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Nitrogen use efficiency of silage corn with contrasting nitrogen fertility sources in a semi-arid system

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Silage corn production in semi-arid environments poses challenges for sustainable intensification and soil health due to the removal of aboveground biomass during harvest. A nine-year field study in northern Utah, USA, evaluated the effects of different nitrogen (N) fertility sources on silage yield, nitrogen use efficiency (NUE), and soil total nitrogen (STN). Treatments included no fertilizer (Control), ammonium sulfate at two rates (112 and 224 kg N ha^{-1} $year^{-1}$; AS100 and AS200), and steer manure compost (224 kg total N ha^{-1} $year^{-1}$). Compost increased STN by 23% compared to synthetic fertilizer treatments but produced 31% lower yields than AS-based treatments. While AS100 and AS200 yielded similarly, AS100 exhibited superior NUE. Despite lower yields and NUE under compost treatment, compost contributed to higher STN. These findings suggest that farmers should integrate compost applications with reduced nitrogen fertilizer rates and adopt additional soil health practices, such as crop rotation and cover cropping, to enhance sustainable soil fertility management in silage corn.

KEYWORDS
nitrogen use efficiency, silage corn, compost, total nitrogen, semi-arid environments

1 Introduction

Arid and semi-arid regions are essential to global food security due to their agricultural potential (Ayangbenro and Babalola, 2021). However, these areas are highly susceptible to land degradation (Reynolds et al., 2011; Badapalli et al., 2023) and face distinct challenges such as limited water availability, short growing seasons, soil nutrient deficiencies, and salinity issues (Creswell et al., 1993; Idowu and Grover, 2000; Ayangbenro and Babalola, 2021). For the past 50 years, farmers around the world have used synthetic fertilizers to increase crop yields, sometimes over-fertilizing, as a form of insurance or because of public policies subsidizing fertilizer costs (Li et al., 2013; Scholz and Geissler, 2018; Wang et al., 2023). Growers may be less concerned about the indirect costs of environmental pollution from excessive nitrogen (N) application due to short-term goals of economic survival (Yadav et al., 2017).

Corn silage serves as a high-energy feed for dairy cows and beef cattle (Allen et al., 2015) and provides a practical solution for utilizing stressed or damaged corn fields (Cecava, 1995). The global market for corn silage is expected to expand at an annual growth rate of 7.84% from 2021 to 2030 (Karnatam et al., 2023). However, its production comes with challenges. Transporting and marketing silage over long distances can be difficult. Furthermore, the extensive removal of aboveground biomass during harvest reduces crop residues, which can heighten the risk of soil erosion, degrade soil quality, and limit soil organic matter inputs (Blanco-Canqui and Lal, 2009; Stella et al., 2019). To sustain yields without degrading the environment, growers often rely on increased fertilizer inputs, which can be costly and may not necessarily improve profitability or soil health (Sheriff, 2005). Improved N management is essential for balancing productivity with environmental stewardship (Olivo et al., 2024). Assessing N use efficiency (NUE) is a crucial approach for assessing and enhancing nutrient management in agriculture, enabling farmers to optimize N fertilizer use by increasing crop yield while reducing environmental risks associated with N leaching (Curtin et al., 2017; Govindasamy et al., 2023). Fertilizer applications are often increased to reach yield targets yet add significant cost not always leading to greater profits and which can negatively affect soils and the environment (Sheriff, 2005). The goal of assessing NUE is to increase the use and uptake of N inputs, while achieving an economically viable yield and reducing the loss of N to the environment (Congreves et al., 2021). However, a low NUE does not always indicate environmental harm, nor does a high NUE guarantee environmentally safe N management (Langholtz et al., 2021). Various factors, including soil conditions, climate, and farm management practices, influence NUE outcomes (Congreves et al., 2021; Langholtz et al., 2021; Govindasamy et al., 2023).

NUE can be assessed using different metrics such as partial factor productivity (PFP), agronomic efficiency (AE), partial nutrient balance (PNB) and uptake efficiency (UE) (Augarten et al., 2019; Fixen et al., 2015). Uptake efficiency (UE) is used to examines plant N uptake in response to N input (Fixen et al., 2015; Augarten et al., 2019; Congreves et al., 2021). Agronomic efficiency (AE) is commonly used to address the question of how much productivity is improved by application of a unit of N (Černý et al., 2012; Augarten et al., 2019). Partial factor productivity (PFP) is used to evaluate the productivity of the cropping system compared to nitrogen application (Augarten et al., 2019). Partial nutrient balance (PNB) is used to calculate how much N is being taken out of the system compared to how much was added (Augarten et al., 2019).

NUE is often discussed regarding the corn grain system, and these values should not be used as the benchmark for the NUE of corn silage. More N is removed with corn silage production than for corn grain since the entire aboveground biomass is removed at harvest; while corn grain production removes the grain, leaving the stalk residue in the field. Because of these differences in N removal rates, the NUE of corn silage should be assessed independently of the NUE for grain production (Augarten et al., 2019). Sparse data on NUE for corn silage production suggests that this additional research on NUE of corn silage will be helpful for assessing the sustainability of these management systems.

Despite this critical distinction, studies specifically targeting NUE in corn silage remain limited—particularly in semi-arid regions like Utah, USA. Most existing research has been conducted in the Midwest USA (Powell et al., 2010; Green et al., 2018; Weaver et al., 2021; Bond, 2025), where environmental conditions differ markedly. Semi-arid regions present unique challenges, including water scarcity, low soil organic matter, limited nutrient availability, and salinity (Creswell et al., 1993; Idowu and Grover, 2000; Ayangbenro and Babalola, 2021), all of which necessitate site-specific management strategies. The lack of research tailored to these environments leaves a significant gap in our understanding and limits opportunities for sustainable system improvements. Advancing corn silage production in semi-arid areas is essential to support reliable livestock feed supplies, enhance regional economies, and promote long-term agricultural sustainability.

