Revista Brasileira de Ciência do Solo

Division - Soil Use and Management | Commission - Lime and Fertilizer

Liming and enhanced-efficiency nitrogen fertilizers: Ammonia volatilization losses from subtropical no-till

Evandro Antonio Minato[(1)], Lucas Hiroshi Suguiura[(1)], Bruno Maia Abdo Rahmen Cassim[(2)], Marcos Renan Besen[(1)], Lúcia Tiemi Naves Yamashita[(1)], Tadeu Takeyoshi Inoue[(1)] and Marcelo Augusto Batista[(1)]*

[(1)] Universidade Estadual de Maringá, Departamento de Agronomia, Maringá, Paraná, Brasil.
[(2)] Universidade de São Paulo, Centro de Energia Nuclear na Agricultura, Piracicaba, São Paulo, Brasil.

ABSTRACT: In tropical and subtropical agricultural no-till (NT), lime and nitrogen (N) fertilizers are surface-applied. The pH increase from liming can enhance ammonia (NH_3) volatilization. This study aimed to quantify NH_3 losses from NT areas treated with different N fertilizers and lime rates and assess the effects on topsoil pH. Field experiments were conducted on clayey soil (*Latossolo Vermelho distroférrico típico*). The experimental design was a randomized complete block design with a 4 × 4 factorial split-plot arrangement and four replications. Main plots received four rates of dolomitic limestone (0, 2.6, 5.4, and 8.1 Mg ha^{-1}) and subplots received four N fertilizers. Nitrogen fertilizers were: conventional urea (46 % N), urea coated with copper (Cu) and boron (B) (Ur-Cu+B; 0.15 % Cu, 0.4 % B, and 44 % N), NBPT-treated urea (Ur-NBPT, 46 % N and 0.53 % NBPT), and ammonium sulfate (AMS, 21 % N and 22 % sulfur). Nitrogen fertilizers were applied during two second-crop corn growing seasons, at 24 and 36 months after liming. Soil pH in the 0.00-0.05 m layer was determined at the end of the experiment. The increase in soil pH due to liming enhanced NH_3-N volatilization losses, regardless of the N fertilizer used. Ammonia volatilization losses ranged from 16 to 32 % in urea plots, 12 to 31 % in Ur-Cu+B plots, 7 to 19 % in Ur-NBPT plots, and 0.2 to 5 % in AMS plots treated with lime rates of 0 to 8.1 Mg ha^{-1}, respectively. For every 1 Mg ha^{-1} of applied lime, NH_3-N volatilization increased by 1.7 to 2.2 % in Ur plots, 1.6 to 5.1 % in Ur-Cu+B plots, 1.3 to 1.5 % in Ur-NBPT plots, and 0.7 to 0.9 % in AMS plots. These results highlight the need to adjust N management after liming, with ammonium-based fertilizers (e.g., AMS) or stabilized urea sources (e.g., Ur-NBPT) being more effective mitigation strategies than urea or Ur-Cu+B in reducing NH_3 volatilization under surface-limed no-till conditions.

Keywords: lime, nitrogen pollution, micronutrients, soil acidity, urea.

***** Corresponding author:**
E-mail: mabatista@uem.br

Received: July 08, 2025
Approved: October 20, 2025

How to cite: Minato EA, Suguiura LH, Cassim BMAR, Besen MR, Yamashita LTN, Inoue TT, Batista MA. Liming and enhanced-efficiency nitrogen fertilizers: Ammonia volatilization losses from subtropical no-till. Rev Bras Cienc Solo. 2026;50:e0250130.
https://doi.org/10.36783/18069657rbcs20250130

Editors: José Miguel Reichert and Tales Tiecher.

INTRODUCTION

No-till (NT) covers approximately 180 million hectares globally (Kassam et al., 2019), making it a key component of conservation agriculture. No-till management practices promotes agroecological sustainability, contributing to increased yields, profitability, and food security, while preserving environmental and social resources (Pittelkow et al., 2015). Most soils managed under NT in humid tropical and subtropical regions have problems with soil acidity, which restricts root growth and reduces crop yield.

Ammonia (NH_3) volatilization is one of the main routes of nitrogen (N) loss from agricultural soils (Chen et al., 2021). This process is a significant contributor to environmental damage, negatively affecting water and soil quality and promoting the formation of acid rain (Good and Beatty, 2011). Furthermore, recent studies demonstrated that NH_3 volatilization increases the concentration of fine particulate matter ($PM_{2.5}$) in the air, having a direct impact on human health (Hill et al., 2019; Wyer et al., 2022). The rate of NH_3 volatilization is influenced by numerous factors, including soil temperature and moisture content (Viero et al., 2014), method of application (Woodley et al., 2020), fertilizer rate (Oliveira et al., 2024), N source (Cassim et al., 2022), soil texture and pH (Sunderlage and Cook, 2018), and the presence of crop residues on the soil surface (Dick, 1984). In NT, greater urease and microbial activity stimulated by crop residues on the soil surface accelerate urea hydrolysis, increasing the risk of N losses.

In NT, lime is applied on the soil surface without incorporation (Caires et al., 2008). The benefits of this method of application are well documented and include a gradual pH increase along the soil profile (Minato et al., 2023a), the maintenance of soil physical quality (Brignoli et al., 2024), enhanced soil biological activity, increased carbon stocks, and improved crop yields (Inagaki et al., 2016). However, when lime and nitrogen (N) fertilizers are applied to the same plots, the increase in soil pH caused by lime dissolution, combined with urea hydrolysis, can promote NH_3 volatilization (Minato et al., 2023b; Cassim et al., 2024a). Consequently, losses due to NH_3 volatilization may decrease N fertilization efficiency and crop yields.

Urea is the most used N fertilizer worldwide. When applied to the surface, urea is hydrolyzed by urease, resulting in the formation of ammonium ions (NH_4^+) and carbon dioxide (CO_2). As urea hydrolysis consumes protons (H^+), the reaction increases the pH of the granulosphere, shifting the equilibrium toward the formation of NH_3, which may be lost to the atmosphere (Rochette et al., 2009; Cantarella et al., 2018). Therefore, under conditions of increased soil pH, such as those found in topsoil following surface liming, N fertilizers, particularly urea-based fertilizers, may have reduced efficiency. Ultimately, this loss of efficiency translates into economic, environmental, and agronomic losses. Recently, Minato et al. (2023b) reported that N losses from urea applied to NT increased by 2.3 to 2.5 % for every 1 Mg ha^{-1} of lime applied.

Enhanced-efficiency fertilizers (EEFs) have emerged as a promising technology for reducing N volatilization losses. In a global meta-analysis, Pan et al. (2016) reported that EEFs reduced NH_3 volatilization by 54 %. This class of fertilizers includes slow-, controlled-, and stabilized-release formulations. Stabilized fertilizers can be further divided into those containing urease inhibitors and those containing nitrification inhibitors (Trenkel, 2010). Urea treated with *N*-(*n*-butyl)thiophosphoric triamide (NBPT) and urea coated with micronutrients such as boron (B) and copper (Cu) are prominent examples of stabilized N fertilizers (Mariano et al., 2019). The mechanism of action of these fertilizers involves the temporary inhibition of urease activity in soil, thereby decreasing the rate of urea hydrolysis (Cassim et al., 2024b).

An in-depth understanding of the relationship between soil chemical properties and N fertilizer dynamics enables the development of effective strategies to mitigate NH_3 emissions. In view of the intensification of production systems and the widespread use

of surface-applied lime in tropical and subtropical regions, it is crucial to investigate NH_3 volatilization losses after liming to increase N use efficiency (NUE) in NT. The hypothesis is that stabilized fertilizers are more effective than urea in reducing NH_3 volatilization loss from limed soils, particularly at higher lime application rates. This study aimed to quantify NH_3 volatilization losses from soils treated with different N fertilizers under increasing lime rates and to assess the associated changes in topsoil pH in a NT.

