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Research Article

Improving nitrogen efficiency and reducing ammonia emissions in wheat: a strategy using cattle slurry and dicyandiamide[1]

Alieze Nascimento da Silva[2], Eveline Ferreira Soares[3], Claudir José Basso[4]

ABSTRACT

Under no-tillage systems, the surface application of cattle slurry may result in significant losses through ammonia volatilization, compromising the nitrogen-use efficiency in wheat. This study evaluated the effects of cattle slurry (CS) application methods (surface *vs*. injection), with or without the nitrification inhibitor dicyandiamide (DCD), on ammonia (NH_3-N) volatilization, nitrogen-use efficiency and wheat yield, under no-tillage conditions. Two field experiments were carried out in contrasting soils (Oxisol and Ultisol). Pre-sowing NH_3-N losses were strongly affected by the source and application method of N. For the Oxisol, the cumulative volatilization reached 10.67 % of the N applied in the NPK treatment, when compared to 7.80 % in the surface-applied CS and 7.25 % in the injected CS. For the Ultisol, the NH_3-N losses from CS were lower than 1 % of the applied ammoniacal N, and the injection reduced emissions up to 58 %, relatively to the surface application. The injected CS treatment combined with DCD (CSi + DCD) increased the nitrogen uptake by 48-141 kg ha^{-1}, and improved the nitrogen-use efficiency by 1.23-2.53 kg of grains, when compared to NPK. Grain yield was also higher in CSi + DCD, with increases of 20.3 % (Oxisol) and 16.2 % (Ultisol), in relation to NPK. The slurry injection associated with the use of DCD enhanced the N retention, reduced NH_3-N losses, and increased wheat yield, representing an efficient alternative to conventional mineral fertilization in subtropical no-tillage systems.

KEYWORDS: *Triticum aestivum*, slurry application methods, greenhouse gas mitigation.

RESUMO

Melhorando a eficiência do nitrogênio e reduzindo as emissões de amônia em trigo com o uso de dejeto líquido de bovino e dicianodiamida

Em sistemas de plantio direto, a aplicação superficial de dejetos líquidos de bovinos pode resultar em perdas significativas de nitrogênio por volatilização de amônia, comprometendo a eficiência de uso do nutriente pelo trigo. Este estudo avaliou os efeitos de métodos de aplicação de dejetos líquidos de bovinos (DLB) (superficial *vs*. injeção), com ou sem o inibidor de nitrificação dicianodiamida (DCD), sobre a volatilização de amônia (NH_3-N), eficiência de uso do nitrogênio e produtividade de trigo, em sistema de plantio direto. Dois experimentos de campo foram conduzidos em solos contrastantes (Latossolo e Argissolo). As perdas de NH_3-N no pré-plantio foram fortemente influenciadas pela fonte e pelo modo de aplicação do N. No Latossolo, a volatilização acumulada atingiu 10,67 % do N aplicado no tratamento NPK, em comparação a 7,80 % para DLB aplicado superficialmente e 7,25 % para DLB injetado. No Argissolo, as perdas de NH_3-N provenientes do DLB foram inferiores a 1 % do N amoniacal aplicado, e a injeção reduziu as emissões em até 58 %, em relação à aplicação superficial. O tratamento com DLB injetado combinado com DCD (DLBi + DCD) aumentou a absorção de N em 48-141 kg ha^{-1} e melhorou a eficiência de uso do nitrogênio em 1,23-2,53 kg de grãos, quando comparado ao NPK. A produtividade de grãos também foi superior no DLBi + DCD, com incrementos de 20,3 % (Latossolo) e 16,2 % (Argissolo), em relação ao NPK. A injeção de DLB associada ao uso de DCD aumentou a retenção de N, reduziu as perdas de NH_3-N e elevou a produtividade do trigo, representando uma alternativa eficiente à adubação mineral convencional em sistemas subtropicais de plantio direto.

PALAVRAS-CHAVE: *Triticum aestivum*, métodos de aplicação de dejetos, mitigação de gases de efeito estufa.

INTRODUCTION

The use of global nitrogen (N) fertilizer has continuously risen, reaching 108 million tons in 2022 (FAO 2024), with projections of a further increase of up to 116 million tons by 2025 (IFA 2025). In Brazil, N accounts for nearly one-third of the fertilizer consumption (PNF 2022), and imports grew 15 % in January 2024 (Conab 2024).

In southern Brazil's crop-livestock systems, cattle slurry (CS) is widely used before wheat sowing, because 75-90 % of the ingested N is excreted by

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[2] Universidade de Cruz Alta, Cruz Alta, RS, Brazil. *E-mail/ORCID*: alieze.agro@gmail.com/0000-0003-3253-0885.
[3] Universidade Federal do Rio Grande do Sul, Porto Alegre, RS, Brazil. *E-mail/ORCID*: soares.eveline@yahoo.com/0000-0003-3675-558X.
[4] Universidade Federal de Santa Maria, Frederico Westphalen, RS, Brazil. *E-mail/ORCID*: claudirbasso@gmail.com/0000-0002-3013-5702.
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ruminants (Whitehead 1995, Bouwman et al. 2013, Bratti et al. 2022), enabling nutrient recycling but contributing to low nitrogen-use efficiency. Moreover, even simpler liquid fractions of livestock waste, such as cattle urine, have demonstrated considerable fertilization potential, increasing maize yield in smallholder systems (Yemata & Mengistu 2024) and reinforcing the agronomic value of recycled livestock nitrogen.

Globally, crops take up only ~33 % of the applied N, whereas ~67 % is lost as NH_3, N_2O and NO_3^- (Park et al. 2021, Peng et al. 2023, Buchen-Tschiskale et al. 2023a, Cassim et al. 2024, IEA 2024). Agriculture, particularly livestock, drives 80-90 % of NH_3 emissions (Aneja et al. 2020, Overmeyer et al. 2021, El Bied et al. 2023), with animal supply chains responsible for 60 % of the global NH_3, 23 % of NO_x and 32 % of N_2O emissions (Uwizeye et al. 2020).