To address this gap, a long-term field experiment was initiated in 2011 to investigate the impacts of contrasting N fertility sources on soil microbial communities and enzyme activities under corn silage production (Ouyang, 2016; Ouyang et al., 2017; Ouyang and Norton, 2020). This project included multiple N treatments, including ammonium sulfate at two application rates (112 and 224 kg N ha^{-1} $year^{-1}$) and steer manure compost at 224 kg N ha^{-1} $year^{-1}$. Ammonium sulfate fertilizer is a widely used fertilizer in neutral to alkaline soils because it provides essential N and sulfur (S), nutrients that are often deficient in soils (Chien et al., 2011; Powlson and Dawson, 2021). Additionally, its ability to enhance soil structure in saline-sodic conditions, improve phosphorus and micronutrient availability through soil acidification in calcareous soils, and reduce N losses via minimizing ammonia volatilization makes it a valuable fertilizer choice in this system (Chien et al., 2011).

Building on this foundation, our research specifically evaluates the effects of these N sources on corn silage yield, N uptake, NUE metrics —UE, AE, PFP, and PNB, and soil total nitrogen (STN). Unlike prior studies that focused on microbial and enzymatic responses, this research directly measures agronomic outcomes, offering practical insights into optimizing N inputs for sustainable silage production in semi-arid environments. We hypothesize that N fertility sources differ in their effects on corn silage productivity, N use efficiency (NUE), and soil total N (STN), with composted manure providing long-term benefits to both crop performance and soil health under semi-arid conditions. This study quantifies the agronomic benefits of ammonium sulfate and compost over multiple years of repeat application, providing practical insights into optimizing N management for sustainable corn silage production.

2 Materials and methods

2.1 Site description and experimental design

The site is located at the UAES Greenville Research Farm (41°45’56.6”N 111°48’52.2”W) in North Logan, Utah, USA. The soil is a highly calcareous Millville silt loam (coarse-silty, carbonatic, mesic Typic Haploxeroll) with a pH of 8.2 (1:2 soil: water). The plots were established in 2011 to investigate N cycling and different N transformations under contrasting N management, as outlined in previous studies (Ouyang, 2016; Kakkar, 2017). Prior to 2011 the field was utilized for conventional cultivation of small grains, involving an annual application of 70 kg N ha^{-1} in the form of urea. The experimental design in this study was a randomized complete block design (RCBD) with four N fertility source treatments and four replications, totaling 16 plots. Each plot measured 9.1 m in length and 3.8 m in width. Treatments were assigned to the same plot each year. The treatments include a no N control (Control), low ammonium sulfate at 112 kg N ha^{-1} $year^{-1}$ (AS100), high ammonium sulfate at 224 kg N ha^{-1} $year^{-1}$ (AS200), and steer manure compost at 224 kg total N ha^{-1} $year^{-1}$ (Compost). Compost was obtained commercially and consisted of composted steer manure, slaughter by-products and woodchips (Miller companies LLC, Hyrum, Utah). Compost N and dry matter content were determined yearly, and these parameters were used to apply the desired total N rate of 224 kg total N ha^{-1} $year^{-1}$ equivalent to approximately 14 ± 1.8 metric ton of dry weight compost ha^{-1} $year^{-1}$. Average compost analysis was 27.1%C, 1.7%N and 14.5 C/N (Supplementary Table S1). Silage corn was planted every May from 2012 until 2021 except for 2017 when a cover crop of vetch was grown.

2.2 Field operations

During early spring of each year pre-plant soil samples were collected from each plot using a Giddings probe with two cores per plot at depths of 0–15 cm, 15–30 cm and 30–60 cm. Soil was weighed, sieved (2 mm) and air-dried before analysis for available P and K. To meet the crop requirement of P and K, fertilization for P and K in each plot was carried out according to the recommendations outlined in the Utah Fertilizer Guide for silage corn (James and Topper, 1993). The fertilizer applications and compost amendments took place in early May of each year. N, P, K fertilizers were applied to the field using an Edge Guard mini push broadcast spreader (The Scotts Company LLC. USA). For compost treatment, the amendment was applied manually and subsequently, bow rakes were utilized to evenly distribute the fertilizers and compost amendments within individual plots. Following this, the amendments were incorporated into the soil through tillage within one day of application.

After the amendments were added and incorporated, the seedbed was prepared, and seeds (DEKALB® Corn Hybrids (glyphosate tolerant) were planted with a row spacing of 76 cm. Within each block, approximately 4 rows of silage corn were planted at a density of 50,000 plants per hectare using a John Deere planter. Throughout the growing season, an overhead sprinkler irrigation system was used to apply water on a weekly basis as required and as available. To control weed growth, glyphosate herbicide (Killzall 41% glyphosate) was applied at a rate of 1.12 kg ha^{-1}. This application was done once via broadcast before the corn reached a height of 30 inches.

2.3 Plant and soil analysis

To analyze STN, topsoil samples were manually collected every year from 2012–2021 in August from the 0–15 cm layer (four cores per plot) using slide hammer soil probe. The soil samples were sieved through a 2 mm mesh, air-dried, and then a subsample was finely ground to pass through a 0.25 mm sieve (60-mesh) for TN analysis using dry combustion with a PrimacsSN (Skalar, Inc. GA, USA). Soil macro and micronutrients were analyzed using the ammonium bicarbonate -DTPA method (Soltanpour, 1985) followed by inductively coupled plasma spectrophotometric analysis (USU Analytical Laboratory, Logan UT USA).

For leaf tissue N analysis, samples of the corn ear leaf were collected approximately 80 days after planting each year. Four corn leaves from each row, located in the middles of the plots, were harvested. In total, eight leaves were sampled per plot. Leaves were dried at 60°C to constant weight, followed by grinding using a Wiley Mill. Subsequently, the subsample was further ground to achieve a particle size equivalent to 0.25 mm (60 mesh).

Once the silage reached maturity in late September, aboveground plant material from the inner two rows of each plot, covering a distance of 3 meters, was harvested using machetes. Plant counts and fresh wet weight were recorded for each row per plot. The harvested corn was subsequently dried at 60°C for approximately one week, and its dry weight was determined. The dried stalks were then coarsely chopped, and a subsample was finely ground using a cutting mill (Wiley Mill). The subsamples were then finely ground with a rolling ball mill to 0.25 mm sieve before total N analysis by combustion (PrimacsSN Skalar, Inc., GA, USA).

2.4 Nitrogen use efficiency

Uptake efficiency (UE), agronomic efficiency (AE), partial factor productivity (PFP), partial nutrient balance (PNB) are important metrics for interpreting NUE. The equations for NUE are adapted from previous studies (Sindelar et al., 2015; Augarten et al., 2019). The metrics and their equations are shown Table 1.

TABLE 1 Nitrogen use efficiency metrics.

