loss (%) across 2023 and 2024 (p< 0.001) (Figure 4A). The subsurface band resulted in a significantly higher N loss (4.9%) compared to surface broadcast (3.1%). The NH_3-N losses were very low in general in the current study, which can be attributed to acidic

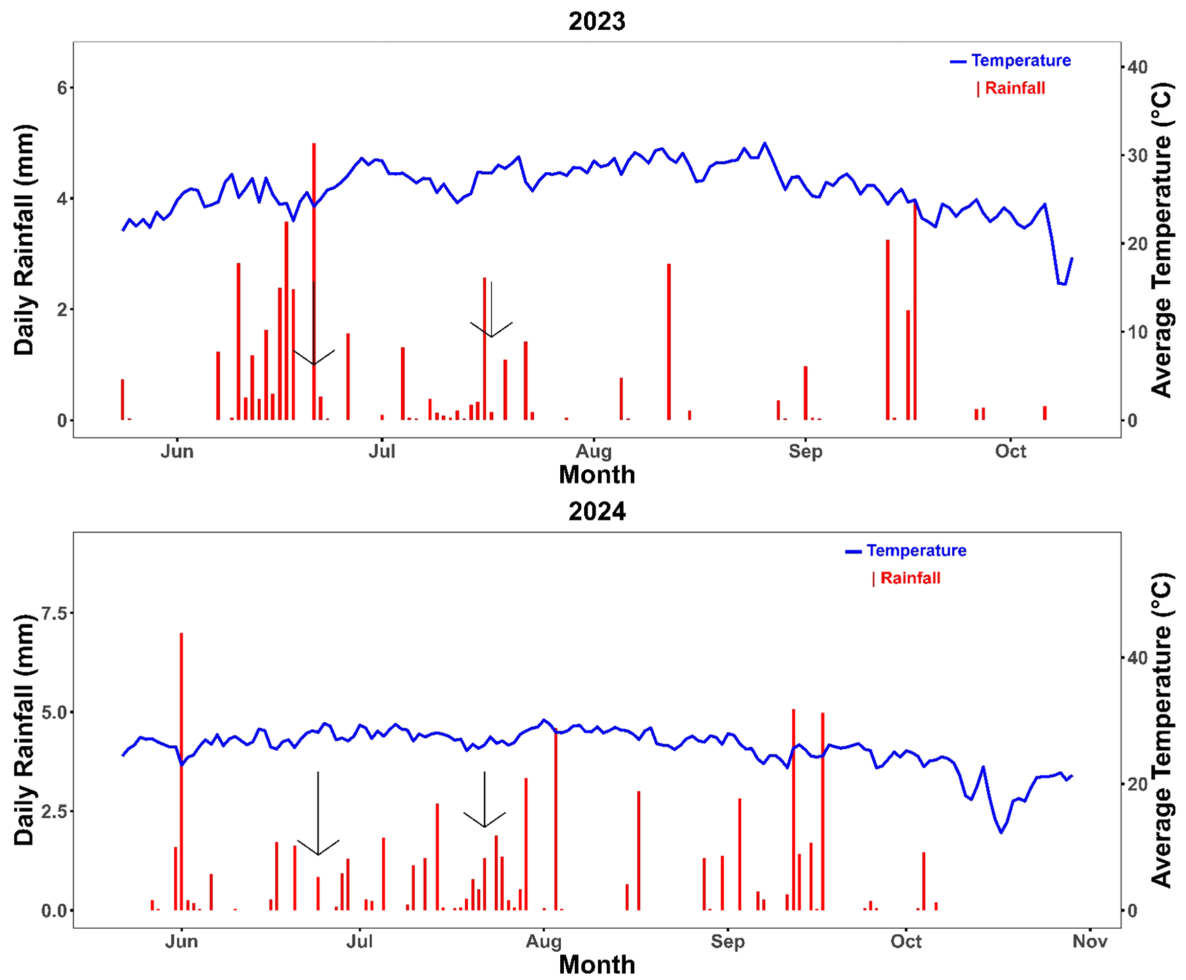

FIGURE 2
Daily rainfall and average temperature data for years 2023 and 2024 throughout the study period. The arrows indicate the dates when fertilizers were applied.

nature soil, favoring NH_4^+ than NH_3 (Harty et al., 2023). The higher NH_3-N losses under subsurface band can be explained by a higher concentration of N in bands. Our study focused on cotton production with 91-cm row spacing, resulting in a higher concentration of urea (g m^{-1} of the band) in bands to compensate for the large row spacing (Rochette et al., 2009b) which might have resulted in higher NH_3-N losses (%). Similarly, Rochette et al. (2009b) reported higher NH_3 concentration and emissions with band application of urea than surface broadcasting. The authors also reported an increase in pH from 6.0 to 8.7 upon band application. From the results of the current study, we can infer that surface broadcasting is more efficient in managing NH_3 losses at higher N rates than subsurface banding on sandy soils.