Under no-tillage, the lack of incorporation intensifies the NH_3 volatilization from CS (Damian et al. 2018, Keskinen et al. 2022, Nyameasem et al. 2022a, Jin et al. 2025, Ofori et al. 2025), especially in the first 24-48 h after application (Fangueiro et al. 2022, van der Weerden et al. 2021, Wang et al. 2021, van der Weerden et al. 2023). For urea, a rapid hydrolysis increases the microsite pH and shifts the NH_4^+/NH_3 equilibrium toward a higher amount of NH_3 (Rochette et al. 2009a, Cantarella et al. 2018), leading to potential losses of up to 64 % of the applied N, whereas slurry may emit 20-30 % of the total ammoniacal nitrogen, depending on environmental conditions (Rochette et al. 2009, Aita et al. 2018, Andersson et al. 2023).

Mitigation strategies such as slurry injection, trailing-shoe application, acidification, and inhibitors can significantly reduce these losses. Injection typically reduces NH_3 emissions by 17-37 %, whereas acidification decreases early losses by 67-80 % (van der Weerden et al. 2021, Andersson et al. 2023). Urease inhibitors (e.g., NBPT) delay urea hydrolysis, reducing NH_3 losses by ~53 % and increasing wheat yield in Brazil by ~6 % (Cantarella et al. 2018), whereas integrated approaches combining NBPT, hydroquinone or plant-derived additives reduce volatilization by 17-40 % and improve yield and nitrogen-use efficiency (Sanz-Cobena et al. 2008, Abalos et al. 2012, Abalos et al. 2014, Sanz-Cobena et al. 2014, Ramalingappa et al. 2023).

Dicyandiamide (DCD), a widely studied nitrification inhibitor, slows NH_4^+ oxidation and improves soil N retention, reducing N_2O emissions and NO_3^- leaching, and increasing crop N uptake (Ramalingappa et al. 2023). In wheat and forage systems, DCD has reduced N_2O emissions by ~50 %, increased dry matter production and decreased the proportion of unaccounted-for N, defined as the fraction of applied N not recovered in plant uptake, soil N pools, or directly measured loss pathways (Aita et al. 2018, Bray et al. 2021, Park et al. 2021).

Studies combining slurry placement and inhibitors consistently report higher N uptake, higher nitrogen-use efficiency and lower N losses in cereals (Meade et al. 2011, Sieling et al. 2014, Franzluebbers 2020, Capra et al. 2025, Sorecha et al. 2025). However, most evidence comes from temperate regions and soil types distinct from the Oxisol and Ultisol that dominate subtropical, no-tillage systems, in southern Brazil.

The interaction between slurry application method and DCD remains poorly understood in local crop-livestock systems. Thus, this study evaluated the effectiveness of CS injection and DCD in reducing NH_3-N losses in wheat grown on contrasting subtropical soils (Oxisol and Ultisol), as well as their impacts on wheat performance and nitrogen-use efficiency.

MATERIAL AND METHODS

Two field experiments were conducted under no-tillage conditions at two locations in the Rio Grande do Sul state, Brazil - one in the northwest and the other in the central region of the state, during the 2015 growing season.

The experiment I was carried out at the Universidade Federal de Santa Maria, in Frederico Westphalen (27º23′S, 53º25′W and 566 m of altitude), in a humid subtropical climate (Cfa), according to the Köppen classification. Meteorological data from an automatic station located at 500 m from the site are shown in Figure 1a. The soil in the area is classified as Dystrophic Red Latosol (Embrapa 2013), corresponding to Rhodic Hapludox (Oxisol) (USDA 2022), with 654 g kg^{-1} of clay, pH (H_2O) of 5.1, SMP index (Shoemaker-McLean-Pratt buffer, used to estimate lime requirement) of 5.6, 5.5 mg dm^{-3} of P, 64.8 mg dm^{-3} of K, 0.2 $cmol_c$ dm^{-3} of Al, 5.5 $cmol_c$ dm^{-3} of H + Al, 7.94 $cmol_c$ dm^{-3} of effective cation exchange capacity (CEC), 57.22 % of base saturation and 28.4 g kg^{-1} of organic matter in the 0.00-0.10 m layer.

The experiment II was conducted at the Universidade Federal de Santa Maria, in Santa Maria (29º42′S, 53º42′W and 80 m of altitude), also under a humid subtropical climate (Cfa). Meteorological data are shown in Figure 1b. The soil in the area is classified as Arenic Dystrophic Red Argisol (Embrapa 2013), corresponding to Typic Hapludalf (Ultisol) (USDA 2022), containing 124.3 g kg^{-1} of clay, 259.1 g kg^{-1} of silt and 616.6 g kg^{-1} of sand, with 13 g kg^{-1} of organic matter, pH of 5.3, 13.2 mg dm^{-3} of P, 72 mg dm^{-3} of K, 41.9 % of base saturation, 6.5 $cmol_c$ dm^{-3} of CEC at pH 7.0, and 1.64 g cm^{-3} of bulk density, in the 0.00-0.10 m layer. The area had remained fallow for one year and had been under no-tillage for two years, with soybean in the summer and ryegrass in the winter.

Both sites present a humid subtropical climate (Cfa), with annual mean temperatures of 18.6 ºC in Frederico Westphalen and 19.1 ºC in Santa Maria, mild winters (12-16 ºC), warm summers

