frontiers | Frontiers in Environmental Science

TYPE Original Research
PUBLISHED 09 October 2025
DOI 10.3389/fenvs.2025.1656231

OPEN ACCESS

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RECEIVED 29 June 2025
ACCEPTED 19 September 2025
PUBLISHED 09 October 2025

CITATION
Kumar S, Bhatia A, Drewer J, Rees RM, Sharma S, Kumar V, Tomer R, Rahman MM and Sutton MA (2025) Mitigating ammonium and nitrate leaching in rice-wheat crop rotation: efficacy of neem coated urea and compost co-application. *Front. Environ. Sci.* 13:1656231. doi: 10.3389/fenvs.2025.1656231

Mitigating ammonium and nitrate leaching in rice-wheat crop rotation: efficacy of neem coated urea and compost co-application

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Introduction: Leaching losses of applied N are an indirect source of nitrous oxide (N_2O) emission, a major greenhouse gas emitted from fertilized soils. Mineral nitrogen (N) leaching research has largely concentrated on nitrate (NO_3^-), while ammonium (NH_4^+) leaching remains understudied. The cultivation conditions for rice and wheat are distinctly different, impacting the leaching losses of both NH_4^+ and NO_3^-.
Methods: This study investigated the influence of different N treatments, i.e., no-N control, neem coated urea (NCU-N 100%; 120 kgN ha^{-1}), 60 kgN ha^{-1} Neem coated urea +30 kgN ha^{-1} compost (75% N); 90 kgN ha^{-1} Neem coated urea +30 kgN ha^{-1} compost (100% N) and 120 kgN ha^{-1} Neem coated urea +30 kgN ha^{-1} compost (125% N) in comparison with prilled urea (PU, 120 kgN ha^{-1}). Compost was applied @ 2.6 tonnes ha^{-1} to all integrated treatments to provide 30 kgN ha^{-1}.
Results and discussion: The peak concentration of soil NH_4^+ and NO_3^- was delayed by two-three days in NCU and integrated NCU + compost compared to PU in both rice and wheat, due to the slow-release effect of neem oil coating in NCU. In rice, the percolation rate of water was almost half than in wheat soil. The mineral N leaching loss in rice ranged from 0.4 to 4.6 kg NH_4^+-N ha^{-1} and 0.46–5.12 kg NO_3-N ha^{-1} during the 2 years. In an annual rice-wheat cycle, the total N leaching loss was 6.2%–7.0% of the applied N fertilizer. The total mineral N loss was higher in PU than NCU by 7.8% and 10% in rice and wheat, respectively. Substitution of 25% of mineral N with compost decreased the total N leaching by 14.8% and 10.3% in rice and wheat, respectively, compared to NCU (100%). The crop N uptake increased significantly ($p < 0.05$) with NCU and integrated NCU + compost (100%) over PU. Application of 125%-N significantly increased the total mineral N leaching. The total mineral-N leaching loss was 15.9% higher in rice than wheat across the different treatments. The integrated N application, combining 75% NCU and 25% compost, can reduce mineral-N leaching, improve nitrogen uptake and maintain economic yields in rice-wheat cropping system.

KEYWORDS

ammonium N leaching, nitrate N leaching, soil nitrate-N, soil ammonium-N, neemcoated urea (NCU), compost, integrated nutrient management

Introduction

Rice and wheat are grown widely on almost all continents, making them globally essential cereal crops playing a crucial role in ensuring food security worldwide (Dey, 2020). The Rice-wheat cropping system (RWCS) is widely cultivated in East and South Asia with an estimated area of 26 and 10 million ha, respectively (He et al., 2022; Jat et al., 2020) and is the key to the food security of the region.

To meet the need of the global food security, and increase the production of wheat and rice crops the consumption of synthetic nitrogen (N) fertilizer for crop cultivation has been increasing over the years (Bhatia et al., 2010; Keikha et al., 2023). China and India are the two largest consumers of chemical fertilizers, consuming 42.3% of the global N fertilizer in 2021 (Sapkota and Takele, 2023). Over-use of N fertilizer may negatively affect soil, groundwater, surface water bodies and impact the environment (Chatterjee et al., 2024). The applied N fertilizers undergo a combination of crop uptake, soil immobilization, and environmental N losses via ammonia volatilization, nitrous oxide emissions, N leaching, and runoff, resulting in a low N use efficiency (**NUE**) ranging from 30%–40% (Dalgaard et al., 2012; Wu and Ma, 2015; Pathak et al., 2016; Juttu et al., 2021; Cowan et al., 2021; Chakrabarti et al., 2024).