MATERIALS AND METHODS

Experimental design and environmental conditions

Field experiments were conducted in 2016 and 2017 at the Technology Diffusion Unit of the Cocamar Cooperativa Agroindustrial, Floresta, Paraná, Brazil (23°35' S and 52°04' W, 392 m a.s.l.). The climate of the area is of the Cfa type (humid subtropical) (Köppen, 2011), with average temperatures of 17 and 28 °C in the coldest and warmest quarters, respectively. Climate data for experimental periods are summarized in figure 1. The soil of the experimental field was classified as a *Latossolo Vermelho Distroférrico típico* with clay texture, according to the Brazilian Soil Classification System (SiBCS) (Santos et al., 2018), corresponding to a Rhodic Eutrustox (Soil Survey Staff, 2014). The field has been managed under NT for over 20 years. Analysis of soil properties in the 0.00–0.20 m layer prior to lime application in 2014 (baseline characterization of the experimental area), showed the following chemical (Pavan et al., 1992) and texture (Bouyoucos, 1962) properties: pH($CaCl_2$) 4.9, 17.7 g dm^{-3} carbon, and 770 g kg^{-1} clay.

The experimental design was a randomized complete block design with a 4 × 4 factorial split-plot arrangement and four replications. Main plots were assigned to four rates of dolomitic limestone (0, 2.6, 5.4, and 8.1 Mg ha^{-1}) applied to the soil surface in 2014. The limestone levels evaluated represent different recommendation scenarios based on the base saturation method (BS%), following the approach proposed by Minato et al. (2023a). The rate of 2.6 Mg ha^{-1} corresponds to the amount required to increase BS% to 70, while 5.4 Mg ha^{-1} corresponds to raising BS% to 90. Finally, 8.1 Mg ha^{-1} refers to the lime requirement for a (theoretical) BS% of 110. The dolomitic limestone used contained 207 g kg^{-1} calcium, 114 g kg^{-1} magnesium, and 90 % effective calcium

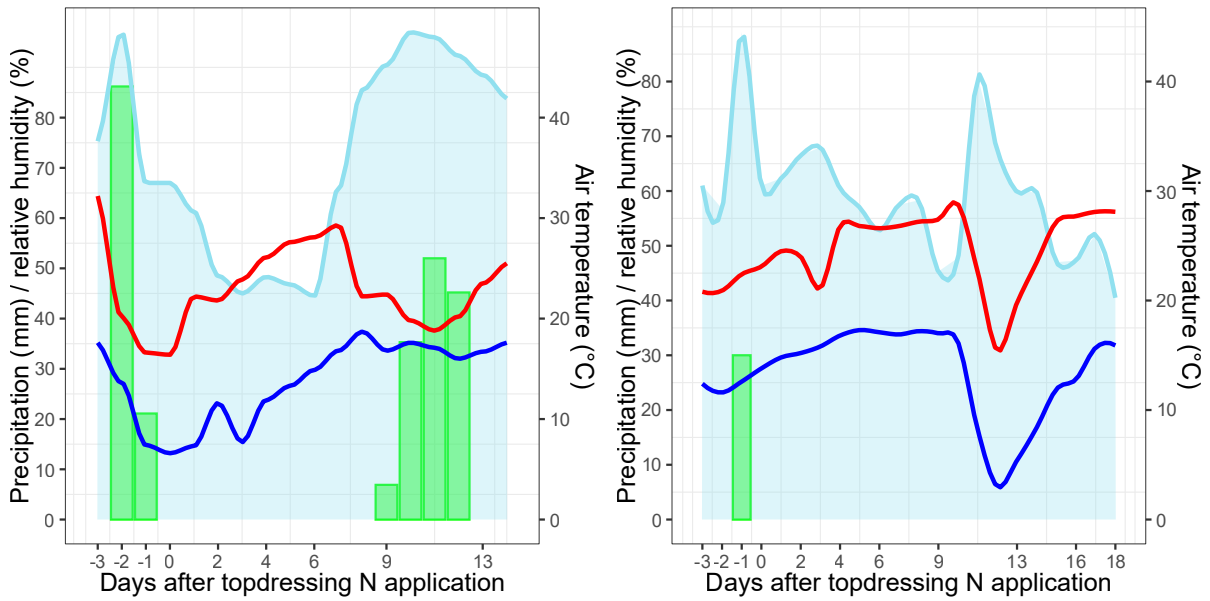

Figure 1. Rainfall, relative humidity, and maximum and minimum temperatures throughout the evaluation periods starting at 24 (left panel) and 36 (right panel) months after liming. The red lines represent the maximum air temperatures, while the blue lines represent the minimum air temperatures.

carbonate equivalent. Lime rates were calculated on a dry basis. After surface liming, plots were cultivated in a soybean–second-crop corn rotation. Subplots were assigned to four N fertilizers, applied at a rate of 100 kg ha^{-1}, and evaluated exclusively within the NH_3 volatilization chambers during two second-crop corn growing seasons. The first application occurred 24 months after liming, and the second, 36 months after liming. In the remaining main plot area (outside the chambers), corn also received 100 kg ha^{-1}, but solely as urea stabilized with NBPT (46 % N), applied at the V4 phenological stage. This procedure was adopted because the experiment was part of a long-term liming trial, and the application of EEFs to the entire main plot could have affected corn yield and soil chemical properties. The long-term results of this trial have been published by Minato et al. (2023a). At the subplot level, the N fertilizers were: conventional urea (46 % N), urea coated with copper and boron (Ur-Cu+B; 0.15 % Cu, 0.4 % B, and 44 % N), NBPT-treated urea (Ur-NBPT, 46 % N and 0.053 % NBPT), and ammonium sulfate (AMS, 21 % N and 22 % S). Nitrogen fertilizers were applied after 20 mm of rainfall.

Capture and determination of volatilized NH_3-N

The capture of volatilized NH_3-N was initiated shortly after N fertilizers were applied to the soil. For this, a semi-static open chamber was constructed using polyethylene terephthalate bottles (Araújo et al., 2009; Figure 2). Each chamber had an area of 0.007854 m^2. Chambers were placed at the center of each experimental unit and were rotated over three points after each sampling to minimize interference from environmental factors. Chambers contained a strip of filter paper (2.5 cm wide and 25 cm long) that captured the volatilized NH_3-N. The base of the strip was immersed in 20 mL of a solution containing 0.05 mol L^{-1} sulfuric acid (H_2SO_4) and 2 % (v/v) glycerin in a 50 cm^3 flask.

Samplings were carried out on days 3, 5, 7, 9, and 13 after N fertilizer application for evaluations performed at 24 months after liming and on days 2, 4, 6, 9, 13, 16, and 18 after N fertilizer application for evaluations performed at 36 months after liming. After each collection, the filter paper strips and the H_2SO_4 + glycerin solution were replaced, and this procedure was repeated until NH_3-N losses stabilized. For the extraction, the filter paper, along with the remaining H_2SO_4 and glycerin solution, was immersed in a container with 25 mL of distilled water. Subsequently, the N derived from volatilized NH_3 was indirectly quantified as NH_4^+ by UV/Vis spectrophotometry, according to the method described by Bower and Holm-Hansen (1980). This methodology is widely employed

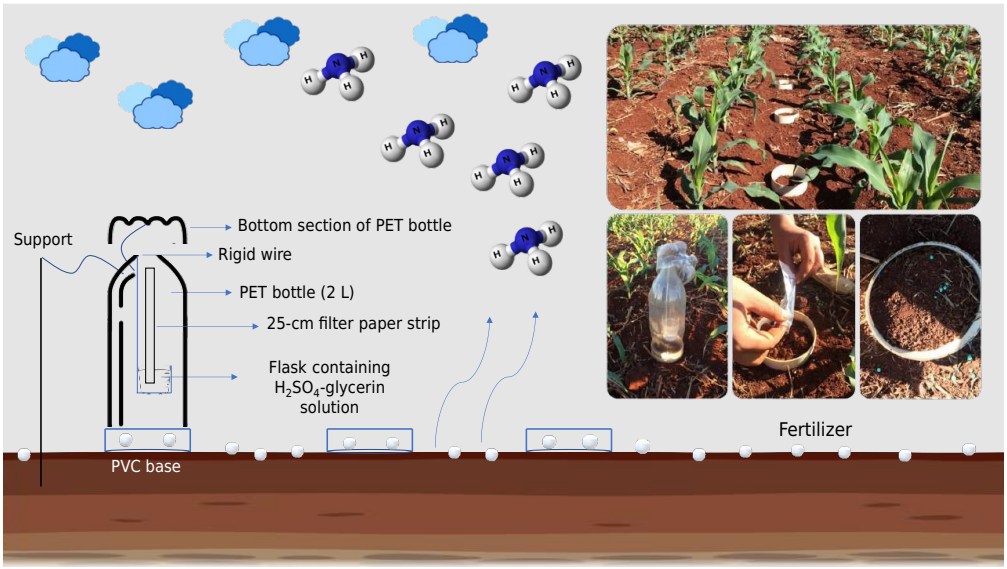

Figure 2. Schematic representation and representative images of the semi-static chamber used for capturing ammonia (NH_3) volatilized from nitrogen fertilizers.

in field experiments to estimate NH_3 volatilization, as reported by Minato et al. (2020, 2023b), Cassim et al. (2021, 2022), and Besen et al. (2022). Thirty-six months after liming, soil samples were collected from within each chamber at a depth of 0.00-0.05 m and subjected to pH analysis. Soil pH was determined in 0.01 mol L^{-1} $CaCl_2$ (soil/solution ratio of 1:2.5), as described by Pavan et al. (1992).