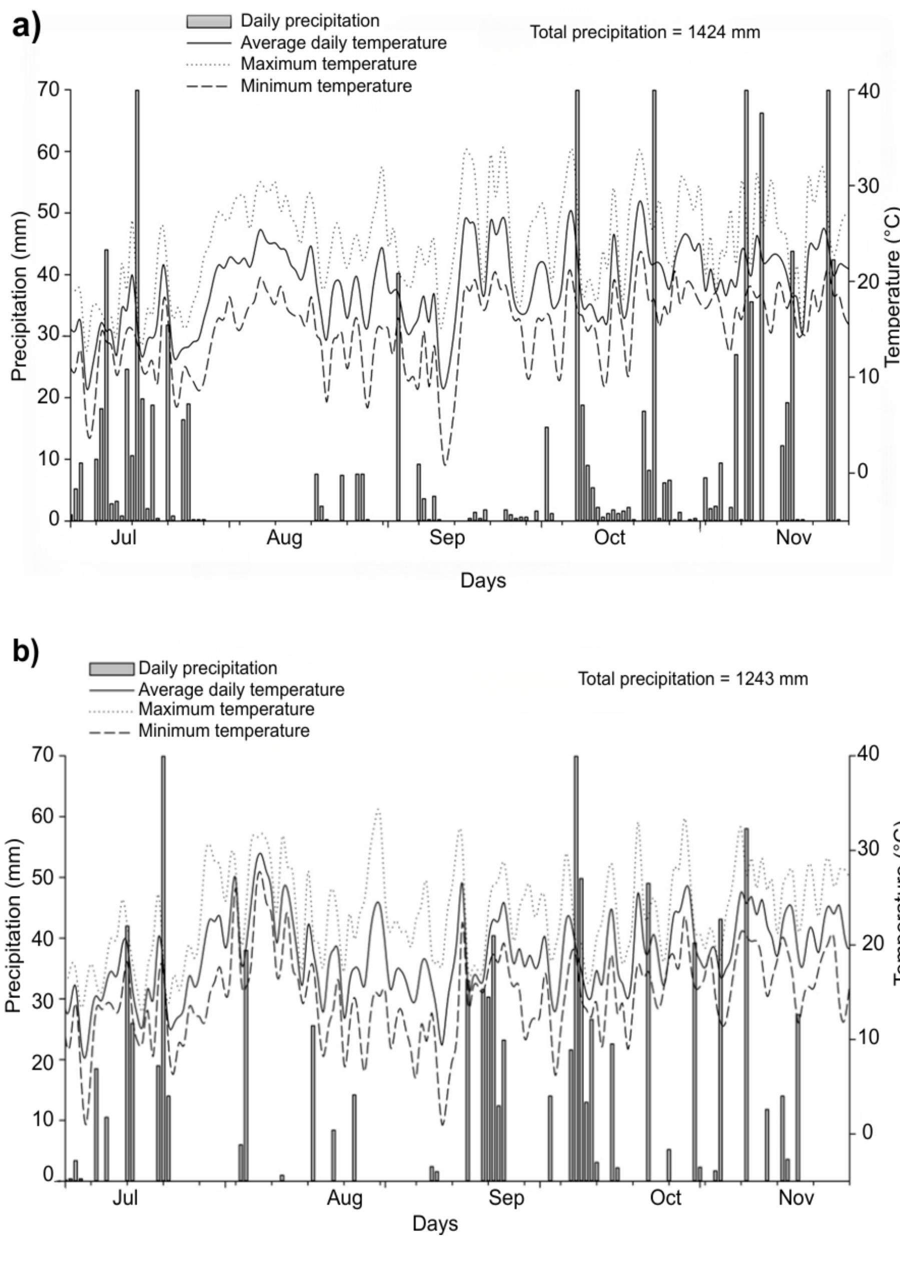

Figure 1. Daily minimum, maximum, and mean air temperatures and rainfall during the experiment. a) Rainfall data sourced from the Frederico Westphalen meteorological station; b) data obtained from the experimental climatological station of the Universidade Federal de Santa Maria.

(23-27 ºC), and well-distributed rainfall totaling 1,700-1,900 mm annually, with monthly averages of 110-180 mm during the wheat season (Brasil 2022). Climatic conditions recorded during the experiments are shown in Figure 1.

Six treatments were applied in 36-m² plots (6 × 6 m), arranged in a randomized complete block design, with four replications. The treatments consisted of: surface-applied cattle slurry (CSs) (T1; application of CS distributed over the soil surface); surface-applied cattle slurry plus dicyandiamide (CSs + DCD) (T2; CS applied on the soil surface with the nitrification inhibitor DCD mixed immediately before application); injected cattle slurry (CSi) (T3; CS applied using a mechanical injector that places the material directly into the soil); injected cattle slurry plus dicyandiamide (CSi + DCD) (T4; injected CS combined with DCD incorporated at the time of application); control (T5; no fertilizer and no DCD); and mineral fertilizer (NPK) (T6; conventional mineral fertilization applied to the soil surface following recommended rates for wheat).

The cattle slurry (CS) used in the experiments originated from lactating dairy cows and consisted of feces, urine, wasted feed and wash water stored in an open anaerobic pit. Its chemical composition is shown in Table 1.

For the experiment I, the liquid cattle slurry used in all organic treatments was designated as cattle slurry (CS) and applied at a rate of 88.8 m³ ha^{-1}, supplying 60 kg ha^{-1} of N, 75 kg ha^{-1} of P and 60 kg ha^{-1} of K. In the NPK treatment, 75 kg ha^{-1} of P_2O_5, 60 kg ha^{-1} of K_2O and 60 kg ha^{-1} of N were applied at sowing, followed by 50 kg ha^{-1} of top-dressed N.

Table 1. Main characteristics of the cattle slurry used and the amount of NPK applied in each experiment.

Characteristics	Experiment I	Experiment II
Cattle slurry (CS)	Frederico Westphalen	Santa Maria
Dry matter (g kg^{-1})	23.10	35.50
Total N (g kg^{-1})	0.93	1.14
TAN[1] (g kg^{-1})	0.38	0.27
pH	7.24	6.90
CS rate (m³ ha^{-1})	88.80	80.00
TAN (kg ha^{-1})	33.30	21.60
Mineral fertilizer (NPK)		
N-urea[2] (kg ha^{-1})	110	110
K_2O (kg ha^{-1})	60	40
P_2O_5 (kg ha^{-1})	75	75

[1] TAN: total ammoniacal nitrogen ($N\text{-}NH_3 + N\text{-}NH_4^+$); [2] The total urea-N rate was split, with 1/3 applied before sowing and 2/3 as topdressing.