Trait	Description	Equation	Unit
UE	Uptake efficiency	$(NUptake - NUptake_0)/FN*100$	%
AE	Agronomic efficiency	(YN-Y0)/FN	
PFP	Partial factor productivity	Y/FN	
PNB	Partial nutrient balance	NUptake/FN	

NUptake = the total N uptake in aboveground biomass in N fertilizer treatment; $NUptake_0$ = the total N uptake in aboveground biomass in plot that received no N fertilizer; YN = the yield of corn silage from the treatments which received N fertilizer; Y0 = yield of control treatment which received no N fertilizer; Y = yield of crop; FN is amount of fertilizer N applied.

2.5 Data analysis

The parameters in this study included 80-day leaf nitrogen content, dry matter yield, N uptake at harvest, NUE indicators (including uptake efficiency (UE), agronomic efficiency (AE), partial factor productivity (PFP), and partial nutrient balance (PNB), and STN content collected annually from the years 2012 to 2021. There was no data collected during 2017 due to the planting and management of a cover crop of hairy vetch.

For each year within the study duration, we performed an analysis of variance (ANOVA) to assess the impact of different fertilizer sources on the above-mentioned parameters. The PROC MIXED procedure available in SAS® OnDemand was utilized. Our examination focused on the significant differences among the treatment groups at each year. Mean differences were considered significant at $p \leq 0.05$.

To gain a comprehensive understanding of the overall treatment effects across the study years, we employed repeated measures analysis of variance (ANOVA) using the PROC MIXED procedure. In this analysis, year was considered a fixed and repeated effect. Blocks and interactions with treatment were considered as random effects. Several covariance structures were evaluated, and the compound symmetry (CS) covariance structure was used. The mean separations were conducted at $p \leq 0.05$ using Tukey's test. To ensure the validity of our statistical tests, we assessed the normality of residuals using the UNIVARIATE procedure in SAS. Additionally, we generated scatterplots of residuals against predicted values to ascertain the presence of common variance. These steps were undertaken to verify the assumptions or to indicate that transformations were needed. This approach enables the detection of treatment differences in datasets collected over multiple years in agronomic field trials (Pagliari et al., 2022).

3 Results

3.1 Silage yield and nitrogen uptake

Contrasting N sources showed inconsistent effects on corn silage yield from 2012 to 2021 (Figure 1). In 2012, Compost displayed the lowest yield, whereas yield for AS200 and AS100 were not significantly different. In 2013, 2014, 2018, and 2021, the yield of Compost treatment was higher than Control. From 2012 to 2021, yields for AS200 were not different from AS100, except for the year 2020. In some years, the yield in the AS100 and AS200 treatments was comparable to Compost treatment (2013, 2016, and 2018), while in other years, AS100 and 200 treatments yielded more than Compost (2012, 2014, and 2020) (Figure 1). Similarly, the pattern of plant uptake of N at harvest was variable year to year (Figure 2). The N uptake for Compost treatment was significantly

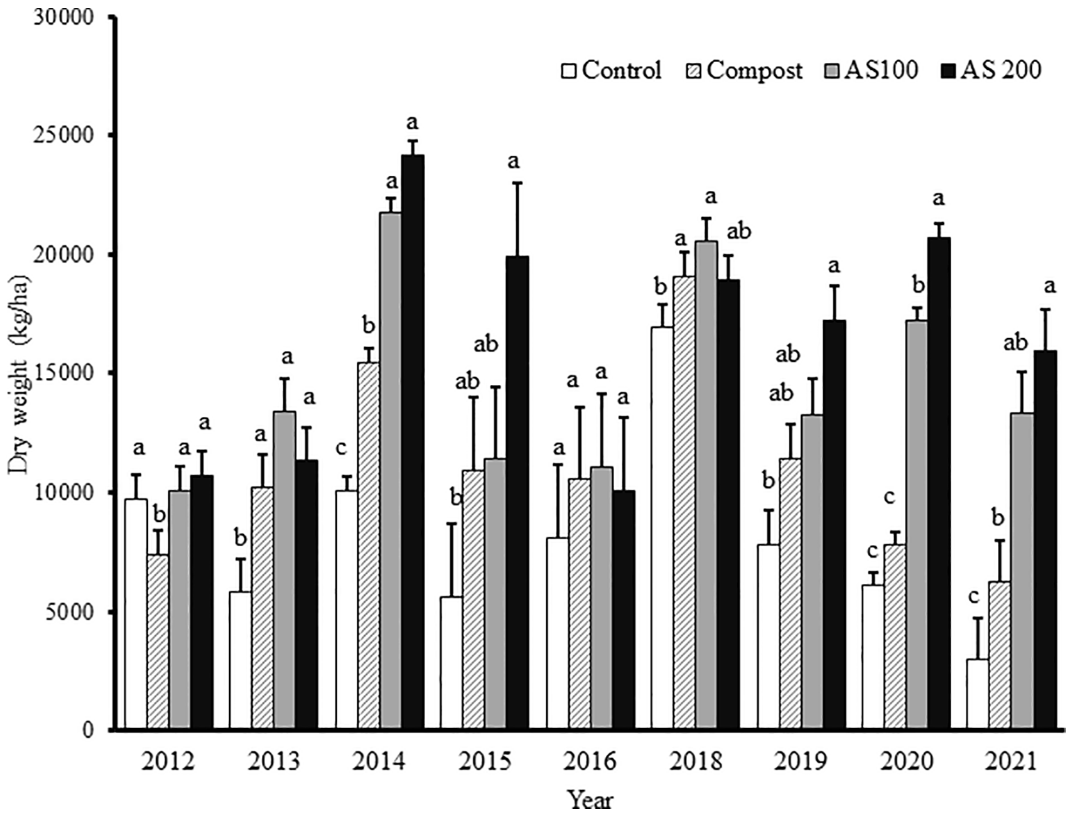

FIGURE 1
Dry matter yield of corn silage at harvest for years 2012-2021. Error bars represent standard errors (n = 4). Different lowercases above the bars indicate a significant difference within each year ($p \leq 0.05$).

higher than Control only in the year 2014 (Figure 2). Nitrogen uptake under Compost tended to be lower than AS treatments; however, this was only significant in 2013 and 2020.