Calculation and statistical analysis

Data on NH_3-N volatilization at 24 and 36 months after surface liming were subjected to nonlinear regression analysis (Silva et al., 2017; Minato et al., 2020; Souza et al., 2023; Soares and Cantarella, 2023; Lisboa et al., 2024). The model with the lowest Akaike information criterion (AIC) was selected (Akaike, 1974). The logistic model (Equation 1) includes three parameters (α, β, and γ), as described by Seber and Wild (2003).

$$\hat{Y} = \frac{\alpha}{1+ \exp^{[-(t-\beta)/\gamma]}} \qquad \text{Eq. 1}$$

in which: $\hat{Y}$ represents the quantity of N volatilized in the form of NH_3-N (kg ha^{-1}) at time t (days); α represents the maximum cumulative volatilization; β represents the time at which the cumulative loss reaches 50 %, corresponding to the curve inflection point (day of the maximum daily loss of NH_3-N); and γ is a parameter used to calculate the maximum daily loss (MDL) of NH_3-N, as shown in equation 2.

$$\text{MDL} = \frac{\alpha}{4\gamma} \qquad \text{Eq. 2}$$

Data regarding total NH_3-N volatilization and soil pH were subjected to the Shapiro–Wilk normality test. The homogeneity of variances was assessed graphically. Given that the assumptions were met, the data were subjected to analysis of variance ($p<0.05$). Regardless of overall significance, the interactions between lime rates and N fertilizer sources were further analyzed to identify more specific responses. When significant, quantitative factors were evaluated using polynomial regression, while qualitative factors were compared using Tukey's test ($p<0.05$).

RESULTS

Effects of surface liming on NH_3-N volatilization losses

Cumulative NH_3-N volatilization followed a sigmoidal pattern. Losses increased gradually from the beginning of the experiment until the day the maximum daily loss was achieved, then stabilized (Figures 3 and 4). According to the adjusted logistic model, the maximum cumulative loss (α) varied according to N source, lime rate, and time after liming (Table 1). Regardless of the evaluation period and lime rate, treatments were found to promote the following descending order of cumulative NH_3-N loss: urea > Ur-Cu+B > Ur-NBPT > AMS. An exception was observed 36 months after the application of 5.4 Mg ha^{-1} lime: the cumulative loss promoted by urea did not differ significantly from that induced by Ur-Cu+B (Figures 3 and 4, and Table 1).

Estimation of β revealed that Ur-NBPT was efficient in delaying the maximum NH_3-N volatilization compared to urea. The peak was delayed by 1 and 4 days at 24 and 36 months after liming, respectively. The partitioning of the analysis of variance for total NH_3-N volatilization revealed significant effects of N fertilizers within each lime rate, as well as significant effects of lime rates within each N source, at 24 and 36 months after liming (Table 2). The increase in volatilization was linear for all N fertilizers, except for Ur-Cu+B at 36 months after liming. For every 1 Mg ha^{-1} increase in applied lime, total NH_3-N volatilization increased by 1.7 to 2.2 % in urea, 1.6 to 5.1 % in Ur-Cu+B, 1.5 to 1.3 % in Ur-NBPT, and 0.9 to 0.7 % in AMS at 24 and 36 months after liming, respectively (Figure 5).

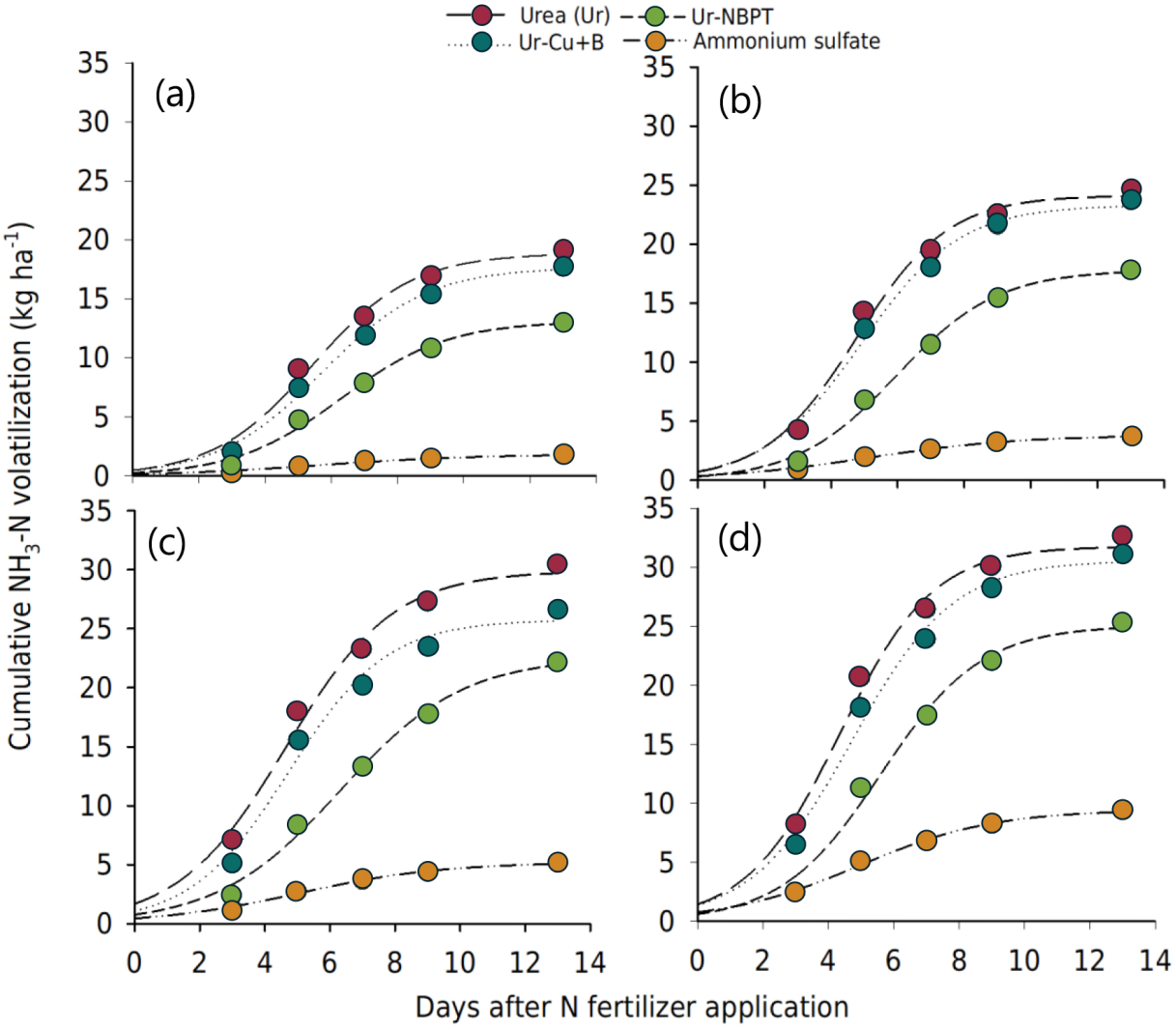

Figure 3. Cumulative ammonia (NH_3-N) volatilization loss from no-till under different nitrogen fertilization treatments (n = 4), as evaluated at 24 months after surface lime application at a rate of (a) 0.0, (b) 2.6, (c) 5.4, and (d) 8.1 Mg ha^{-1}. Fitted model parameters are shown in table 1.