3.2 Lint yield

There was no significant difference in lint yield among treatments across both study years (p = 0.46) (Figure 4B). Lint yield ranged from 1617 to 1732 kg/ha across all treatments. Although NH_3 losses were higher under subsurface band, the lint yield was comparable to surface broadcasting. Lint yield is a complex trait in cotton, influenced by the interplay of various factors, including weather conditions, soil properties, N availability, and N uptake (Cetin and Basbag, 2010). Nevertheless, the findings of the present study align with previous research (Warren et al., 2008; Halvorson and Del Grosso, 2013), which also reported no significant differences in yield between subsurface banding and surface broadcasting. The application through subsurface band results in a higher concentration of N in narrow bands, which can result in an increase in soil pH (Rochette et al., 2009b). The sudden changes in soil pH might result in a lower N uptake in cotton (Guo et al., 2022). The lower N uptake coupled with higher NH_3-N losses under subsurface band might have resulted in no differences in lint yield in the current study. Results of the current study are in contradiction with other studies which have reported a positive effect of subsurface band over surface broadcast in cotton and corn (*Zea mays* L.) (Tewolde et al., 2009; Tewolde et al., 2023). However, these studies differed from the current study in terms of N source and soil texture.

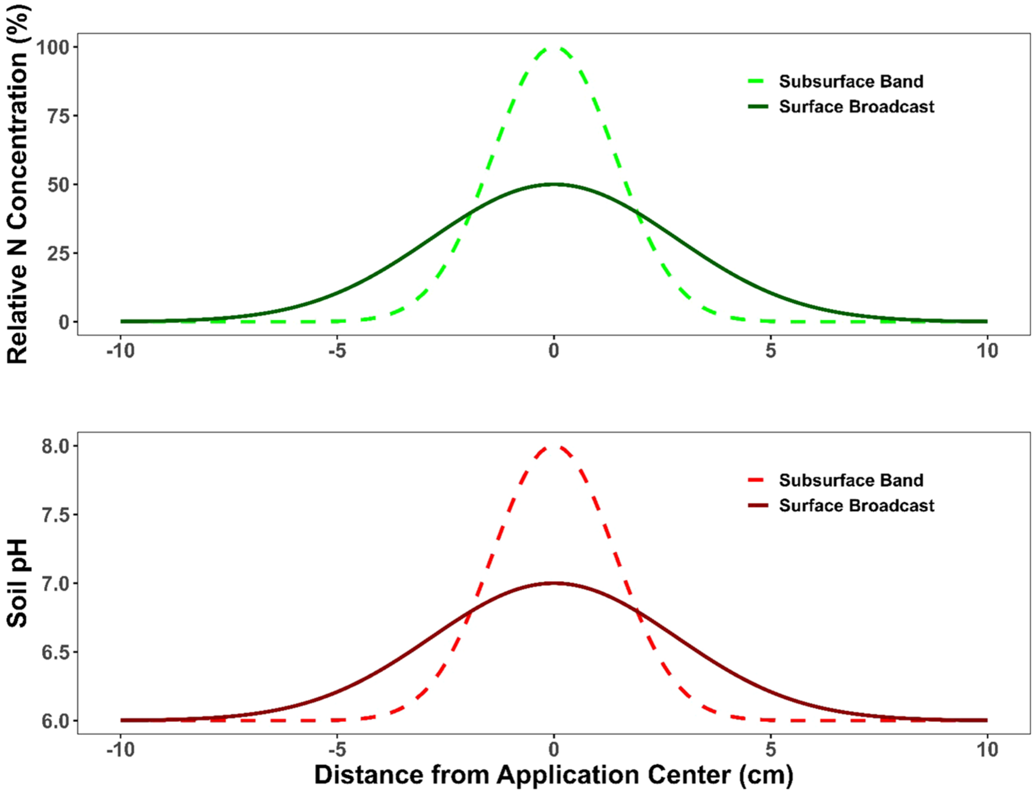

FIGURE 3
Conceptual illustration of relative N concentration and soil pH changes around subsurface band (dashed) and surface broadcast (solid) applications in sandy soils. Subsurface banding creates higher localized N and pH spikes than surface broadcasting.