The surface-applied CS (CSs) was manually distributed using watering cans, whereas the nitrification inhibitor DCD (Agrotain Plus®) was mixed with the CS at a rate of 7 kg ha^{-1} at the moment of application. The injected CS (CSi) was applied using a mechanical injector (Model DAOL-i 4000 Tandem, MEPEL). The wheat (cv. Quartzo OR, Biotrigo) was sown on July 30, 2015. In the experiment II, CS was likewise used in all organic treatments, applied entirely at six days before sowing, at a rate of 80 m³ ha^{-1}, providing 45.4 kg ha^{-1} of N, 25.6 kg ha^{-1} of P and 80 kg ha^{-1} of K. Because this CS dose did not fully meet the crop's nutritional requirements, supplemental N and P were applied at 37 days after sowing, supplying 64.6 kg ha^{-1} of N and 16.4 kg ha^{-1} of P_2O_5.

In the NPK treatment, 75 kg ha^{-1} of P_2O_5, 30 kg ha^{-1} of K_2O and 20 kg ha^{-1} of N were applied at sowing, followed by 90 kg ha^{-1} of top-dressed N at 40 days after sowing. The wheat (cv. TBIO Sinuelo) was sown on June 22, 2015, at a seeding rate of 160 kg ha^{-1}.

The plant measurements adhered to the growth stage descriptions proposed by Large (1954), and the nitrogen concentration was analyzed according to Tedesco et al. (1995). Based on dry matter production, nitrogen accumulation and grain yield, the following indices were calculated (Craswell & Godwin 1984, Fageria 1998): agronomic nitrogen efficiency, apparent nitrogen recovery, physiological efficiency and nitrogen-use efficiency.

Ammonia emissions were evaluated only in the treatments without DCD (control, NPK, CSs and CSi), since the nitrification inhibitor does not influence NH_3 volatilization (Pujol 2012). Measurements were performed using semi-open static chambers (Nömmik 1973) at 0, 24, 48, 72, 120, 168 and 240 hours after N application. Foam sponges soaked with a trapping solution were used to retain volatilized ammonia. After sampling, the sponges were extracted with KCl, and ammoniacal N was quantified using the semi-micro Kjeldahl distillation method (Tedesco et al. 1995). Hourly fluxes and cumulative NH_3 losses were then calculated.

Statistical analyses were conducted using analysis of variance (Anova). Treatment means were compared with the Tukey test at 5 % of significance and the Fisher's LSD test at 1 %. Analyses were carried out using the Genes software (Cruz 2007) and SigmaPlot (Systat Software, Inc.).

RESULTS AND DISCUSSION

Pre-sowing ammonia volatilization in wheat was strongly driven by the interaction between the source of N, its application method and soil-climate conditions, as shown by the temporal N-NH_3 flux patterns (Figure 2) and cumulative losses (Figure 4). In the Oxisol (experiment I), surface-applied urea (NPK) generated the highest pre-sowing emissions, with a pronounced peak around 120 h after application and a cumulative emission factor of 10.67 % of the applied N. This behavior is consistent with the well-known dynamics of surface-applied urea, in which rapid hydrolysis increases microsite pH, maintains high total ammoniacal nitrogen (TAN; $NH_3 + NH_4^+$) concentrations in the upper millimeters of the soil, and promotes intense NH_3 volatilization under warm and moist conditions (Bronson et al. 1989, Rochette et al. 2009, Cantarella et al. 2018).

By contrast, the cattle slurry treatments showed lower emission factors, even though injected slurry (CSi) occasionally exhibited a slightly higher instantaneous peak than surface-applied slurry (CSs) (Figure 2). This transient peak likely reflects a localized TAN concentration in injection slots; however, the cumulative emission factors - 7.80 % for CSs and 7.25 % for CSi - demonstrate that subsurface placement effectively reduced contact between TAN and the soil-air interface, thereby limiting overall NH_3 losses. These findings are in line with field experiments and reviews, indicating that slurry injection or banding reduces volatilization, when compared with surface application, especially on fine-textured or moist soils (Webb et al. 2010, Nyord et al. 2012, Emmerling et al. 2020, Fangueiro et al. 2021, van der Weerden et al. 2021, Nyameasem et al. 2022, Andersson et al. 2023, van der Weerden et al. 2023).

The contrasting behavior observed in the Ultisol (experiment II) highlights the key role of soil physical properties. In this coarse-textured soil, pre-sowing N-NH_3 fluxes were much smaller, and emission factors remained below 1 % for all slurry treatments (Figures 2 and 4). The rapid infiltration of slurry into the sandy matrix, together with lower surface moisture and milder temperatures in the critical first 24 to 72 hours after application, shortened the TAN residence at the soil's surface and reduced the potential for NH_3 loss. Similar reductions have been reported where high permeability, low water-filled pore space or cooler conditions favor a rapid TAN movement away from the soil-air boundary (Bronson et al. 1989, Keskinen et al. 2022, Ma et al. 2022). Although N_2O was not measured in this study, its known sensitivity to soil moisture and structure (Mazzetto et al. 2015, Taghizadeh-Toosi et al. 2023) reinforces the dominant role of physical conditions in controlling gaseous N losses from manures and fertilizers.

Climatic variability between sites, documented in Figure 1, further amplified these soil-driven differences. In Frederico Westphalen (Oxisol), the total rainfall during the wheat cycle exceeded long-term averages, with several rainfall events occurring