Nitrate leaching, accounts for a significant portion of applied N (10%–30%), is a major N loss pathway in fertilized soils. It is a primary contributor to both groundwater pollution and surface water eutrophication, and indirect nitrous oxide losses (IPCC, 2006). The leaching of available nitrate (NO_3^--N) through the soil profile poses significant challenges to environmental health and agricultural productivity (Singh and Singh, 2001; Xiong et al., 2010; Reading et al., 2019; Song et al., 2021). Consistent N leaching removes NO_3^- from the root zone, hindering crop growth and yields (Padilla et al., 2018; Khan et al., 2023). However, the extent and rate of N leaching in soil are highly variable, influenced significantly by agri-management factors like irrigation and N fertilizer, as well as soil, crop and climate (Shi et al., 2020; Ivić et al., 2021; Zhao et al., 2022; Khan et al., 2023). Zhang et al. (2013) found that average NO_3^--N concentrations in groundwater were higher than 10 ppm in wells near the agricultural ecosystems of wheat, corn and cotton due to irrigation coupled with intensive N fertilizer applications.

Given that rice requires three times more water than wheat per kg of grain (Bouman, 2009), NO_3^--N leaching losses may significantly differ in rice and wheat crops. In rice-wheat rotations, dry-wet conditions facilitate the movement of NO_3^- from the soil surface into the groundwater (Liu et al., 2010). When the soil is flooded after the harvest of wheat prior to the transplanting of rice, the accumulated NO_3^- within the soil becomes prone to leaching downward. Di and Cameron (2000) found a quadratic relationship between potentially leachable N and annual leaching losses; as leachable N increased, annual N leaching followed a parabolic, rather than linear, pattern.

In today's intensive agricultural systems, no single N source may be able to meet crop's N demand. Integrated Nitrogen Management (INM) addresses this by combining synthetic and organic sources, such as compost, to enhance soil fertility, microbial activity, and increase nutrient uptake (Baruah and Baruah, 2015; Paramesh et al., 2023). By integrating good quality, decomposable, and local organic materials, INM provides an economical and sustainable approach to nutrient supply, reducing dependence on external fertilizers, protects soil health, and improves both nitrogen use efficiency and groundwater quality (Selim, 2018; Wang et al., 2019; Song et al., 2020; Paramesh et al., 2023). INM significantly reduces nitrogen losses, including emissions of reactive nitrogen species and leaching losses (Bhatia et al., 2023; Zhang et al., 2012; Yao et al., 2019; Mohanty et al., 2020). The reduction in N leaching can be attributed to stimulated microbial growth and temporary nutrient immobilization (Lehmann and Schroth, 2002). Studies have reported 30%–70% lower annual NO_3^--N leaching losses with INM in rice-wheat system (Aulakh et al., 2000; Yu-Hua et al., 2007; Zhang et al., 2017) and maize-wheat systems (Huang et al., 2017), with some leached NO_3^- potentially utilized by subsequent crops.

Leaching losses of NH_4^+ in crops has received considerably less attention than NO_3^-. Leaching losses of NH_4^+ are not common, as NH_4^+ is rapidly converted into NO_3^- under aerobic conditions in the soil. Nitrate may be rapidly lost through leaching in the acid soils, and through denitrification in the neutral and alkaline soils, whereas NH_4^+-N mostly remains in soil with little leaching (Dai et al., 2023). At lower soil pH levels, there is increased NH_4^+ retention onto soil colloids (Sarkar and Haldar, 2009). The cation exchange capacity (CEC) of soil can affect NH_4^+ leaching, especially in rice fields. Soils with low CEC tend to retain less NH_4^+, thereby increasing the amount of ion that can be leached away with irrigation water.

In India the use of Neem coated urea (NCU) is mandatory for agricultural use, and it has effectively replaced prilled urea use in the country. NCU with a coating of 350 ppm neem oil over urea granules, is a slow-release fertilizer having nitrification inhibitory properties has been often reported to reduce nitrous oxide emissions from cropped soils (Cowan et al., 2021; Paul et al., 2024). Use of nitrification inhibitor Dimethylphenylpiperazinium (DMPP), applied at low concentrations, was evaluated by Díez-López et al. (2008), and significant reductions in NO_3^- leaching were reported in maize with no significant change in yield. However, in irrigated rice, the leaching of soil NH_4^+-N may also occur, especially with the application of nitrification inhibitors, which help in retaining NH_4^+ in soil for a longer duration (Drury et al., 2017). The leaching losses in rice-wheat system, which offers very diverse cropping conditions in an annual crop cycle, have not been evaluated under the integrated application of slow-release coated urea and organic nitrogen. Thus, the objectives of this study were to assess the impact of integrated application of Neem coated urea (NCU) and compost on (a) concentration of soil ammonium (NH_4^+) and nitrate (NO_3^-) (b) leaching losses of ammonium (NH_4^+) and nitrate (NO_3^-), and (c) grain yield and nitrogen uptake in rice-wheat crop rotation.