At 24 months after application of the highest lime rate, the increase in NH_3-N loss compared to the unlimed control was 68, 72, 92, and 350 % in urea, Ur-Cu+B, Ur-NBPT, and AMS treatments, respectively (Table 1). Similarly, 36 months after application of the highest rate, the increase in NH_3-N loss was 100, 158, 171, and 2300 % in urea, Ur-Cu+B, Ur-NBPT, and AMS, respectively (Table 1).

Among the N fertilizers evaluated, AMS resulted in the lowest total NH_3-N volatilization means across all lime rates (Table 3). At 24 months after liming, Ur-NBPT significantly reduced volatilization compared to conventional urea only at the 5.4 and 8.1 Mg ha^{-1} lime rates. However, at 36 months after liming, Ur-NBPT was effective in reducing volatilization losses at all lime rates. Overall, Ur-Cu+B did not differ significantly from conventional urea.

Effect of surface liming and N fertilization on topsoil pH

The increase in lime rate led to a rise in soil pH in the 0.00–0.05 m layer (Figure 6), which varied according to N source. For all lime rates, plots fertilized with AMS exhibited the greatest reductions in soil pH.

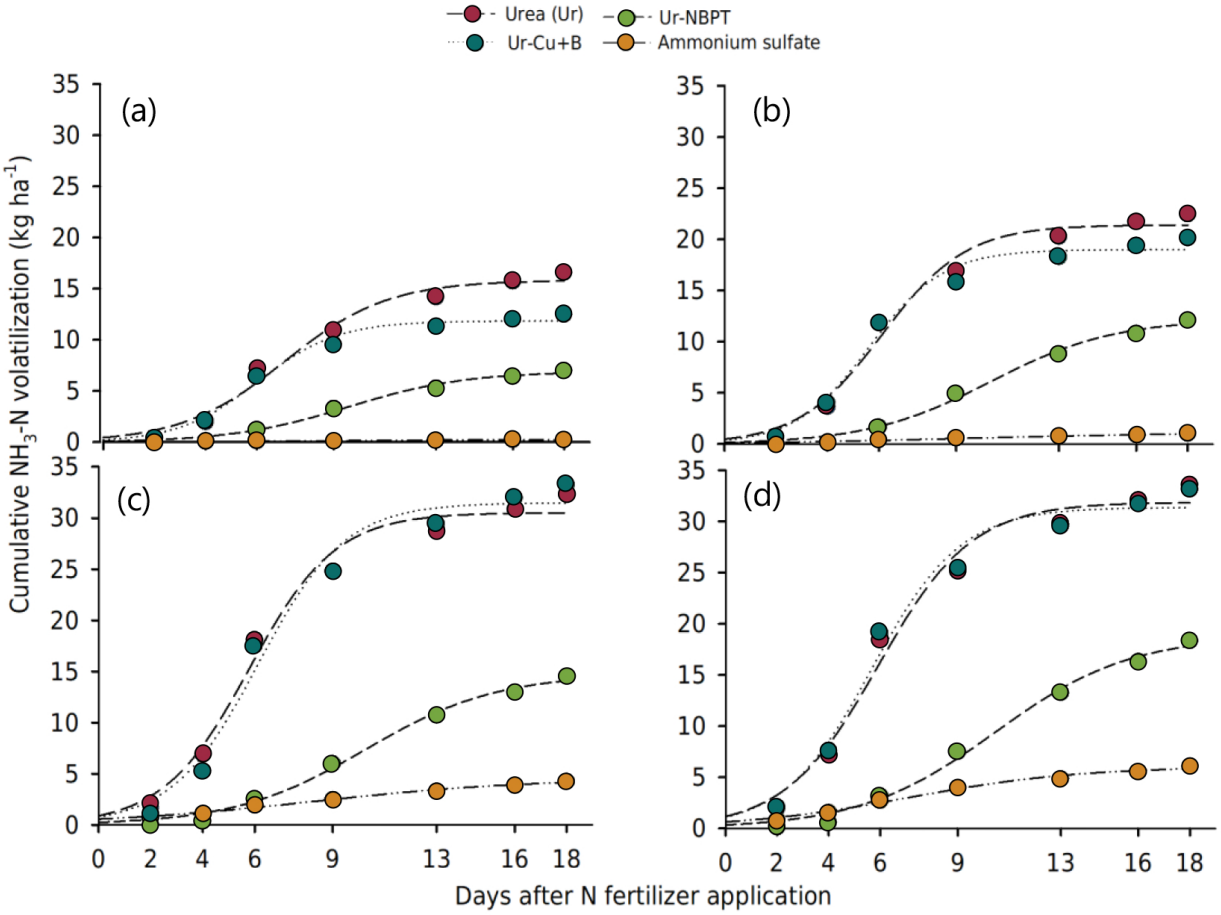

Figure 4. Cumulative ammonia (NH_3-N) volatilization loss from no-till under different nitrogen fertilization treatments (n = 4), as evaluated at 36 months after surface lime application at rates of (a) 0.0, (b) 2.6, (c) 5.4, and (d) 8.1 Mg ha^{-1}. Fitted model parameters are shown in table 1.

DISCUSSION

This study modeled the relationship of cumulative NH_3-N loss as a function of lime rate and time at two evaluation periods (24 and 36 months after liming). The findings demonstrated that alternative N sources may contribute to enhancing N fertilizer utilization by crops grown on tropical soils under NT. Overall, the lower values of maximum cumulative volatilization (parameter α) achieved by other N sources underscore the advancement of urea-based EEFs. In general, EEFs act by reducing N losses in the soil and extending its availability to plants. This is achieved through mechanisms that slow down the transformation, solubilization, or release of the nutrient (Cassim et al., 2024b). In tropical and subtropical regions, which usually have more acidic soils, the magnitude of loss reduction depends on the applied rate and adopted technology (Otto et al., 2017; Cassim et al., 2021). Another important factor is rainfall after application, which facilitates the timely solubilization of N fertilizer (Viero et al., 2014).

Among urea-based fertilizers, Ur-NBPT proved to be the most efficient in mitigating NH_3 volatilization. After application to soil, NBPT is transformed into its oxygen analog NBPTO, which forms a tridentate bond with urease active sites, blocking the enzyme and thereby reducing urease activity (Manunza et al., 1999). On the other hand, Ur-Cu+B had little effect in mitigating NH_3 volatilization losses. Micronutrients such as Cu and B can temporarily inhibit urease. Copper promotes noncompetitive inhibition by binding to urease sulfhydryl groups (Shaw, 1954; Cantarella et al., 2018). In the case of B, the molecular conformation of boric acid (H_3BO_3) resembles that of urea, allowing it to bind

to urease at the same enzyme sites (Benini et al., 2004). The similar efficiency of Ur-Cu+B to urea is likely due to the low concentrations of B and Cu in the coating layer, which are not sufficient to mitigate NH_3 volatilization. For example, in a study conducted by Cassim et al. (2024c), urea coated with B in the form of 0.8 % H_3BO_3 reduced volatilization losses by 25 % in relation to urea.