The inconsistent year-to-year response in yield and plant N at harvest complicated the determination of treatment effects in the individual years. However, the impact of N source treatments on yields was significant based estimates from repeated measures analysis for the complete record of 2012-2021. The response of corn silage yield to N source was: AS200 and AS100 yielded the highest, followed by Compost, and then Control (Figure 3). The estimated yields from repeated measure for control, compost, AS100, and AS200 were 7.9, 11.1, 14.9, and 17.2 Mg ha^{-1}, respectively (Figure 3). While Compost significantly increased yield by 3.21 Mg ha^{-1} (40.5%) compared to Control, this treatment still yielded 3.74 Mg ha^{-1} (25.5%) and 6.12 Mg ha^{-1} (35.51%) less than the AS100 and AS200 treatments, respectively.

The results obtained from repeated measures analysis (log -transformed) revealed that the average estimates of N uptake by corn silage were 42.0, 70.5, 105.3, and 163.1 kg N ha^{-1} for the Control, Compost, AS100, and AS200 treatments, respectively (Figure 3). Compared to Control, N uptake under Compost, AS100, and AS200 were 68%, 105% and 288% increased over control uptake, respectively.

3.2 Corn leaf N content

From 2012 to 2021, corn ear leaves at 80 days showed N concentrations of 1.37% in the control, 1.53% with compost, 1.81% with AS100, and 2.36% with AS200 (Supplementary Figure S1). AS200 had the highest N concentration, followed by AS100, while the control and compost treatments had similar N levels (Supplementary Figure S1). The observed N concentrations in the corn ear leaves of this study were found to be below the sufficiency range when compared to the recommendations from the (University of Wisconsin, 2016).

3.3 Nitrogen use efficiency indicators

3.3.1 Uptake efficiency

The response of UE to different treatments varied from year to year. For instance, in 2012, the UE under the compost treatment was negative because the dry matter yield was lower than that of the control treatment (Supplementary Table S2, Figure 1). In 2013, the UE under the compost and AS200 treatments were significantly lower than AS100. In 2014, 2016, 2019, and 2020, the UE under the compost treatment was significantly lower than UE under the

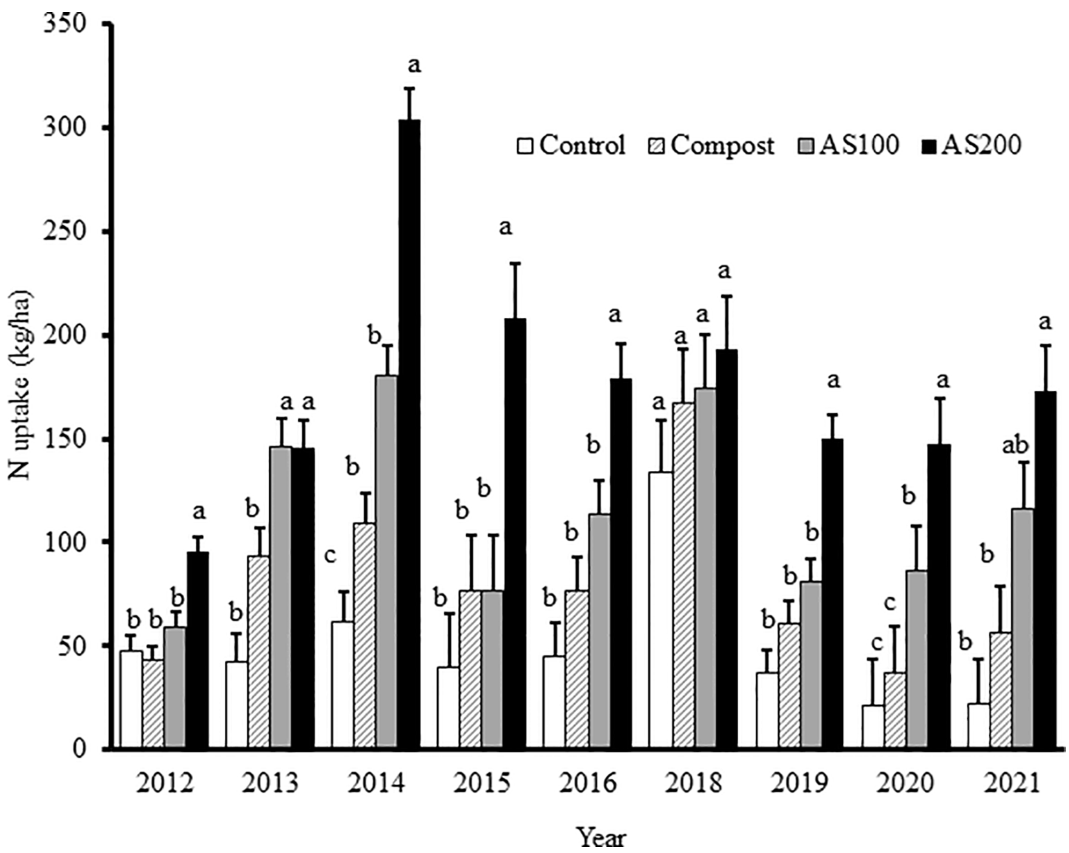

FIGURE 2
Nitrogen uptake of silage corn in aboveground biomass at harvest from 2012 to 2021. Error bars represent standard errors (n = 4). Different lowercases above the bars indicate a significant difference within each year (p ≤0.05).