Materials and methods

Experimental site details

The field experiment was carried out for 2 years growing rice in the Kharif (rainy season, July to October) and wheat in the Rabi (winter season, November to April) during 2021–22 and 2022–23 at the experimental farm of the ICAR-Indian Agricultural Research

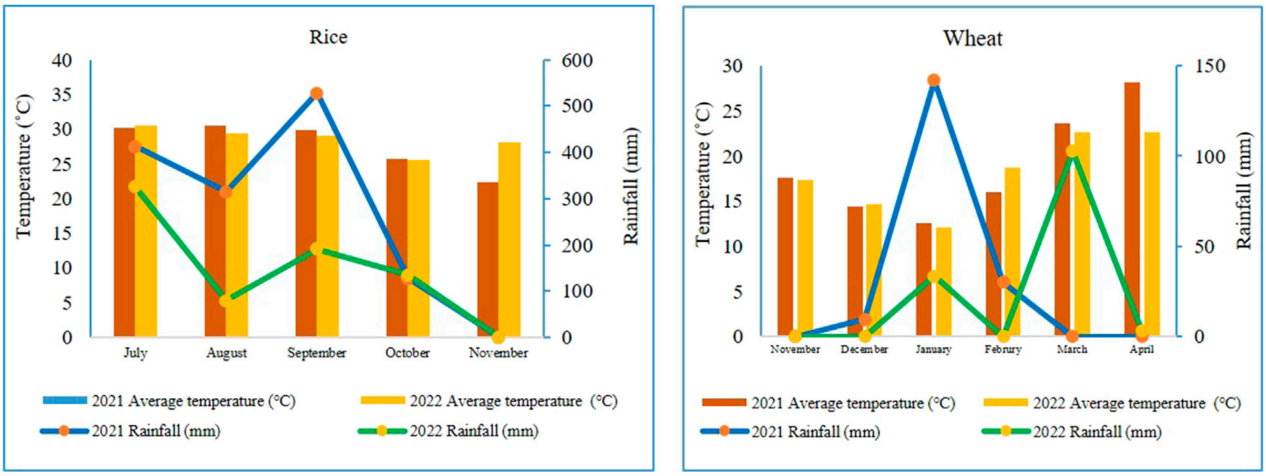

FIGURE 1
Temperature and Rainfall during rice and wheat cultivation period.

TABLE 1 Nitrogen treatments and their details.

Treatment code	Treatment details	% Of recommended N applied
CONT	Control	nil
PU	120 kg N ha^{-1} Prilled urea	100%
NCU	120 kg N ha^{-1} Neem coated urea	100%
N50C25	60 kg N ha^{-1} Neem coated urea + 30 kg N ha^{-1} compost	75%
N75C25	90 kg N ha^{-1} Neem coated urea + 30 kg N ha^{-1} compost	100%
N100C25	120 kg N ha^{-1} Neem coated urea + 30 kg N ha^{-1} compost	125%

Institute (IARI), New Delhi, India (Supplementary Figure S1). The site is located at 28∘40′N and 77∘12′E, with an altitude of 228 m above mean sea level in the Indo-Gangetic alluvial tract. The region experiences a subtropical, semi-arid climate characterized by hot, dry summers and mild winters, with an annual rainfall of 750 mm, primarily occurring from July to September. The temperature and rainfall data, were collected using the sensors attached to the eddy covariance flux tower on the experimental site.

During the rice cultivation seasons of 2021 and 2022, the mean maximum and minimum temperatures from July to October were 33.8 °C and 24.5 °C in 2021, and 33.7 °C and 23.9 °C in 2022, respectively. The total rainfall during the rice cultivation period was 1382 mm and 751 mm, during the 2 years (Figure 1). During wheat cultivation (November to April), the mean maximum temperatures ranged from 25.5 °C to 27.1 °C and mean minimum temperatures from 10.3 °C to 10.9 °C. Total rainfall was 139 mm in 2021–22 and 181.5 mm in 2022–23.