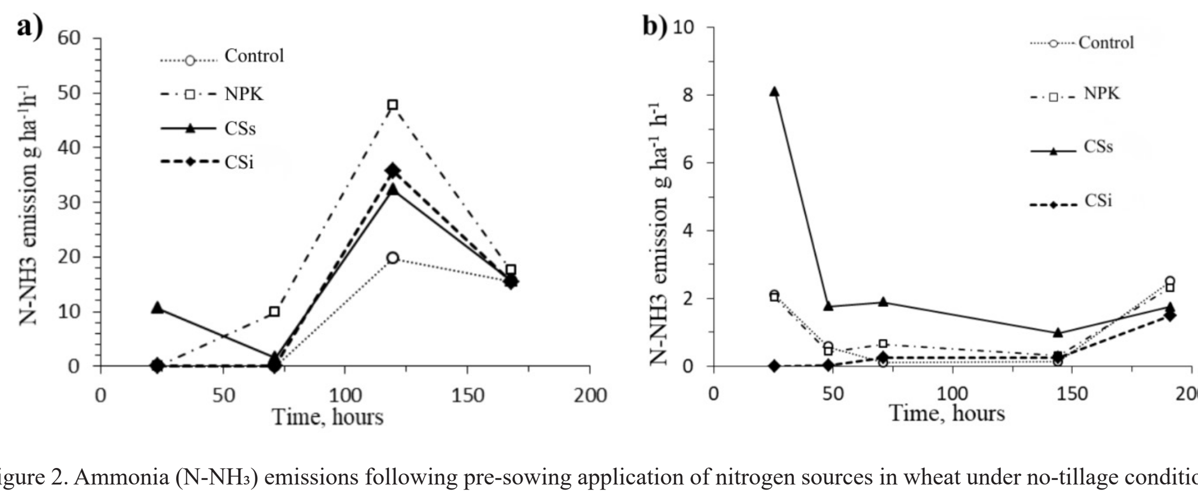

Figure 2. Ammonia (N-NH_3) emissions following pre-sowing application of nitrogen sources in wheat under no-tillage conditions. a) Experiment I - conducted in Frederico Westphalen (Oxisol); b) Experiment II - conducted in Santa Maria (Ultisol). Treatments: control (without N); mineral fertilization (NPK); surface-applied cattle slurry (CSs), and injected cattle slurry (CSi). Vertical bars represent the least significant difference (LSD 0.01).

immediately before and after N applications. Under such conditions, high surface moisture, restricted gas diffusion at the soil-atmosphere interface and sustained urease activity in crop residues favor NH_3 volatilization from surface-applied urea (Rochette et al. 2009, Webb et al. 2010, Cantarella et al. 2018). In Santa Maria (Ultisol), drier intervals after application and rapid slurry infiltration limited the time during which TAN remained exposed, resulting in very low emission factors. These responses agree with multi-site syntheses, showing that soil texture, water-filled pore space and short-term weather after spreading are dominant regulators of NH_3 and N_2O emission factors from land-applied manure (van der Weerden et al. 2021, van der Weerden et al. 2023, Wang et al. 2024).

Overall, the pre-sowing emission factors observed here - 10.67 % of the applied N for urea, 7.80 and 7.25 % of the applied TAN for, respectively, surface and injected slurry - fall within or below typical ranges reported for temperate and subtropical systems and are lower than the 20-30 % of TAN sometimes reported for cattle manure under favorable volatilization conditions (Aita et al. 2018, Emmerling et al. 2020, Andersson et al. 2023). These results therefore support slurry injection as a robust mitigation strategy in no-tillage wheat, especially when combined with site-specific soil texture and rainfall considerations.

Post-sowing volatilization was dominated by urea topdressing, as illustrated by the flux dynamics in Figure 3 and the cumulative losses in Figure 5. In the experiment I, only the NPK treatment received post-sowing urea, resulting in a secondary NH_3 peak of 36.36 g ha^{-1} h^{-1} of N-NH_3 around 79 h after application, whereas slurry-derived TAN contributed minimally at this stage, because most of it had already been infiltrated or transformed. In the experiment II, all fertilized treatments received urea topdressing, and a common volatilization event occurred at approximately 70 h after application, with NPK showing the largest instantaneous peak, followed by slurry-based treatments and the control.

These patterns closely match meta-analytical and experimental evidence, indicating that most NH_3 losses from surface-applied urea occur within 2 to 5 days after application, driven by rapid hydrolysis, sharp pH increases in the upper soil layer and limited gas diffusion in moist, residue-covered surfaces (Rochette et al. 2009a, Cantarella et al. 2018, Ma et al. 2022). Urease inhibitors such as NBPT have been shown to reduce NH_3 losses and often increase yields in cereals (Sanz-Cobena et al. 2008, Abalos et al. 2012, Abalos et al. 2014, Cantarella et al. 2018), but, in the present study, urea was deliberately applied without inhibitors to focus on the effects of slurry placement and nitrification inhibition. Even under these conditions, cumulative NH_3 losses after topdressing remained lower in slurry-based strategies than in NPK, suggesting that a partial substitution of mineral N with organic N from dairy slurry can mitigate volatilization while sustaining yield (Asing et al. 2008, Capra et al. 2023, Zhu et al. 2023, Capra et al. 2025). These results highlight that an effective mitigation of NH_3 emissions in high-input wheat

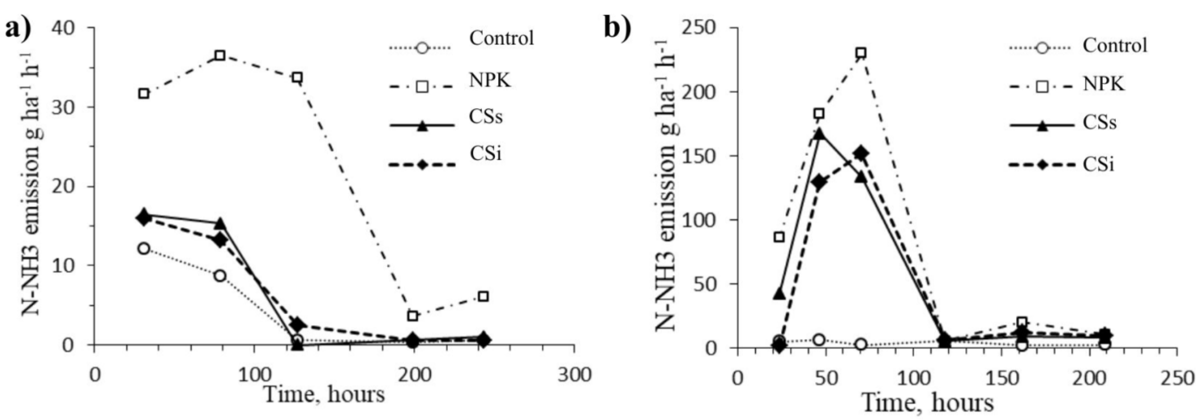

Figure 3. Ammonia (N-NH_3) emissions following urea topdressing in wheat under no-tillage conditions. a) Experiment I - conducted in Frederico Westphalen (Oxisol), where only the mineral fertilization treatment (NPK) received topdressing urea after sowing; b) Experiment II - conducted in Santa Maria (Ultisol), where all fertilized treatments received topdressing urea. Treatments: control (without N); mineral fertilization (NPK); surface-applied cattle slurry (CSs); and injected catlle slurry (CSi). Vertical bars represent the least significant difference (LSD 0.01).

systems requires both improved slurry management and better strategies for synthetic N, including the combined use of inhibitors, optimized timing and alternative placement (Rose et al. 2018, Park et al. 2021, Taghizadeh-Toosi et al. 2023, Cassim et al. 2024).