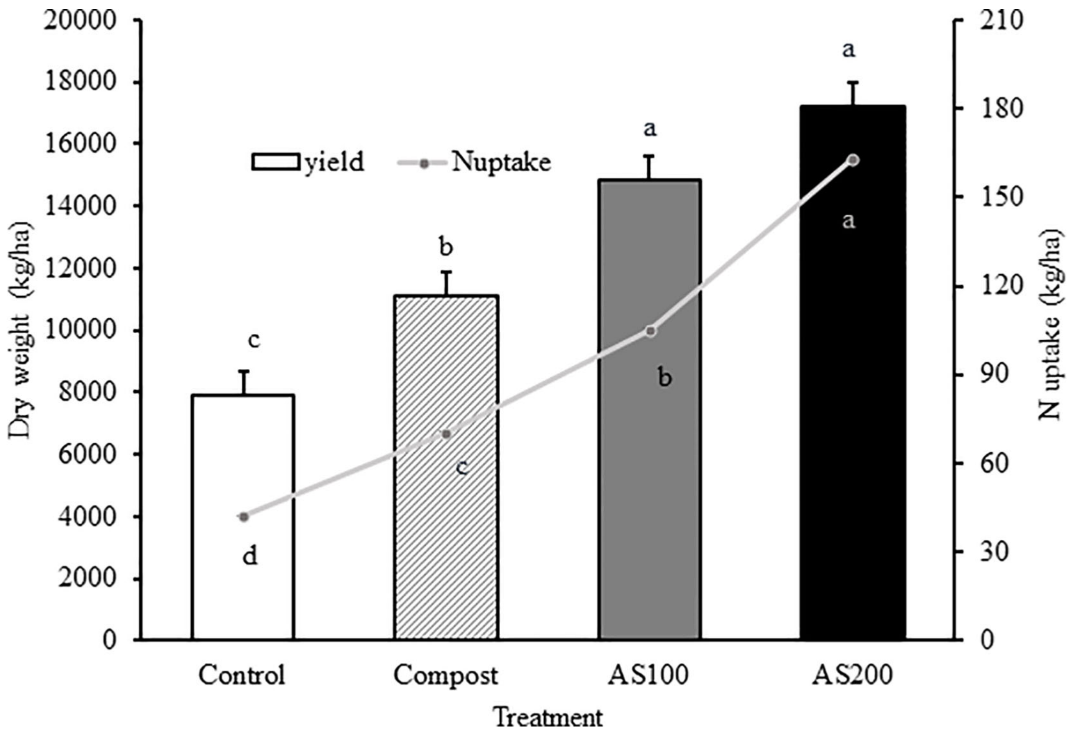

FIGURE 3
Effects of contrasting nitrogen sources on yield and N uptake in silage corn. Repeated measures were employed to analysis the impacts of effects of contrasting N sources on yield and N uptake in silage corn calculated from 2012-2021. Error bars represent standard errors (n = 36). Different lowercases above the bars indicate a significant difference by treatment ($p \leq 0.05$).

AS100 and AS200 treatments. However, in 2018, differences in UE among the treatments could not be detected (Supplementary Table S2).

The result from repeated measure estimated from 2012 to 2019 showed that estimate of value of UE from compost, AS100, and AS200 treatments were 13.4%, 57.8%, and 56.7%, respectively (Figure 4A). From this result, it indicated that AS100 and AS200 treatment performed better than compost in terms of UE response. However, the values of UE under the AS200 and AS100 treatments were not significantly different (Figure 4A).

3.3.2 Agronomic efficiency

In 2013, the AE value under compost and AS200 treatments did not show a significant difference and was significantly lower than that observed under the AS100 treatment. However, in both 2014 and 2020, the AE showed a clear and significant response to N fertilizer, with the AS100 treatment producing the highest value, followed by the AS200 treatment and then the compost treatment. In 2021, the value of AE under AS100 and AS200 treatments were comparable and AS100 was significantly higher than that observed in the compost treatment (refer to Supplementary Table S2). From 2015 to 2019, the N fertilizer treatment did not have a significant impact on AE. These variations and inconsistencies in the AE response to N treatment suggest that seasonal conditions influence corn silage AE (Hlisnikovský et al., 2020). Results from repeated measures for 2012-2021 show that the estimated mean of AE for AS100, AS200, and compost were 62.1, 41.7 and 14.4, respectively (Figure 4B). AS100 had the highest value of AE, followed by AS200 and compost had the lowest value.

3.3.3 Partial factor productivity

In this study, the numerical value of PFP was highest for the AS100 treatment (Supplementary Table S2). However, at a significance level of $p \leq 0.05$, the PFP values showed inconsistency across growing seasons. Specifically, the PFP value of AS100 was the highest in all growing seasons except for 2015 and 2019, when the PFP values for AS100 and AS200 were not significantly different. The PFP values for compost and AS200 were comparable from 2012 to 2019, except in 2014. In 2014, 2020 and 2021, the PFP values for AS100 were the highest, followed by AS200 and compost.

Repeated measures analysis demonstrated that the PFP values for AS100, AS200, and compost were 132.56, 76.9, and 49.6, respectively (Figure 4C). According to corn silage benchmark efficiency ranges from the study of Augarten et al. (2019), the PFP value of AS100 was the highest and within the range of high efficiency (PFP > 108), while the PFP values under AS200 and compost were in the low efficiency range (PFP < 81).

3.3.4 Partial nutrient balance

PNB value is interpreted based on whether the value is greater than or less than 1.0 (Augarten et al., 2019; Fixen et al., 2015).