The soil of the experimental site is categorized as well drained, with the groundwater table at approximately 6.6 and 10 m below the surface during the rainy and dry seasons, respectively. The soil type is Ustochrept and texture is loamy (21% clay, 33% silt and 46% sand). The soil of the experimental site is alluvial in origin having a bulk density (BD) of 1.42 g cm^{-3}, pH (1:2 soil: water) 8.1, organic carbon content 4.4 g kg^{-1}, total N 0.30 g kg^{-1}, Olsen P 0.008 g kg^{-1}, ammonium acetate extractable K 0.14 g kg^{-1}, electrical conductivity 0.4 dS m^{-1} and cation exchange capacity of (4.8 cmol (C) kg^{-1}),. Soil physico-chemical properties were determined by standard procedures as given in Page et al. (1982).

Treatments, experimental design and crop cultivation practices

A 2-year experiment in rice-wheat crop rotation was conducted using six treatments with four replicate plots (7 m × 6 m) at farms of ICAR-Indian Agricultural Research Institute, New Delhi. The treatments were control (no N); neem coated urea (NCU, 100%N @ 120 kg N ha^{-1}); prilled urea (PU, 100%N @ 120 kg N ha^{-1}); and three integrated treatments: 60 kg N ha^{-1} Neem coated urea +30 kg N ha^{-1} compost (75% N); 90 kg N ha^{-1} Neem coated urea +30 kg N ha^{-1} compost (100% N) and 120 kg N ha^{-1} Neem coated urea +30 kg N ha^{-1} compost (125% N) growing rice in the rainy season and wheat in the winter season, in a completely randomized block design (Table 1). The chemical N fertilizer was applied in 3/4 split doses at key crop stages (details are given in Table S, Supplementary Material). In the three integrated NCU and

TABLE 2 Composition of leaf compost.

Parameter	Value
pH (1:5 sample: water)	7.34
Electrical conductivity (EC)	0.85 mS/cm
Total carbon	33.2%
Total nitrogen	1.15%
Total phosphorous	0.06%
Total potassium	0.47%
C: N ratio	28.87

compost treatments, 75, 100% and 125% N was applied through integrated application of NCU (46% N) and leaf compost having 1% N on dry weight basis (Table 2). Compost was applied @ 2.6 tonnes ha^{-1} to provide 30 kg N ha^{-1}). Neem coated urea (NCU) was commercially procured (IFFCO make) having a neem oil coating of 350 ppm over urea granules. The leaf compost was applied 5–7 days before transplanting/sowing of crops. Neither rice nor wheat crops received basal urea N fertilizer; however, each plot received a basal application of 26 kg P ha^{-1} and 50 kg K ha^{-1}. In rice, the P and K was applied before puddling of soil, while in wheat, it was broadcast on soil surface and incorporated using a cultivator. Rice variety PB1718 and wheat variety HD2967 was cultivated in both years. Excessive rainfall, (630 mm higher than the normal average) was observed in 2021 Kharif season (Figure 1). The plots were irrigated at 2–3 days' interval days in rice and 15 and 25 irrigations were given in 2021 and 2022, respectively. In wheat 6 and 7 irrigations were applied during the two study years. Rice crop was transplanted in the third week of July and harvested in the second week of November, whereas wheat was sown in the last week of November and harvested in the first week of April during the 2 years. The crops were cultivated following standard farming practices of the region. Heavy rainfall along with high wind speed during October 2022 caused partial lodging of the rice crop under all the treatments.

Estimation of soil ammonium and nitrate N

Soil samples (0–15 cm depth) were collected in triplicate every 8–10 days throughout the growing period of both rice and wheat crops, using a 5.7-cm diameter core sampler for soil NH_4^+-N and NO_3^--N analysis. After each split N application, additional samples were taken on alternate days for 1 week. The soil samples were extracted with 2 M KCl and filtered with Whatman Grade 42 filter paper. And the NH_4^+ and NO_3^- concentration measured by colorimetric methods using N flow auto analyser (San++, Skalar, Netherlands). NO_3^- was determined by reducing it to NO_2^- using a copperized cadmium column. The nitrite was then detected by diazotizing with sulfanilamide and coupling with N-(1-naphthyl) ethylenediamine dihydrochloride and measuring absorbance at 520 nm (Knepel, 2003). NH_4^+ was measured by using salicylate and dichloroisocyanurate in an alkaline phosphate buffer, and measuring the absorbance of the indophenol complex at 578 nm by modified Berthelot method (Krom, 1980).