Table 1. Parameters of the logistic model estimating the cumulative loss, maximum daily loss, and percentage increase in cumulative ammonia (NH_3-N) loss for each combination of nitrogen (N) fertilizer and lime rate

N fertilizer	Lime rate	Estimated parameters			MDL	Increase in cumulative NH_3-N loss[1]
		α	γ	β		
	Mg ha^{-1}	kg ha^{-1} NH_3-N		day	kg ha^{-1} day^{-1} NH_3-N	%
24 months after surface lime application						
Urea (Ur)	0	19	0.67	5	7	-
Ur-Cu+B	0	18	0.63	6	7	-
Ur-NBPT	0	13	0.62	6	5	-
AMS	0	2	0.42	6	1	-
Ur	2.6	23	0.68	5	9	21
Ur-Cu+B	2.6	24	0.73	5	8	33
Ur-NBPT	2.6	18	0.66	6	7	38
AMS	2.6	4	0.44	5	2	100
Ur	5.4	30	0.60	5	12	58
Ur-Cu+B	5.4	26	0.67	5	10	44
Ur-NBPT	5.4	23	0.53	6	11	77
AMS	5.4	5	0.46	5	3	150
Ur	8.1	32	0.70	4	11	68
Ur-Cu+B	8.1	31	0.65	5	12	72
Ur-NBPT	8.1	25	0.65	6	10	92
AMS	8.1	9	0.49	5	5	350
36 months after surface lime application						
Ur	0	16	0.50	7	8	-
Ur-Cu+B	0	12	0.64	6	5	-
Ur-NBPT	0	7	0.44	10	4	-
AMS	0	0.25	0.33	8	0.2	-
Ur	2.6	21	0.61	6	9	31
Ur-Cu+B	2.6	19	0.70	6	7	58
Ur-NBPT	2.6	12	0.42	10	7	71
AMS	2.6	1	0.23	9	1	300
Ur	5.4	31	0.60	6	13	94
Ur-Cu+B	5.4	31	0.60	6	13	158
Ur-NBPT	5.4	15	0.40	10	9	114
AMS	5.4	5	0.24	8	5	1900
Ur	8.1	32	0.55	6	14	100
Ur-Cu+B	8.1	31	0.59	6	13	158
Ur-NBPT	8.1	19	0.38	10	12	171
AMS	8.1	6	0.30	7	5	2300

[1] Compared to the same unlimed N fertilizer within the same year. MDL; maximum daily loss (MDL = $\frac{\alpha}{4\gamma}$); AMS: ammonium sulfate; α: maximum cumulative volatilization; β: time at which 50 % of the losses occur, corresponding to the curve inflection point; γ: parameter of the equation used to calculate the MDL.

Table 2. *P*-values for the effects of factors on total NH_3–N volatilization at 24 and 36 months after liming

Sources of variation	24 months after liming	36 months after liming
Block	-	-
Liming (L)	<0.001	<0.001
Error (L)	-	-
N fertilizer (N)	<0.001	<0.001
N × L	0.525	<0.001
N/L_0	<0.001	<0.001
N/L_1	0.046	<0.001
N/L_2	<0.001	<0.001
N/L_3	<0.001	<0.001
L/N_1	<0.001	<0.001
L/N_2	<0.001	0.045
L/N_3	<0.001	<0.001
L/N_4	<0.001	<0.001
Error (N)	-	-

L_0: 0 Mg ha^{-1} of lime; L_1: 2.6 Mg ha^{-1} of lime; L_2: 5.4 Mg ha^{-1} of lime; L_3: 8.1 Mg ha^{-1} of lime; N_1: Ur-Cu+B; N_2: AMS; N_3: Ur-NBPT; N_4: Ur.

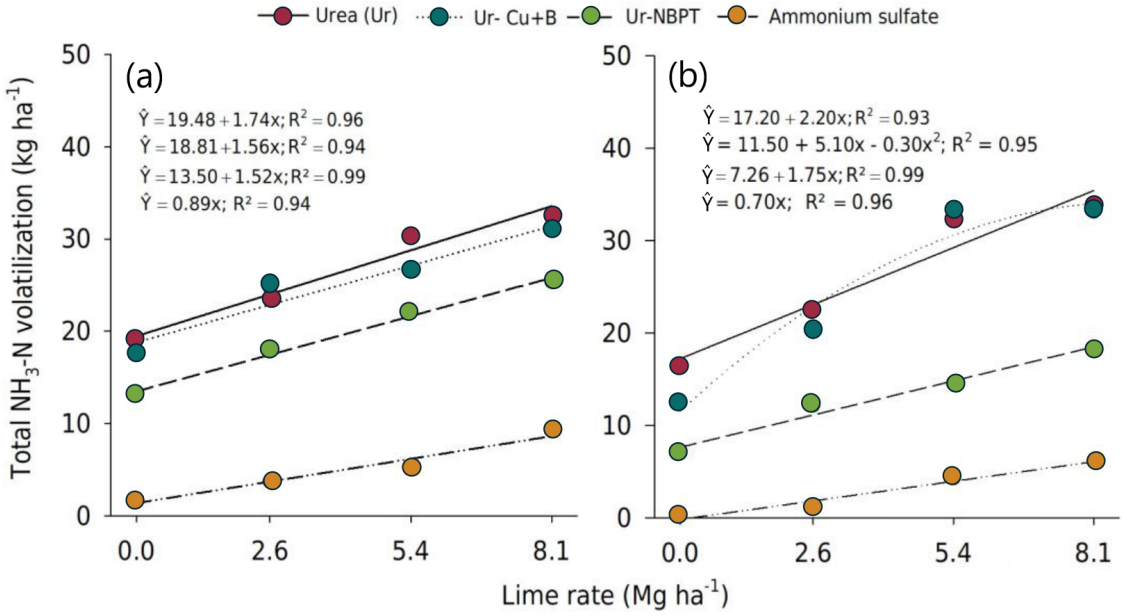

Figure 5. Total ammonia (NH_3-N) volatilization loss as a function of lime rate under different nitrogen fertilization treatments (n = 4) at (a) 24 and (b) 36 months after liming.

In a recent study, Ur-Cu+B was effective in minimizing NH_3 volatilization in a tilled Oxisol, reducing losses by 23 %; however, no effect was observed on soil subjected to surface liming (Besen et al., 2022). These findings corroborate those of the current study and agree with the review by Cantarella et al. (2018), who reported that NH_3 volatilization mitigation with H_3BO_3 and Cu is inconsistent. Some studies indicated a reduction in NH_3 volatilization (Cancellier et al., 2016; Dominghetti et al., 2016), whereas others did not observe significant effects (Faria et al., 2014; Ribeiro et al., 2020).

The lower β values at 24 months (compared to 36 months on average) after surface liming suggest that a residual effect of the pH increase may have contributed to the acceleration of volatilization. Studying the effect of lime rates on N losses from urea through NH_3-N volatilization, Minato et al. (2023b) also observed an earlier peak in the evaluation year closest to surface liming.

Over the months, however, the increase in pH resulting from surface liming becomes less prominent, owing to the dissolution and degradation of limestone (Minato et al., 2023a). Thus, at 36 months after surface application, the limestone's residual effect was possibly less pronounced. Furthermore, the climatic conditions at 36 months may have delayed volatilization, helping to explain the differences between evaluation periods. Under dry soil conditions, urease hydrolysis rates are reduced, leading to lower volatilization losses (Das et al., 2024).

Table 3. Means of total NH_3–N volatilization of N fertilizers within each liming rate at 24 and 36 months after liming

N fertilizer	Ammonia volatilization			
	0 Mg ha^{-1}	2.6 Mg ha^{-1}	5.4 Mg ha^{-1}	8.1 Mg ha^{-1}
	kg ha^{-1}			
	24 months after liming			
AMS	1.77 b	3.71 b	5.12 c	9.36 c
Ur-NBPT	13.06 a	17.84 a	22.15 b	25.36 b
Ur-Cu+B	17.68 a	23.67 a	26.66 ba	31.12 ba
Ur	19.13 a	24.74 a	30.45 a	32.57 a
	36 months after liming			
AMS	0.24 c	1.01 c	4.27 c	6.10 c
Ur-NBPT	7.03 b	12.13 b	14.54 b	18.35 b
Ur-Cu+B	12.46 ba	20.13 a	32.30 a	33.16 a
Ur	16.58 a	22.46 a	33.26 a	33.61 a

Different lowercase letters in the same column indicate differences among N fertilizer means according to Tukey's test ($p<0.05$).