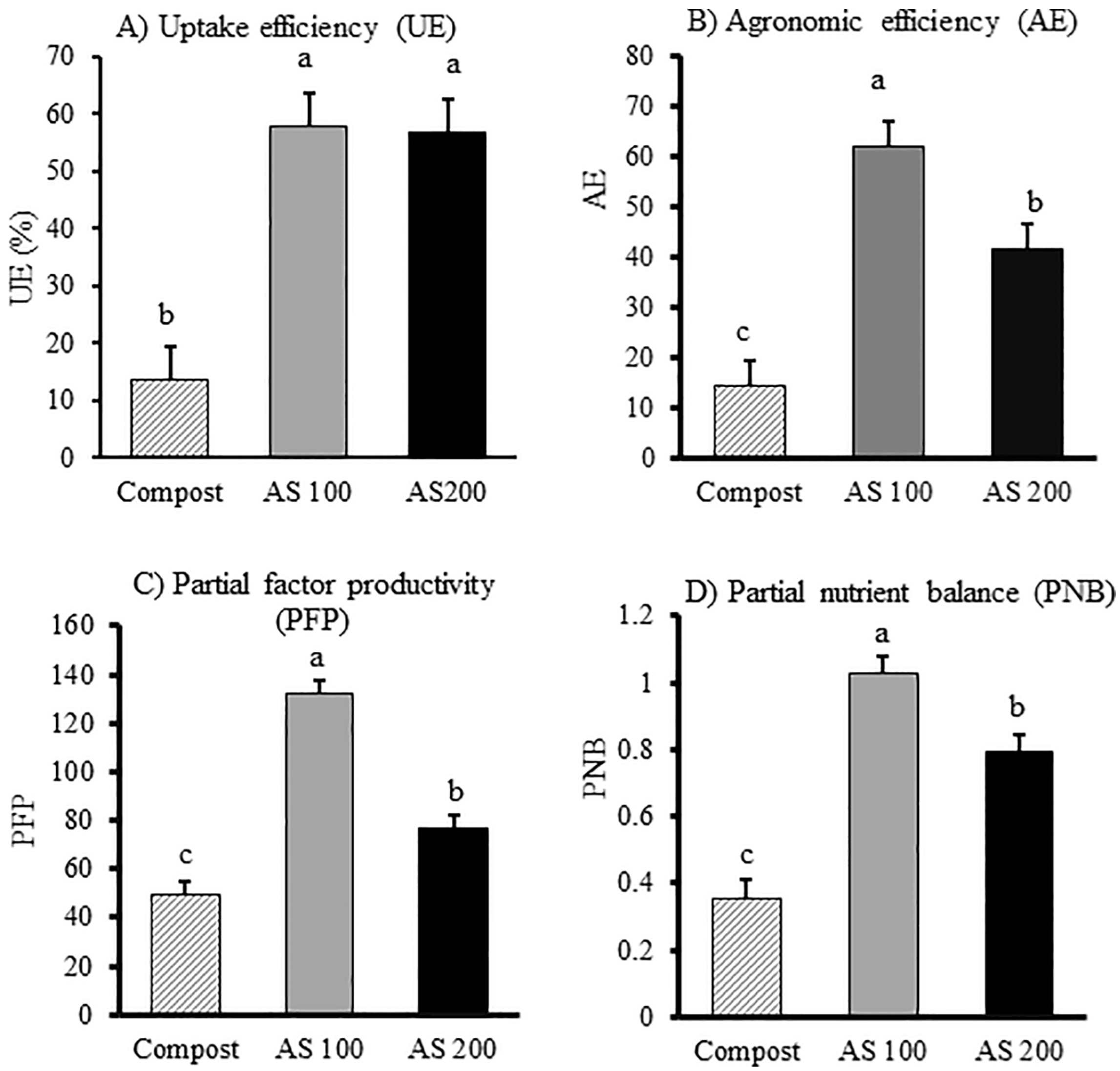

FIGURE 4
Effect of contrasting N sources on nitrogen use efficiency (NUE) indicators of corn silage. Repeated measures were employed to analysis the effects of contrasting N sources on NUE indicators: **(A)** Uptake efficiency (UE), **(B)** Agronomic efficiency (AE), **(C)** Partial factor productivity (PFP), and **(D)** Partial nutrient balance (PNB). The NUE data were collected from 2012-2021. Error bars represent standard errors (n = 36). Different lowercases above the bars indicate a significant difference ($p \leq 0.05$).

AS100 produced high PNB values in 2013 and 2018 (Supplementary Table S1). However, over the years, PNB under AS100 were insignificantly different from AS200 in 2012, 2014–2016 and 2019-2021. Compost treatment had the lowest PNB values, except for 2015 and 2016, which were not significantly different from those of AS100 and AS200 (Supplementary Table S2).

Figure 4D displays the PNB values obtained from repeated measures analysis, which indicates that AS100, AS200, and compost treatments resulted in PNB values of 1.03, 0.79, and 0.36, respectively. As per the classification proposed by Augarten et al. (2019), AS100, AS200, and Compost treatments exhibited mid, low, and very low partial nutrient balance, respectively.

3.4 Soil total nitrogen

The results from this study showed that the STN response to fertilizer treatments varied by year (Supplementary Figure S2). Compost treatment had the highest STN content in 2013, 2014, and 2021. Control treatment exhibited the lowest STN content in 2013 and 2014, and AS100 had the lowest STN in 2021. In the remaining years, N fertilization treatments did not significantly affect STN, although the STN levels under compost treatment were numerically higher than the others. Based on the repeated measures analysis from 2011-2021, the STN content of 1.28 g kg^{-1} was highest under Compost, which was significantly greater than Control (1.05g kg^{-1}), AS100 (1.01 g kg^{-1}), and AS200 (1.06 g kg^{-1})

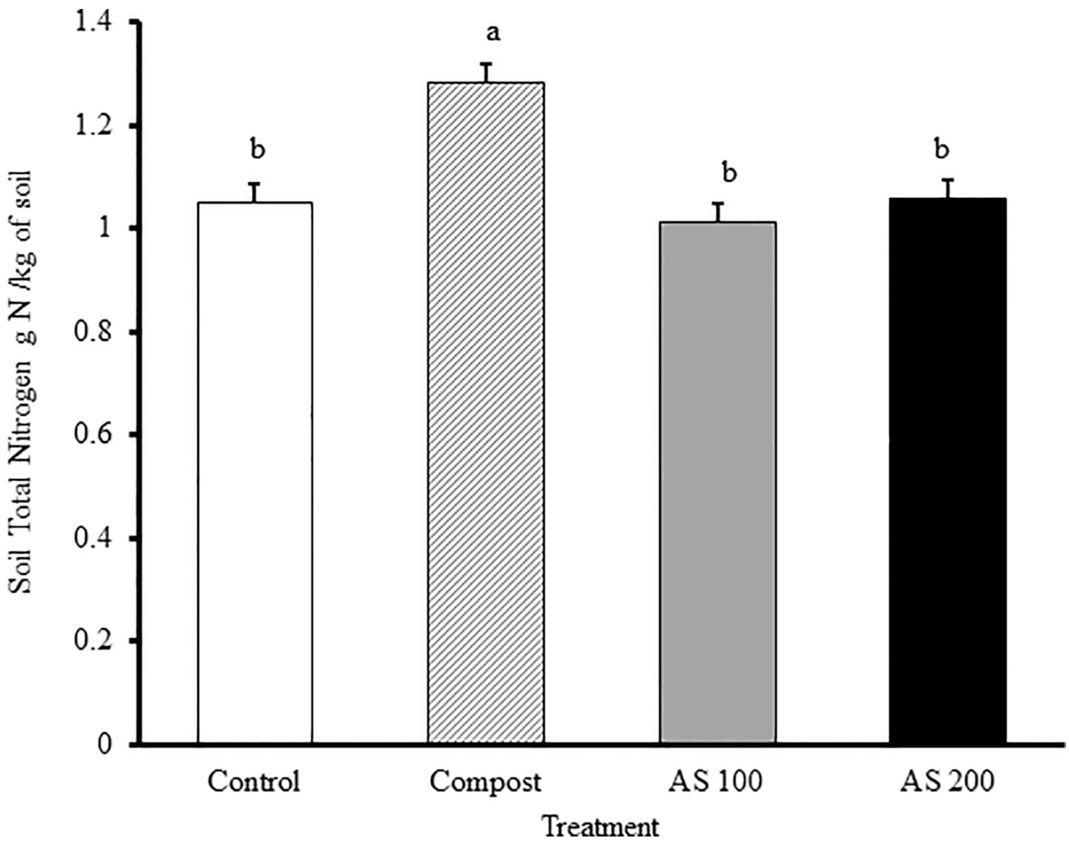

FIGURE 5
Effect of contrasting nitrogen sources on soil total nitrogen (STN). Soil samples were collected in August at a depth of 0–15 cm from 2011 to 2021. Error bars represent standard errors (n = 40). Different lowercase letters above the bars indicate a significant difference among treatments ($p \leq 0.05$) by repeated measures analysis.