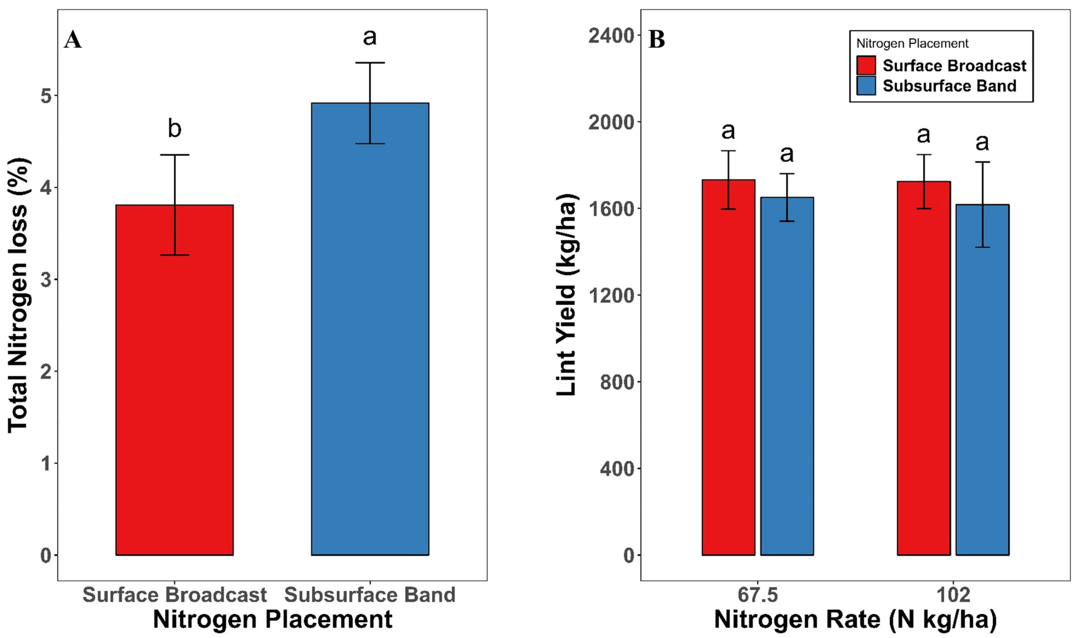

FIGURE 4
(A) Total nitrogen loss (%) across nitrogen placement methods for 2023 and 2024. Different letters represent significant differences between placement methods at $p < 0.05$. **(B)** Combined lint yield (kg/ha) across different nitrogen placement methods and rates for 2023 and 2024. The same letters indicate that there was no significant difference in lint yield among nitrogen placement methods and rates.

Tewolde et al. (2009) used poultry litter in the experiment with N content of 2-3% whereas Tewolde et al. (2022) conducted experiment on clay loam soil, which has higher buffering capacity than sandy soil. The N uptake and NH_3 losses are influenced by soil properties and N sources, which might have resulted in contradicting results in the current study.

Considering the lack of yield advantage with subsurface banding and the higher NH_3; losses observed under this method, surface broadcasting may present a more practical option for growers in similar production systems. Furthermore, subsurface banding typically requires more passes and specialized equipment, resulting in higher labor and fuel demands, whereas surface broadcasting is faster and uses simpler machinery (Way et al., 2013). These factors, coupled with comparable lint yields, suggest that surface broadcasting may be a more efficient and feasible N placement method under the conditions of this study.

4 Conclusion

Subsurface band resulted in higher NH_3 emissions compared to surface broadcast. When N was applied at a higher rate, subsurface band resulted in significantly higher cumulative N-NH_3 emissions as compared to surface broadcast. Although NH_3 losses were higher under the subsurface band, there was no difference in lint yield between the subsurface band and surface broadcast. The findings of the current study highlight that subsurface banding was ineffective in reducing NH_3 losses in cotton production systems.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

KS: Data curation, Formal analysis, Methodology, Writing – original draft. ED: Validation, Writing – review & editing. SS: Data curation, Writing – review & editing. AS: Data curation, Writing – review & editing. LS: Project administration, Writing – review & editing. HS: Conceptualization, Funding acquisition, Investigation, Project administration, Resources, Supervision, Validation, Visualization, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declare that no Generative AI was used in the creation of this manuscript.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fagro.2025.1625163/full#supplementary-material

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