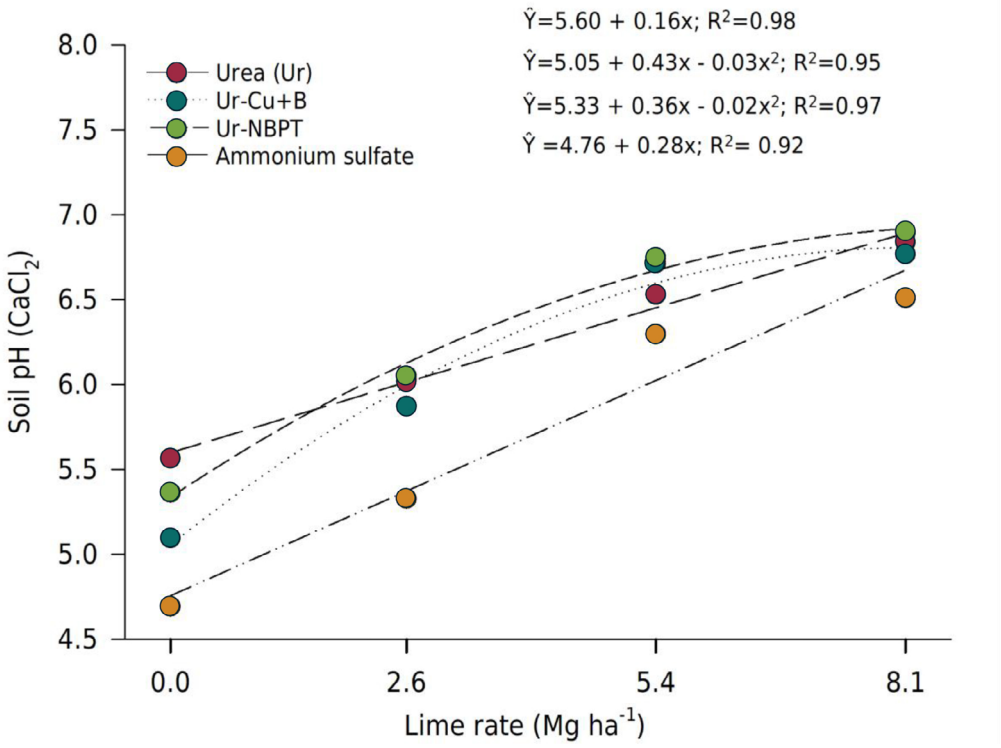

Figure 6. Soil pH in the 0.00-0.05 m layer as a function of lime rate under different nitrogen fertilization treatments (n = 4), 36 months after liming.

Liming enhances N losses via volatilization because it elevates the soil pH, as observed at 36 months after surface liming. Similarly, in an experiment conducted with soils from the state of Paraná, Cassim et al. (2024a) observed an increase in total NH_3 volatilization from EEFs when these sources were applied in combination with surface limestone and straw, simulating no-till conditions. Our finding is consistent with reports by Mandal et al. (2016) and Sha et al. (2019), who documented an increase in NH_3 volatilization losses with increasing soil pH. At higher soil pH, the rate of urea hydrolysis increases, leading to the formation of NH_3 and predisposing N to volatilization losses (Sengik et al., 2008). Furthermore, due to the increased pH, the equilibrium between NH_4^+ and NH_3 in the soil shifts toward NH_3. This phenomenon is especially important in low-CEC soils, whose properties favor N losses via volatilization. For example, these soils have lower NH_4^+ adsorption power and lower capacity to resist the pH changes (buffering capacity) induced by liming and urea hydrolysis (Sunderlage and Cook, 2018).

In the case of the clayey *Latossolo* (Rhodic Eutrustox) studied here, AMS had the lowest NH_3 losses after liming. In soils with pH below 7 and with AMS added, NH_4^+ remains in an ionic, stable form, whereas urea is enzymatically hydrolyzed to ammoniacal N, a process that increases pH in the granulosphere and, subsequently, leads to NH_3 volatilization (Cassim et al., 2024a). In both evaluation periods, total volatilization in AMS plots did not exceed 10 % of the applied N at any of the studied rates, in agreement with the findings of Powlson and Dawson (2022). The authors summarized data from 41 scientific publications and observed that, in soils with pH in water <7, most N losses were <5 %. In soils with pH in water >7, AMS application led to losses of 15–35 % of the applied N.

On the other hand, at the end of the experiment, it was observed that AMS resulted in the greatest reduction in topsoil pH at 36 months in plots without liming. This effect results from the nitrification process of ammoniacal N, in which, for each mole of NH_4^+ oxidized, two moles of H^+ are released (Cassim et al., 2024b). Furthermore, Fageria et al. (2010) suggest that during nitrate (NO_3^-) leaching, the removal of basic cations as accompanying ions may also contribute to acidification, since these cations are subsequently replaced by H^+ in the exchange complex. The less pronounced acidifying effect of urea-based sources is explained by their lower acidity index (Pauletti and Motta, 2019). Consistent with these results, Chien et al. (2008) reported that the liming requirements of soils fertilized with AMS may be 1.4 to 2.3 times those of soils receiving ammonium nitrate or urea to neutralize soil acidity.

The efficiency of N fertilizers in mitigating NH_3 volatilization losses may vary depending on the liming method used, particularly whether lime is surface-applied or incorporated into the soil (Besen et al., 2022). Given the well-known benefits of applying lime without mechanical incorporation in tropical and subtropical fields under NT, this liming method should be preferably maintained. Finally, even when applying lime at rates consistent with the regional recommendation for this study (2.6 Mg ha^{-1} to raise BS% to 70) (Pauletti and Motta, 2019), we still observed increases in cumulative NH_3-N losses. Overall, considering the linear increase in total NH_3-N volatilization with higher lime rates, our results suggest that surface applications above the recommended rate may enhance NH_3-N losses from the N sources evaluated. This was evident with the 8.1 Mg ha^{-1} rate. It resulted in 32 and 50 % greater NH_3 losses from urea at 24 and 36 months after liming (Table 3), respectively, compared with the 2.6 Mg ha^{-1} rate.

Future studies should investigate the response of NUE to these amendment practices, given that, depending on the N source and lime rate, liming can significantly increase N losses, potentially reducing NUE. The use of specific tools, such as isotope labels (e.g., 15N), can better qualify assessments of N fertilizer dynamics in soil–plant–atmosphere systems, contributing to the development of more sustainable N fertilization strategies.

CONCLUSION

Surface liming under NT increases topsoil pH, thereby enhancing NH_3-N volatilization. For urea, losses reached up to 32 % of the applied N and increased with higher lime rates. Under the conditions of this study, the results indicate that surface applications of lime at rates exceeding those recommended by the BS% method can intensify NH_3-N volatilization losses from N fertilizers.

Our findings also indicate that ammonium-based N sources, such as AMS, and EEFs, such as urea treated with NBPT (Ur-NBPT), should be preferred over conventional urea due to their greater effectiveness in reducing total volatilization and delaying the volatilization peak following liming under NT. However, when using AMS, the greater potential for long-term soil acidification must be considered.

DATA AVAILABILITY

All data were generated or analyzed in this study.

FUNDING

Evandro Minato and Marcos Besen acknowledge the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES) for the doctoral fellowships awarded during their PhD studies. Lucas Suguiura acknowledges CAPES for a master's scholarship under the Academic Excellence Program (PROEX). Bruno Cassim acknowledges the postdoctoral fellowship provided by Fundação de Amparo à Pesquisa do Estado de São Paulo (FAPESP) (grant number #2025/11112-1). Marcelo Batista acknowledges CNPq for the research productivity grant (process No. 312764/2023-5).

AUTHOR CONTRIBUTIONS

Conceptualization: Evandro Antonio Minato (equal) and Marcelo Augusto Batista (equal).

Data curation: Bruno Maia Abdo Rahmen Cassim (equal), Evandro Antonio Minato (equal) and Marcos Renan Besen (equal).

Formal analysis: Evandro Antonio Minato (equal) and Lucas Hiroshi Suguiura (equal).

Funding acquisition: Marcelo Augusto Batista (equal) and Tadeu Takeyoshi Inoue (equal).

Investigation: Bruno Maia Abdo Rahmen Cassim (equal), Evandro Antonio Minato (equal), Lucas Hiroshi Suguiura (equal) and Marcos Renan Besen (equal).

Methodology: Evandro Antonio Minato (lead).

Project administration: Evandro Antonio Minato (equal), Marcelo Augusto Batista (equal) and Tadeu Takeyoshi Inoue (equal).

Resources: Marcelo Augusto Batista (equal) and Tadeu Takeyoshi Inoue (equal).

Supervision: Evandro Antonio Minato (lead).

Validation: Bruno Maia Abdo Rahmen Cassim (equal), Evandro Antonio Minato (equal) and Marcos Renan Besen (equal).