treatments (Figure 5). Overall, the STN under Control was not significantly different from that under AS100 and AS200 treatments. The compost treatment resulted in significant increases in STN levels compared to the Control, AS100, and AS200 treatments, with percentage increases of approximately 21.90%, 26.73%, and 20.75%, respectively. Specifically, compost treatment elevated STN levels by about 0.24 g kg^{-1} (23.1%) compared to the other treatments, demonstrating its effectiveness in enhancing levels (Figure 5).

3.5 Micronutrients in the soil

Micronutrients such as Cu, Fe, Mn, Ni, and Zn were in the high range, while S was in the medium range and P was in the very high range. Fertilizer treatments did not significantly impact soil nutrients except for P. The P concentrations in control, compost, AS100, and AS200 were 13.1, 19.3, 9.38, and 8.5 mg/kg, respectively. P in compost was significantly increased (Supplementary Table S3). This finding agreed with previous studies (Eghball and Power, 1999; Reeve et al., 2012).

4 Discussion

4.1 Contrasting N sources effects on yield and nitrogen uptake of corn silage

In this study, there was a considerable yield variation ranging from 2-20, 5-24, 8-24, and 8–29 Mg ha^{-1} for the control, compost, AS100, and AS200 treatments, respectively from 2012 to 2021 (Figure 1) demonstrating that yields of corn silage was influenced by the growing season (Biswas and Ma, 2016). In 2012, the compost treatment had the lowest yield possibly attributed to N immobilization, where soil microbes compete with the growing crop for available nitrogen, potentially limiting crop growth and yield (Geisseler et al., 2021).

Overall results showed that the yield of corn silage was improved by application of compost and ammonium sulfate fertilizer (Figure 3). However, there was no significant difference in corn yield between the AS100 treatment, which received 112 kg of N ha^{-1}, and the AS200 treatment, which received 224 kg of N ha^{-1} (Figure 3). For sustainable maize production on volcanic soil in Bea Cameroon, an N fertilization rate between 50 and 100 kg of N ha^{-1} is considered optimal (Ngosong et al., 2019). However, in the midwestern United States, optimizing N rates for maximum ecosystem value requires an N rate of about 156 kg of N ha^{-1} (Ewing and Runck, 2015). Meanwhile, there are several studies have suggested that applying fertilizer rates ranging from 0 to 101 kg of N ha^{-1} can increase corn yield, but this increase levels off at 101 kg of N ha^{-1} (McSwiney and Robertson, 2005; Hejazi and Soleymani, 2014; Biswas and Ma, 2016).

In this study, we found that N uptake increased with higher rates of fertilizer which agreed with previous studies (Amado et al., 2013; Biswas and Ma, 2016; Davies et al., 2020). However, our study also supports the claim that higher N uptake does not necessarily lead to increased biomass production (Anas et al., 2020).

4.2 Contrasting N sources effects on nitrogen use efficiency indicators

In our study, AS100 and AS200 treatments were considered to have high UE, while Compost was below the typical range according to the NUE benchmarking for corn silage (Augarten et al., 2019). For AE, AS100 had the highest value, followed by AS200, with Compost having the lowest value. This indicates that nitrogen applied under the AS100 treatment improved productivity more per unit than the other treatments (Augarten et al., 2019). According to the same study, we also found that PFP under AS100 was in the high-use efficiency range, while Compost and AS200 were in the low-use efficiency range (Augarten et al., 2019). The results from this study illustrate that the AS100 treatment outperformed the AS200 treatment in terms of NUE. This finding supports previous studies indicating that higher application rates of AS fertilizer led to a decrease in AE and PFP (Amado et al., 2013; Chen et al., 2018; Boulelouah et al., 2022). The lower AE and PFP under compost treatment likely reflects the limited availability of nitrogen in this organic material and the slow release of nitrogen from compost fertilizer.

The AS100 treatment showed the highest PNB value, slightly exceeding 1. This increase in PNB above 1, as observed in Augarten et al.'s research (2019), indicates potential soil organic matter mining, where more N is removed in the crop than applied. However, it is noteworthy that the PNB value for AS100 remains within the acceptable range of high low-to-mid use efficiency ($0.92 < PNB < 1.08$). In contrast, the PNB value for AS200 treatment (PNB=0.79) falls within the range of low use efficiency, indicating that more N is being applied than removed by the crop (Augarten et al., 2019). A PNB value less than 1 signifies N surplus and can lead to potential nitrogen losses such as volatilization and leaching (Fageria and Baligar, 2005; Andrews et al., 2018). Therefore, reductions in application N may be necessary. Compost treatment had an extremely low PNB value (PNB=0.38) indicating that a considerable amount of N was being retained in the soil but unavailable for plant uptake due to slow N mineralization or even immobilization (Fageria and Baligar, 2005; Andrews et al., 2018).

4.3 Yield and nitrogen use efficiency under compost treatment

The yield under compost treatment demonstrated a significant increase relative to the control. This finding contrasts with that of Lin et al. (2022), who observed that the yield of corn under the compost treatment was not significantly different from control treatment. The duration of the experiment can affect the accuracy of the results, and in this regard, the study conducted by Lin et al. (2022) spanned only two growing seasons. In contrast, our study continued for nine years (2012-2021), providing more comprehensive data to evaluate the impact of different N source treatments on crop yield. The limited duration of that study experiment may have contributed to the absence of significant differences in yield between the organic fertilizer and control treatments reported in their study (Lin et al., 2022). It is well-known that the yield of corn can be influenced by the growing season (Biswas and Ma, 2016), and the response to nitrogen fertilizer treatments can also vary from year to year. These factors could explain why Lin et al. (2022) results differ from ours and highlights the importance of conducting long-term experiments to account for variability in crop growth and nutrient uptake over time.