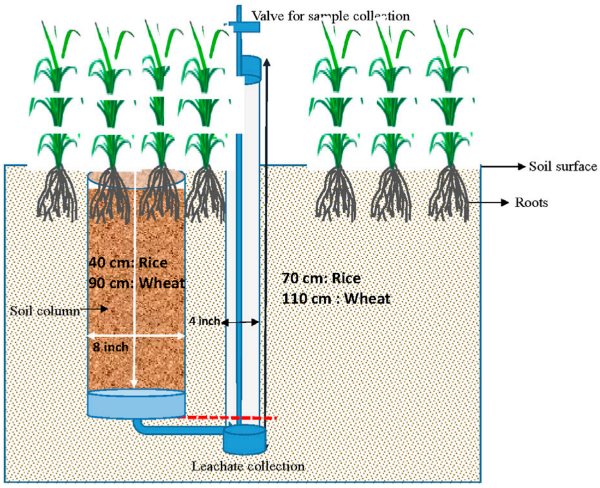

FIGURE 2
Setup for sampling of leachates in rice and wheat crops.

Collection of leachate samples

Locally fabricated lysimeters were installed in three replicate plots of each treatment, respectively to collect the leached water samples at 40 cm and 90 cm below the surface level in rice and wheat crops, respectively. The lysimeter was fabricated using two HDPE pipes, with 20 cm (8-inch) and 10 cm (4-inch) diameters. The 20 cm diameter pipe was installed at 40 and 90 cm depth below the surface with soil column inside it, whereas the 10 cm diameter pipe was placed in parallel at a depth of 70 cm and 110 cm in rice and wheat, respectively. The soil column was extracted and packed carefully with minimal disturbance to maintain the soil bulk density in the 20 cm pipe. The upper part of the 20 cm pipe was open and aligned with the soil surface, as shown in Figure 2. A nipple installed at the end of the 20 cm pipe connected both the tubes with the help of a soft tube (Figure 2). The leachate from the 20 cm soil column was collected in the 10 cm reservoir pipe through the soft connector tube. The 10 cm (diameter) pipe was placed 15-cm above the surface level and capped to avoid mixing irrigation and rainfall water with leachate samples. A hole was drilled on the top lid of the 10 cm pipe for inserting the PTFE tubing with stop cork for collecting the leachate samples with the help of a hand vacuum pump. The leachate collected was immediately transferred to HDPE plastic bottles and capped.

The leachate was collected every 8–10 days in rice and every 12–15 days in wheat and the volume of leachate collected was recorded. To determine the percolation rate of water the total amount of leachate collected in each crop season was divided by the total number of days of leachate collection during the respective season (Islam et al., 2024).

Estimation of leaching loss of mineral N

The leaching loss of mineral N was determined by measuring the concentrations of NH_4^+-N and NO_3-N (NO_3^- and NO_2^- combined) in the leachate samples collected from each replicated treatment plot at different time intervals during the crop growth period. The collected leachate samples were filtered through the Whatman No. 42 filter paper and directly analyzed by measuring the concentrations of NH_4^+-N and NO_3^--N by colorimetric methods using an N-flow auto-analyzer (San++, Skalar Netherlands). NO_3^- was determined by reducing it to NO_2^- (Knepel, 2003) as per the procedure given in the section above. NH_4^+ was quantified by measuring the absorbance of the indophenol complex at 578 nm by modified Berthelot method (Krom, 1980) as per the detailed procedure given in the above section. The concentrations of NH_4^+-N and NO_3^--N were quantified in mg L^{-1}. The readings of blank were subtracted from the sample values. The leaching losses of mineral N was a sum of the measured concentrations of NH_4^+-N and NO_3^--N in the collected leachate sample during each sampling event.

The leachate samples were collected 11 times during both rice and wheat crop growth period in each year. The total NH_4^+-N and NO_3^--N leaching during the entire crop growth period was estimated using the below Equation 1.

$$\text{Total N leached}\left(NH_4^+\text{-N and } NO_3^-\text{-N}\right)(\text{mg N}) = \sum_{i=1}^{n}(Ci \times Vi) \quad (1)$$

Where, Ci is the concentration of sum of NH_4^+-N and NO_3^--N in mg L^{-1} present in the collected leachate at time i, Vi is the amount of leachate (L) collected at time i, and n is the number of leachate collection events.