The emission factors observed in this study fall within or below typical values reported for surface-applied manures and fertilizers, confirming that NH_3 losses largely depend on the proportion of ammoniacal nitrogen exposed at the soil surface (van der Weerden et al. 2021, van der Weerden et al. 2023). Swedish field experiments on clay soils, for example, reported cumulative losses of 23-32 % of applied TAN within 70 hours, with reductions of 17-37 % under trailing-shoe or injection application (Andersson et al. 2023). In southern Brazil, dairy slurry losses ranged from 22 % in the winter to 82 % in the summer (Aita et al. 2018), demonstrating a high volatilization potential under favorable environmental conditions. In this context, the comparatively modest cumulative losses observed here (≤ 10.67 %) indicate that pre-sowing slurry application under no-tillage - particularly with injection - is an effective mitigation strategy, especially in sandy or well-drained soils.

The integration of flux data (Figures 2 and 3) with cumulative emissions (Figures 4 and 5) provides a comprehensive picture of N-NH_3 dynamics across treatments and sites. In the Oxisol, cumulative pre-sowing losses reached 3.61 kg ha^{-1} of N-NH_3 in the NPK treatment, clearly exceeding the slurry-based treatments. In the Ultisol, the cumulative losses were markedly lower for all fertilized treatments, with injected slurry showing the smallest emissions (~0.09 kg ha^{-1}). These outcomes corroborate the well-documented benefits of slurry injection, trailing-shoe application, and acidification in reducing NH_3 volatilization from manures (Webb et al. 2010, Fangueiro et al. 2021, Kavanagh et al. 2021, Overmeyer et al. 2021, Pereira et al. 2022, Silva et al. 2022).

When compared with international benchmarks, the emission factor for surface-applied urea in the Oxisol (10.67 %) is close to the IPCC Tier 1 default for synthetic fertilizers (Arndt et al. 2020) and similar to values reported for non-tilled wheat fertilized with urea under Mediterranean conditions (Guardia et al. 2021). In contrast, emission factors for surface-applied and injected slurry in the Oxisol (7.80 and 7.25 %) and the very low losses in the Ultisol (< 1 %) were well below the 20 % default often assigned to manure N in inventories (Arndt et al. 2020, van der Weerden et al. 2021). This suggests that pre-sowing slurry injection under no-tillage, especially on well-drained or sandy soils, can substantially reduce NH_3 emissions relative to both conventional manure and urea-based fertilization.

These results are consistent with meta-analyses showing that improved slurry management and technological additives - such as acidifiers, biochar, and urease or nitrification inhibitors - reduce NH_3 and

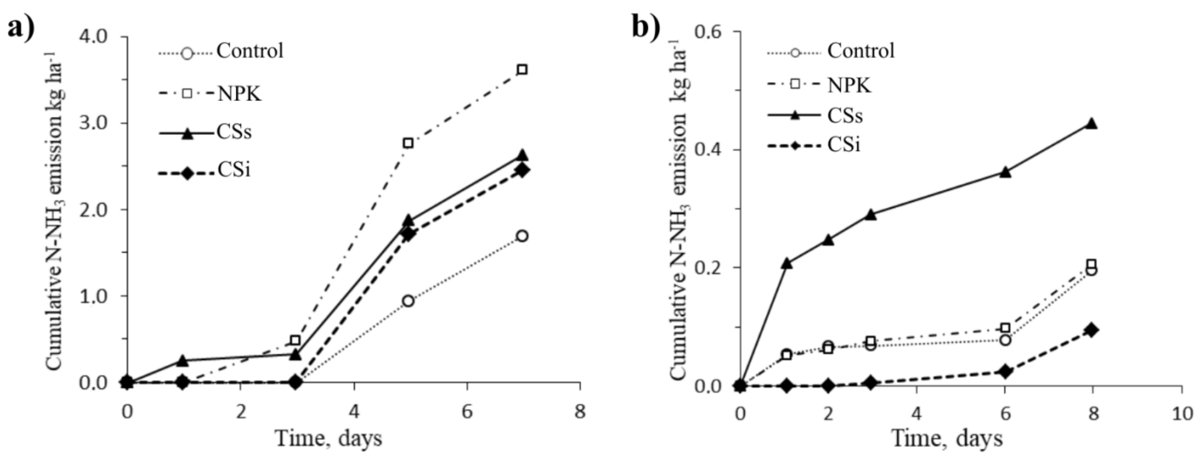

Figure 4. Cumulative amonnia (N-NH_3) losses following cattle slurry (CS) application at pre-sowing in wheat under no-tillage conditions. a) Experiment I - conducted in Frederico Westphalen (Oxisol); b) Experiment II - conducted in Santa Maria (Ultisol). Treatments: control (without N); mineral fertilization (NPK); surface-applied cattle slurry (CSs); and injected cattle slurry (CSi). Vertical bars represent the least significant difference (LSD 0.01).