Visualization: Bruno Maia Abdo Rahmen Cassim (equal), Lucas Hiroshi Suguiura (equal), Lúcia Tiemi Naves Yamashita (equal) and Marcos Renan Besen (equal).

Writing – original draft: Bruno Maia Abdo Rahmen Cassim (equal), Evandro Antonio Minato (equal), Lucas Hiroshi Suguiura (equal) and Marcos Renan Besen (equal).

Writing – review & editing: Bruno Maia Abdo Rahmen Cassim (equal), Evandro Antonio Minato (equal), Lucas Hiroshi Suguiura (equal), Lúcia Tiemi Naves Yamashita (equal), Marcelo Augusto Batista (equal) and Marcos Renan Besen (equal).

REFERENCES

Akaike H. A new look at the statistical model identification. IEEE Trans Automat Contr. 1974;19:716-23. https://doi.org/10.1109/TAC.1974.1100705

Araújo ES, Marsola T, Miyazawa M, Soares LHB, Urquiaga S, Boddey RM, Alves BJR. Calibração de câmara semiaberta estática para quantificação de amônia volatilizada do solo. Pesq Agropec Bras. 2009;44:769-76. https://doi.org/10.1590/S0100-204X2009000700018

Benini S, Rypniewski WR, Wilson KS, Mangani S, Ciurli S. Molecular details of urease inhibition by boric acid: Insights into the catalytic mechanism. J Am Chem Soc. 2004;126:3714-5. https://doi.org/10.1021/ja049618p

Besen MR, Minato EA, Cassim BMAR, Macon CR, Zampar EJO, Inoue TT, Batista MA. The efficiency of stabilized fertilizers in reducing ammonia loss is influenced by liming method. Commun Soil Sci Plant Anal. 2022;53:1552-64. https://doi.org/10.1080/00103624.2022.2060248

Bouyoucos GJ. Hydrometer method improved for making particle size analyses of soils. Agron J. 1962;54:464-5. https://doi.org/10.2134/agronj1962.00021962005400050028x

Bower CE, Holm-Hansen T. A salicylate–hypochlorite method for determining ammonia in seawater. Can J Fish Aquat Sci. 1980;37:794-8. https://doi.org/10.1139/f80-106

Brignoli FM, Geraldini APB, Tormena CA, Araújo MA, Batista MA. Liming and phosphate fertilization influence soil fertility, physical properties, and carbon stock in a subtropical Ferralsol in Brazil. Soil Till Res. 2024;244:106268. https://doi.org/10.1016/j.still.2024.106268

Caires EF, Garbuio FJ, Churka S, Barth G, Corrêa JCL. Effects of soil acidity amelioration by surface liming on no-till corn, soybean, and wheat root growth and yield. Eur J Agron. 2008;28:57-64. https://doi.org/10.1016/j.eja.2007.05.002

Cancellier EL, Silva DRG, Faquin V, Gonçalves BA, Cancellier LL, Spehar CR. Ammonia volatilization from enhanced-efficiency urea on no-till maize in Brazilian cerrado with improved soil fertility. Cienc Agrotec. 2016;40:133-44. https://doi.org/10.1590/1413-70542016402031115

Cantarella H, Otto R, Soares JR, Silva AGB. Agronomic efficiency of NBPT as a urease inhibitor: A review. J Adv Res. 2018;13:19-27. https://doi.org/10.1016/j.jare.2018.05.008

Cassim BMAR, Cordioli VR, Chilante GF, Mazzi FL, Muniz AS, Inoue TT, Batista MA. Effects of straw mulching, liming, and soil texture on ammonia volatilisation: A study of conventional and enhanced efficiency fertilisers. Soil Res. 2024a;62:SR23164. https://doi.org/10.1071/SR23164

Cassim BMAR, Lisboa IP, Besen MR, Otto R, Cantarella H, Inoue TT, Batista MA. Nitrogen: from discovery, plant assimilation, sustainable usage to current enhanced efficiency fertilizers technologies – A review. Rev Bras Cienc Solo. 2024b;48:e0230037. https://doi.org/10.36783/18069657rbcs20230037

Cassim BMAR, Lisboa IP, Degryse F, Silva RC, Prestes CV, Lavres J, Otto R. Combined use of NBPT and micronutrients in granulated or coated urea: A new approach to reduce ammonia volatilization losses from soil. Soil Use Manage. 2024c;40:e13148. https://doi.org/10.1111/sum.13148

Cassim BMAR, Besen MR, Kachinski WD, Macon CR, Almeida Junior JHV, Sakurada R, Inoue TT, Batista MA. Nitrogen fertilizers technologies for corn in two yield environments in South Brazil. Plants. 2022;11:1890. https://doi.org/10.3390/plants11141890

Cassim BMAR, Kachinski WD, Besen MR, Coneglian CF, Macon CR, Paschoeto GF, Inoue TT, Batista MA. Duromide increase NBPT efficiency in reducing ammonia volatilization loss from urea. Rev Bras Cienc Solo. 2021;45:e0210017. https://doi.org/10.36783/18069657rbcs20210017

Chen L, Liu X, Hua Z, Xue H, Mei S, Wang P, Wang S. Comparison of nitrogen loss weight in ammonia volatilization, runoff, and leaching between common and slow-release fertilizer in paddy field. Water Air Soil Pollut. 2021;232:132. https://doi.org/10.1007/s11270-021-05083-6

Chien SH, Gearhart MM, Collamer DJ. The effect of different ammoniacal nitrogen sources on soil acidification. Soil Sci. 2008;173:544. https://doi.org/10.1097/SS.0b013e31817d9d17

Das S, Mohapatra A, Sahu K, Panday D, Ghimire D, Maharjan B. Nitrogen dynamics as a function of soil types, compaction, and moisture. PLoS ONE. 2024;19:e0301296. https://doi.org/10.1371/journal.pone.0301296

Dick WA. Influence of long-term tillage and crop rotation combinations on soil enzyme activities. Soil Sci Soc Am J. 1984;48:569-74. https://doi.org/10.2136/sssaj1984.03615995004800030020x

Dominghetti AW, Guelfi DR, Guimarães RJ, Caputo ALC, Spehar CR, Faquin V. Nitrogen loss by volatilization of nitrogen fertilizers applied to coffee orchard. Cienc Agrotec. 2016;40:173-83. https://doi.org/10.1590/1413-70542016402029615

Fageria NK, Santos AB, Moraes MF. Influence of urea and ammonium sulfate on soil acidity indices in lowland rice production. Commun Soil Sci Plant Anal. 2010;41:1565-75. https://doi.org/10.1080/00103624.2010.485237

Faria LA, Nascimento CAC, Ventura BP, Florim GP, Luz PHC, Vitti GC. Hygroscopicity and ammonia volatilization losses from nitrogen sources in coated urea. Rev Bras Cienc Solo. 2014;38:942-8. https://doi.org/10.1590/S0100-06832014000300026

Good AG, Beatty PH. Fertilizing nature: A tragedy of excess in the commons. PLoS Biol. 2011;9:e1001124. https://doi.org/10.1371/journal.pbio.1001124

Hill J, Goodkind A, Tessum C, Thakrar S, Tilman D, Polasky S, Smith T, Hunt N, Mullins K, Clark M, Marshall J. Air-quality-related health damages of maize. Nat Sustain. 2019;2:397-403. https://doi.org/10.1038/s41893-019-0261-y

Inagaki TM, Sá JCM, Caires EF, Gonçalves DRP. Lime and gypsum application increases biological activity, carbon pools, and agronomic productivity in highly weathered soil. Agric Ecosyst Environ. 2016;231:156-65. https://doi.org/10.1016/j.agee.2016.06.034

Kassam A, Friedrich T, Derpsch R. Global spread of conservation agriculture. Int J Environ Stud. 2019;76:29-51. https://doi.org/10.1080/00207233.2018.1494927

Köppen W. The thermal zones of the Earth according to the duration of hot, moderate and cold periods and to the impact of heat on the organic world. Meteorol Z. 2011;20:351-60. https://doi.org/10.1127/0941-2948/2011/105