This study also found that Compost yield remained lower than the average yield observed under AS100 and AS200 (Figure 3), aligning with previous studies (Chivenge et al., 2011; Seufert et al., 2012; Wei et al., 2016). An integrated analysis of long-term experiments conducted by Wei et al. (2016) indicated that despite the application of organic amendments over a decade, organic amendment still produced lower yield compared to chemical fertilizer. The effectiveness of organic amendments in increasing yield is contingent upon several factors, including the quality of organic resources, soil fertility status, farming system, management practices, and site characteristics (Chivenge et al., 2011; Seufert et al., 2012; Wei et al., 2016).

Available N is the major factor that affects crop yield (Berry et al., 2002). Numerous studies have substantiated those organic amendments, such as compost, animal manure, or cover crops, slowly release N that is available to plants, yet they do not provide an adequate N supply to meet the demands of crops during the peak of the growing season (Pang and Letey, 2000; Berry et al., 2002; Seufert et al., 2012). Therefore, while farming systems that exclusively relied on organic amendments have the potential to substantially increase yield, there must be substantial resources accessible. Otherwise, this system may fail to generate enough yield to satisfy food demand and may create nutrient imbalance (Pang and Letey, 2000; Berry et al., 2002; Seufert et al., 2012; Wei et al., 2016). N rate is not the only factor affecting corn yield. Other factors, such as rainfall, irrigation, soil texture and quality, farming management practices, planting date, and environmental conditions throughout the growing season, also significantly affect corn yield variability (Chivenge et al., 2011; Seufert et al., 2012; Wei et al., 2016; Hlisnikovský et al., 2020).

In the current study, Compost treatment did not result in an improvement in NUE compared to the ammonium sulfate treatment. This observation is consistent with the findings of Lin et al. (2022), who reported lower NUE of corn under organic fertilizers compared to chemical fertilizers. Despite using the same quantity of total N in the compost and AS200 treatments, not all of the total N in the compost was readily available for plant uptake, which explains the lack of improvement in NUE and lower yield. Compost is considered a slow-release fertilizer that gradually releases plant-available nutrients over time. Sullivan et al. (2018) reported that within the first year of application, plant-available N released from compost was less than 10% of its total N content (Sullivan et al., 2018). The timing of fertilizer N availability versus plant demand is an especially crucial determinant of maize yields and NUE (Zhu et al., 2025). Additional nutrients in compost may become available over years, although at a slower rate (Geisseler et al., 2021). However, insufficient N supply from compost can lead to a decrease in crop yield, N uptake, and NUE as we observed. The availability of N from the compost applied did not build significantly over the length of the experiment while preseason available P and K were higher in the compost treatment plots for most years (data not shown).

4.4 Contrasting N sources effects on soil total N

The results from this study showed that the STN response to fertilizer treatments varied by growing season. Although compost did not have a significant impact on STN in many years, it consistently produced numerically higher levels STN. The results from this study underscored the variable response of STN to fertilizer treatments, which is contingent upon the specific growing season under investigation and our ability to detect small absolute changes in STN. These fluctuations in STN levels, influenced by seasonal variations and their intricate interactions with the timing of soil amendments (Turner et al., 2015; Hurisso et al., 2018), posed challenges in discerning the impacts of fertilizers on STN. Future studies should take additional seasonal samples for multiple nitrogen pools and soil health indicators.

Repeated measurements in this experiment (2011-2021) revealed that compost treatment led to an approximately 23% increase in STN compared to other treatments. In contrast, ammonium sulfate treatments did not yield similar improvements, consistent with findings from other (Steiner et al., 2007; Gao et al., 2022). Earlier studies on the same plots investigating various aspects of the soil N cycle also showed that compost treatment enhanced the diversity of microbial communities and promoted N mineralization compared to AS fertilizer treatments (Ouyang, 2016; Ouyang and Norton, 2020).

Although the application of compost significantly increased soil N, the yield, N uptake, and NUE were lower compared to the use of ammonium sulfate fertilizer treatments. These observations suggest that composts with similarly low N availability need to be supplemented with additional available N to maintain yields. Based on the observed yields, the compost N supply was roughly equivalent to 40 kg N/ha (< 20% of total N available) and so yields would be responsive to an additional 60–80 kg N/ha in a readily available form. Preseason soil testing should be used to adjust macronutrient P and K fertilization after compost or manure applications. Similarly, research conducted by Gao et al., 2022, demonstrated that compost fertilizer enhanced STN levels while commercial fertilizer did not (Gao et al., 2022). Our findings are in line with Steiner et al. (2007), which found that organic fertilizers improve soil fertility but do not sustain crop productivity (Steiner et al., 2007). Numerous studies have shown that incorporating both organic and inorganic fertilizers increases yield, STN, and NUE (Li et al., 2012; Ding et al., 2018; Gao et al., 2022). Therefore, farmers may want to consider combining composts, manures and fertilizers for optimum silage corn production.

5 Conclusions

Long-term field experiments are crucial to assess fertilization effects on yield and NUE. AS100 achieved a yield comparable to AS200 and demonstrated higher NUE, challenging conventional belief that increased nitrogen application rate ensures maximum yield and profitability. Yield under compost treatment exhibited a notable 41% increase compared to control but was approximately 31% lower than the average yield under AS100 and AS200 treatments. Compost did not supply enough available N to meet crop demand, resulting in lower yield and NUE, but had the advantage of improving STN. Therefore, to maintain soil health, farmers may consider supplementing compost amendments with N fertilizers and practicing good soil health practices including crop rotation or cover crops for sustainable corn silage production.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material. Further inquiries can be directed to the corresponding author.

Author contributions

PM: Investigation, Writing – review & editing, Conceptualization, Methodology, Writing – original draft, Formal analysis, Data curation. AK: Investigation, Writing – review & editing, Writing – original draft. JN: Resources, Funding acquisition, Writing – original draft, Project administration, Formal analysis, Conceptualization, Writing – review & editing, Supervision, Data curation, Investigation, Methodology.

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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.

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Supplementary material

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