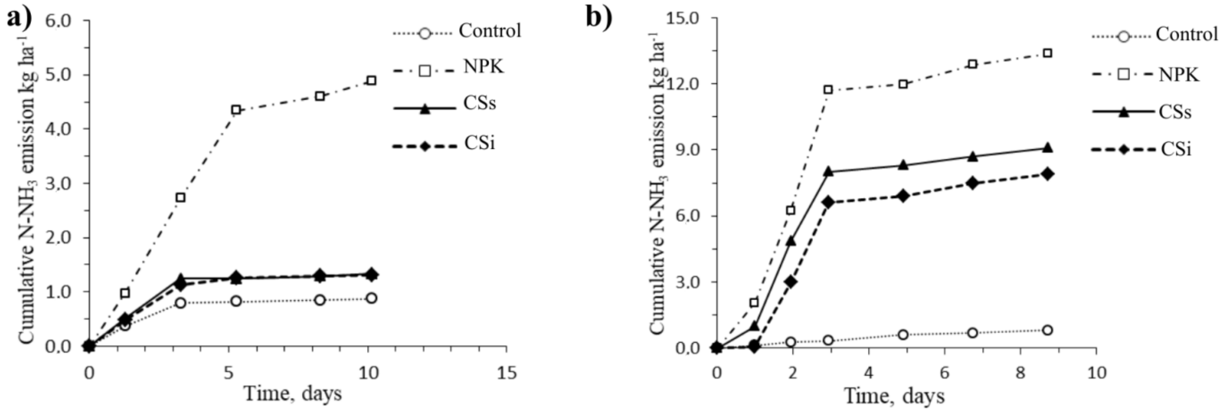

Figure 5. Cumulative ammonia (N-NH_3) losses following urea topdressing application in wheat under no-tillage conditions. a) Experiment I - conducted in Frederico Westphalen (Oxisol), where only the NPK received post-sowing urea; b) Experiment II - conducted in Santa Maria (Ultisol), where all fertilized treatments received topdressing urea. Treatments: control (without N); mineral fertilization (NPK); surface-applied cattle slurry (CSs); and injected cattle slurry (CSi). Vertical bars represent the least significant difference (LSD 0.01).

N_2O emissions without necessarily penalizing yields (Emmerling et al. 2020, Hagner et al. 2021, Wang et al. 2021, Pereira et al. 2022, El Bied et al. 2023, Wang et al. 2024). They also resonate with recent studies on full N balances in grasslands, indicating that a substantial fraction of slurry N may be lost as N_2 or retained in soil organic pools rather than recovered by plants or emitted as NH_3 and N_2O, particularly under improved placement strategies (Buchen-Tschiskale et al. 2023, Dannenmann et al. 2025, Jin et al. 2025, Ofori et al. 2025).

The mitigation potential of CSi and CSi + DCD did not compromise crop performance; instead, it translated into higher shoot dry matter production, N uptake and grain yield (Table 4). In both experiments, CSi + DCD produced the highest biomass and grain yield, surpassing NPK by 20.3 % in the Oxisol and 16.2 % in the Ultisol, whereas injected slurry without DCD (CSi) also outperformed surface-applied slurry (CSs). These responses indicate that placing slurry below the soil surface and delaying nitrification enhanced the synchronicity between N availability and wheat demand, especially under the above-average rainfall observed during the wheat cycle.

The strong increases in N uptake (48 to 141 kg ha^{-1} relative to the control) are consistent with studies showing that nitrification inhibitors such as DCD and 3,4-dimethylpyrazole phosphate (DMPP) increase soil inorganic N retention, reduce N_2O and NO_3^- losses, and increase yields by 5-10 % across systems (Abalos et al. 2014, Rose et al. 2018, Park et al. 2021, Tufail et al. 2023, Wang et al. 2024). Evidence from dairy effluent and slurry-based systems further supports the capacity of inhibitors to improve N-use efficiency without compromising forage or grain yields (Cowley et al. 2019, Franzluebbers 2020, Mdlambuzi et al. 2021, Cosentino et al. 2024, Sorecha et al. 2025).

Table 4. Wheat shoot dry matter production, nitrogen uptake, and grain yield under cattle slurry (CS) management strategies in no-tillage system.

Experiment I	Dry matter production	Nitrogen uptake	Grain yield
Treatments*		kg ha^{-1}	
Control	2,125 c	20.90 d	398.8 c
NPK	3,259 a	50.10 bc	828.3 b
CSs	2,927 b	45.86 c	862.3 b
CSs + DCD	3,167 ab	56.82 b	911.8 ab
CSi	3,087 ab	45.78 c	920.9 ab
CSi + DCD	3,355 a	68.63 a	962.7 a
CV %	4.50	13.50	12.24
Experiment II			
Control	3,835.50 d	74.65 e	1,222.34 c
NPK	8,220.40 a	202.46 ab	2,269.14 b
CSs	7,302.10 b	165.50 cd	2,133.83 b
CSs + DCD	7,783.80 ab	184.04 bc	2,126.22 b
CSi	7,556.95 b	150.69 d	2,080.95 b
CSi + DCD	8,180.60 a	215.90 a	2,546.88 a
CV %	24.64	12.8	8.27

* NPK: mineral fertilizer; CSs: cattle slurry applied to the soil surface; CSi: cattle slurry injected into the soil; DCD: dicyandiamide. Means followed by the same letter in a column do not differ significantly according to the Tukey test ($p < 0.05$).

The superior agronomic performance of CSi + DCD is also in line with long-term trials in wheat and mixed rotations, where organic fertilization with manure or compost, often combined with legumes, matched or exceeded yields obtained with mineral N alone (Sørensen & Amato 2002, Gutser et al. 2005, Ball-Coelho et al. 2006, Meade et al. 2011, Sieling et al. 2014, Fontaine et al. 2022, Kristensen et al. 2022, Salehi et al. 2025). Recent results from organic wheat systems in the northern Great Plains show that cattle manure can sustain or increase grain yield and agronomic performance relative to mineral N fertilization programmes (Carr et al. 2025). Our findings extend this evidence to subtropical no-tillage wheat, demonstrating that dairy slurry, when strategically injected and combined with DCD, can rival or outperform NPK in both yield and environmental performance.

The nitrogen efficiency indices (agronomic nitrogen efficiency, apparent nitrogen recovery, physiological efficiency and nitrogen-use efficiency; Table 5) provide an integrated assessment of treatment performance and reinforce the advantages of CSi + DCD. In both soils, CSi + DCD achieved the highest agronomic efficiency and apparent N recovery, exceeding NPK by 1.23 kg of grains kg^{-1} of N in the experiment I and 2.53 kg of grains kg^{-1} of N in the experiment II, showing clear gains in apparent nitrogen recovery. These results confirm that subsurface slurry application combined with nitrification inhibition maximizes plant recovery of applied N and improves the conversion of absorbed N into grain production, even under rainfall regimes that typically enhance N losses.