Lisboa IP, Cassim BMAR, Brasil PHE, Pereira FL, Prestes CV, Carvalho HWP, Lavres Junior J, Bendassolli JA, Otto R. Association of NBPT and zinc sources into urea: A new approach to slow down nitrogen releasing and reduce losses. J Soil Sci Plant Nutr. 2024;24:6962-79. https://doi.org/10.1007/s42729-024-02017-z

Mandal S, Thangarajan R, Bolan NS, Sarkar B, Khan N, Ok YS, Naidu R. Biochar-induced concomitant decrease in ammonia volatilization and increase in nitrogen use efficiency by wheat. Chemosphere. 2016;142:120-7. https://doi.org/10.1016/j.chemosphere.2015.04.086

Manunza B, Deiana S, Pintore M, Gessa C. The binding mechanism of urea, hydroxamic acid and *N*-(*N*-butyl)-phosphoric triamide to the urease active site. A comparative molecular dynamics study. Soil Biol Biochem. 1999;31:789-96. https://doi.org/10.1016/S0038-0717(98)00155-2

Mariano E, Sant Ana Filho CR, Bortoletto-Santos R, Bendassolli JA, Trivelin PCO. Ammonia losses following surface application of enhanced-efficiency nitrogen fertilizers and urea. Atmos Environ. 2019;203:242-51. https://doi.org/10.1016/j.atmosenv.2019.02.003

Minato EA, Brignoli FM, Esper Neto M, Besen MR, Cassim BMAR, Lima RS, Tormena CA, Inoue TT, Batista MA. Lime and gypsum application to low-acidity soils: Changes in soil chemical properties, residual lime content and crop agronomic performance. Soil Till Res. 2023a;234:105860. https://doi.org/10.1016/j.still.2023.105860

Minato EA, Besen MR, Esper Neto M, Cassim BMAR, Zampar EJO, Inoue TT, Batista MA. Ammonia volatilization and nitrogen status in second-season corn after lime and gypsum application in no-till. Acta Sci Agron. 2023b;45:e58774. https://doi.org/10.4025/actasciagron.v45i1.58774

Minato EA, Cassim BMAR, Besen MR, Mazzi FL, Inoue TT, Batista MA. Controlled-release nitrogen fertilizers: Characterization, ammonia volatilization, and effects on second-season corn. Rev Bras Cienc Solo. 2020;44:e0190108. https://doi.org/10.36783/18069657rbcs20190108

Oliveira CLB, Cassimiro JB, Silveira DS, Belisario MP, Heinrichs R, Cassim BMAR, Batista MA, Moro E. Potential of enhanced efficiency nitrogen fertilizers in reducing nitrogen and carbon losses in a sandy soil integrated crop-livestock system. J Environ Manage. 2024;371:122898. https://doi.org/10.1016/j.jenvman.2024.122898

Otto R, Zavaschi E, Souza GJM, Machado BA, Mira AB. Ammonia volatilization from nitrogen fertilizers applied to sugarcane straw. Rev Cienc Agron. 2017;48:413-8. https://doi.org/10.5935/1806-6690.20170048

Pan B, Lam SK, Mosier A, Luo Y, Chen D. Ammonia volatilization from synthetic fertilizers and its mitigation strategies: A global synthesis. Agric Ecosyst Environ. 2016;232:283-9. https://doi.org/10.1016/j.agee.2016.08.019

Pauletti V, Motta ACV. Manual de adubação e calagem para o estado do Paraná. 2. ed. Curitiba: SBCS/NEPAR; 2019.

Pavan MA, Bloch MF, Zempulski HC, Miyazawa M, Zocoler DC. Manual de análise química do solo e controle de qualidade. Londrina: Instituto Agronômico do Paraná; 1992.

Pittelkow CM, Liang X, Linquist BA, van Groenigen KJ, Lee J, Lundy ME, van Gestel N, Six J, Venterea RT, van Kessel C. Productivity limits and potentials of the principles of conservation agriculture. Nature. 2015;517:365-8. https://doi.org/10.1038/nature13809

Powlson DS, Dawson CJ. Use of ammonium sulphate as a sulphur fertilizer: Implications for ammonia volatilization. Soil Use Manage. 2022;38:622-34. https://doi.org/10.1111/sum.12733

Ribeiro RH, Besen MR, Simon PL, Bayer C, Piva JT. Enhanced-efficiency nitrogen fertilizers reduce winter losses of nitrous oxide, but not of ammonia, from no-till soil in a subtropical agroecosystem. Soil Use Manage. 2020;36:420-8. https://doi.org/10.1111/sum.12575

Rochette P, Angers DA, Chantigny MH, MacDonald JD, Bissonnette N, Bertrand N. Ammonia volatilization following surface application of urea to tilled and no-till soils: A laboratory comparison. Soil Till Res. 2009;103:310-5. https://doi.org/10.1016/j.still.2008.10.028

Santos HG, Jacomine PKT, Anjos LHC, Oliveira VA, Lumbreras JF, Coelho MR, Almeida JA, Araújo Filho JC, Oliveira JB, Cunha TJF. Sistema brasileiro de classificação de solos. 5. ed. rev. ampl. Brasília, DF: Embrapa; 2018.

Seber GAF, Wild CJ. Nonlinear regression. Hoboken, NJ: Wiley-Interscience; 2003.

Sengik E, Kiehl JC, Silva MGA, Palangana DC, Lawder MR. Perdas de amônia em solo e de resíduos orgânicos autoclavados e tratados com uréia. Acta Sci Agron. 2008;23:1099-105. https://doi.org/10.4025/actasciagron.v23i0.2565

Sha Z, Li Q, Lv T, Misselbrook T, Liu X. Response of ammonia volatilization to biochar addition: A meta-analysis. Sci Total Environ. 2019;655:1387-96. https://doi.org/10.1016/j.scitotenv.2018.11.316

Shaw WHR. The inhibition of urease by various metal ions. J Am Chem Soc. 1954;76:2160-3. https://doi.org/10.1021/ja01637a034

Silva AGB, Sequeira CH, Sermarini RA, Otto R. Urease inhibitor NBPT on ammonia volatilization and crop productivity: A meta-analysis. Agron J. 2017;109:1-13. https://doi.org/10.2134/agronj2016.04.0200

Soares JR, Cantarella H. Dynamics of ammonia volatilization from NBPT-treated urea in tropical acid soils. Sci Agric. 2023;80:e20220076. https://doi.org/10.1590/1678-992X-2022-0076

Soil Survey Staff. Keys to Soil Taxonomy. 12th ed. Washington, DC: United States Department of Agriculture, Natural Resources Conservation Service; 2014.

Souza TL, Oliveira DP, Santos CF, Reis THP, Cabral JPC, Resende ERS, Fernandes TJ, Souza TR, Builes VR, Guelfi D. Nitrogen fertilizer technologies: Opportunities to improve nutrient use efficiency towards sustainable coffee production systems. Agric Ecosyst Environ. 2023;345:108317. https://doi.org/10.1016/j.agee.2022.108317

Sunderlage B, Cook RL. Soil property and fertilizer additive effects on ammonia volatilization from urea. Soil Sci Soc Am J. 2018;82:253-9. https://doi.org/10.2136/sssaj2017.05.0151

Trenkel ME. Slow and controlled-release and stabilized fertilizers: An option for enhancing nutrient use efficiency in agriculture. 2nd ed. Paris: International Fertilizer Association; 2010.

Viero F, Bayer C, Fontoura SMV, Moraes RP. Ammonia volatilization from nitrogen fertilizers in no-till wheat and maize in southern Brazil. Rev Bras Cienc Solo. 2014;38:1515-25. https://doi.org/10.1590/S0100-06832014000500017

Woodley AL, Drury CF, Yang XY, Phillips LA, Reynolds DW, Calder W, Oloya TO. Ammonia volatilization, nitrous oxide emissions, and corn yields as influenced by nitrogen placement and enhanced efficiency fertilizers. Soil Sci Soc Am J. 2020;84:1327-41. https://doi.org/10.1002/saj2.20079

Wyer KE, Kelleghan DB, Blanes-Vidal V, Schauberger G, Curran TP. Ammonia emissions from agriculture and their contribution to fine particulate matter: A review of implications for human health. J Environ Manage. 2022;323:116285. https://doi.org/10.1016/j.jenvman.2022.116285