Table 5. Agronomic nitrogen efficiency (ANE), apparent nitrogen recovery (ANR), physiological efficiency (PE), and nitrogen-use efficiency (NUE) in wheat under cattle slurry (CS) application in no-tillage systems.

Experiment I	ANE	ANR	PE	NUE
	%			
Control	-	-	-	-
NPK	2.9 b	27.2 bc	39.8 a	10.3 ab
CSs	3.3 b	23.4 c	33.2 ab	7.3 d
CSs + DCD	3.8 ab	33.4 b	29.5 ab	9.5 bc
CSi	3.7 ab	23.4 c	37.9 a	8.8 c
CSi + DCD	4.2 a	44.1 a	25.4 b	11.2 a
Experiment II	EAN	RAN	EF	EUN
Control	-	-	-	-
NPK	9.5 b	116.2 ab	34.5 a	39.9 a
CSs	8.3 b	82.6 cd	38.7 a	31.5 b
CSs + DCD	8.2 b	99.4 bc	36.4 a	35.9 ab
CSi	7.8 b	69.1 d	38.0 a	24.7 c
CSi + DCD	12.1 a	128.5 a	30.8 a	39.5 a

* NPK: mineral fertilizer; CSs: cattle slurry applied to the soil surface; CSi: cattle slurry injected into the soil; DCD: dicyandiamide. Means followed by the same letter in a column do not differ significantly according to the Tukey test ($p < 0.05$).

Such responses are in agreement with global syntheses reporting that nitrification inhibitors reduce N_2O emissions and nitrate leaching while increasing nitrogen-use efficiency by 10-15 % and yields by 5-10 % (Abalos et al. 2014, Rose et al. 2018, Guo et al. 2022, Taghizadeh-Toosi et al. 2023). Meta-analytical work indicates that DCD tends to be particularly effective in clayey and loamy soils, whereas DMPP may perform better under alkaline or sandy conditions (Guo et al. 2022, Tufail et al. 2023), which helps to explain the strong agronomic response of CSi + DCD in the Oxisol. Although some studies in Brazilian Oxisols have reported limited effects of DCD on N_2O emissions from urine patches (Mazzetto et al. 2015), the clear yield and efficiency gains observed here suggest that its performance is highly context-dependent and can be enhanced when combined with injected dairy slurry rather than surface-applied excreta.

The nitrogen-use efficiency values observed in this study fall within or above the typical range reported for cereals under combined mineral and organic fertilization (Gutser et al. 2005, Meade et al. 2011, Sieling et al. 2014, Cassim et al. 2024). Lower efficiencies in some treatments can be attributed to NH_3 volatilization and nitrate leaching under high rainfall, as widely described in slurry management and greenhouse gas studies (Huygens et al. 2022, Manley et al. 2022, Taghizadeh-Toosi et al. 2023, van der Weerden et al. 2023). Even under these challenging conditions, CSi + DCD maintained a high agronomic nitrogen efficiency, apparent nitrogen recovery, and nitrogen-use efficiency, underscoring the robustness of this strategy for improving N retention and use efficiency in subtropical no-till wheat.

At the global scale, only about one-third of anthropogenic N inputs are recovered in harvested products, whereas the remainder is lost to the environment as NH_3, NO_x, N_2O, NO_3^- and other reactive forms, contributing to air and water pollution and climate forcing (Bouwman et al. 2013, Buchen-Tschiskale et al. 2023, Peng et al. 2023, IEA 2024). Livestock systems are particularly important, accounting for a large share of NH_3, N_2O and NO_x emissions along global supply chains (Aneja et al. 2020, Uwizeye et al. 2020, Bray et al. 2021, Mazur et al. 2021, Bratti et al. 2022). Improving the management of cattle slurry in crop-livestock systems is therefore crucial to closing N cycles and reducing the environmental footprint of food production (Whitehead 1995, Mdlambuzi et al. 2021, Yemata & Mengistu 2024, De Boer et al. 2024).

Our results show that, in subtropical no-tillage wheat, integrating slurry injection with nitrification inhibition can simultaneously reduce NH_3 emissions to levels comparable to or lower than those of synthetic fertilizers, increase N uptake and grain yield, and enhance N-use efficiency, particularly in sandy or well-drained soils. These outcomes are aligned with the concept of yield-scaled mitigation of N losses - reducing emissions per unit of product rather than in absolute terms alone (Sanz-Cobena et al. 2014, Peng et al. 2023, Cassim et al. 2024). They also reinforce the notion that strategies combining improved placement, inhibitors and partial substitution of mineral fertilizer with organic N can play a central role in the sustainable intensification of crop-livestock systems in southern Brazil and similar regions (Sørensen & Amato 2002, Sieling et al. 2014, Damian et al. 2018, Carr et al. 2025).

CONCLUSIONS

1. The effects of cattle slurry (CS) on ammonia volatilization and wheat performance under no-tillage conditions varied according to soil type and application method;
2. In the Oxisol, slurry injection did not reduce pre-sowing NH_3-N volatilization, but increased N uptake and grain yield, when compared with surface application;
3. In the Ultisol, slurry injection markedly reduced pre-sowing NH_3-N losses, confirming a greater mitigation potential in sandy, well-drained soils;
4. Across both experimental sites, injected cattle slurry combined with the nitrification inhibitor dicyandiamide (DCD) (CSi + DCD) consistently enhanced N uptake, grain yield and all nitrogen-use efficiency indices relative to surface-applied slurry;
5. Compared with mineral fertilization, the NPK treatment resulted in the highest NH_3-N emissions, whereas slurry-based strategies - especially CSi + DCD - achieved equal or superior yields with lower N losses;
6. Overall, integrating slurry injection with nitrification inhibition using DCD represents an effective strategy to improve nitrogen-use efficiency and reduce emissions in subtropical no-tillage wheat systems.

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