The amount of NH_4^+-N and NO_3^--N leached from soil (mg N m^{-2}) during the entire crop growth period was calculated by dividing the total amount of N leached (mg N) by the soil surface area of the lysimeter pipe (m^2). Finally, the seasonal or cumulative N leaching loss of NH_4^+-N and NO_3^--N during the crop growth period was reported as kg N ha^{-1}.

Crop biomass and grain yield and total nitrogen uptake

Yields of rice and wheat were determined by harvesting a 1 m^2 area in each plot in triplicate. The grains were separated from the straw, dried, and weighed. Grain moisture was immediately determined after weighing (14%). The straw and grain samples were analyzed for total N content using the Kjeldahl method (Page et al., 1982). The N uptake by crops was estimated by using the following Equation 2:

Nitrogen uptake by above ground biomass (kg ha^{-1}) =

$$\frac{\text{Grain yield}\left(\frac{kg}{ha}\right) \times \text{Grain N }(\%) + \text{Straw yield}\left(\frac{kg}{ha}\right) \times \text{Straw N }(\%)}{} \quad (2)$$

Statistical analysis

Analysis of variance (ANOVA), using both one-way and two-way methods, was performed to assess significant differences in N treatment effects. In the one-way ANOVA, treatment effects were independently analyzed for the 2021–22 and 2022–23 seasons for rice and wheat. For the two-way ANOVA, a linear mixed-effects model was employed, incorporating treatment as a fixed effect and year as a random effect. This approach accounted for temporal variability, allowing for year-to-year fluctuations in the response variable and providing more precise estimates of treatment effects. Additionally, *post hoc* comparisons were conducted using Tukey's Honest Significant Difference (HSD) test at a significance level of p = 0.05 (Tukey, J. W. 1949). We also evaluated the effect of the of the different N fertilizer application on soil NH_4 and NO_3- N leaching by repeated measures ANOVA. The N treatments was between subject factor, and the NO_3/NH_4-N leachate collected at each sampling event as the within subject variable. The normality of distribution of leachate data was examined before the repeated measures ANOVA using Shapiro–Wilk's test. The Greenhouse–Geisser adjusted F-values were used to test the significance of leachate collection events under different treatments and their interactions. All statistical analyses were performed using the SPSS Statistics 25.0 software.

Results

Ammonium and nitrate N concentration in rice and wheat soil

In the study conducted over two rice seasons, the synthetic fertilizer NCU and PU was applied to rice crop in four splits during 2021 and three splits in 2022. Each application of urea resulted in corresponding peaks of NH_4^+ in the soil for all fertilized treatments in both years (Figure 3). In 2021, the first split application of chemical N occurred 18 days after transplanting, which caused an increase in soil of NH_4^+ content (Figure 3). While the peak NH_4^+ concentration was observed in the PU treatment on day 20, the slow-release effect of NCU delayed the peak concentration by 2 days compared to PU (Figure 3). In year 2021, the highest NH_4^+ concentration was observed in the N100C25 treatment (100% NCU + 25% Compost) at 30.26 kg N ha^{-1}, which was 2 days after the peak of 29.26 kg N ha^{-1} in the PU treatment in. In the integrated 100% treatment (N75C25), the NH_4^+ concentration was lower than in the NCU (100%) alone treatment following each split N application. In the second year of the study, significantly higher NH_4^+ concentrations in the rice soil were observed in the NCU, N75C25, and N100C25 treatments compared to the PU treatment.

NO_3^- levels (NO_3^- + NO_2^- combined) were much lower in soil than NH_4^+ in both the years during rice growth period (Figure 3). Highest NO_3^- was observed in N100C25 (18.81 kg N ha^{-1}) followed by PU (16.65 kg N ha^{-1}) after the first split of N fertilizer application. Under the integrated treatments with NCU and compost, a slow-conversion to NO_3^- was observed compared to PU in both rice and wheat crops. In 2022, the release pattern of NH_4^+ and NO_3^- in rice soil was similar to 2021 after each split of N fertilizer application.

During 2021–22 wheat crop, the highest NH_4^+ concentration of 32.5 kg N ha^{-1} was recorded in the integrated N100C25 (100% NCU + 25% Compost) treatment, followed by T5 (75% NCU + 25% Compost) and the lowest in the N50C25 among the fertilized treatments (Figure 4). The NO_3^- levels were similar in 100% NCU and the integrated N75C25 treatment in wheat in both the years.

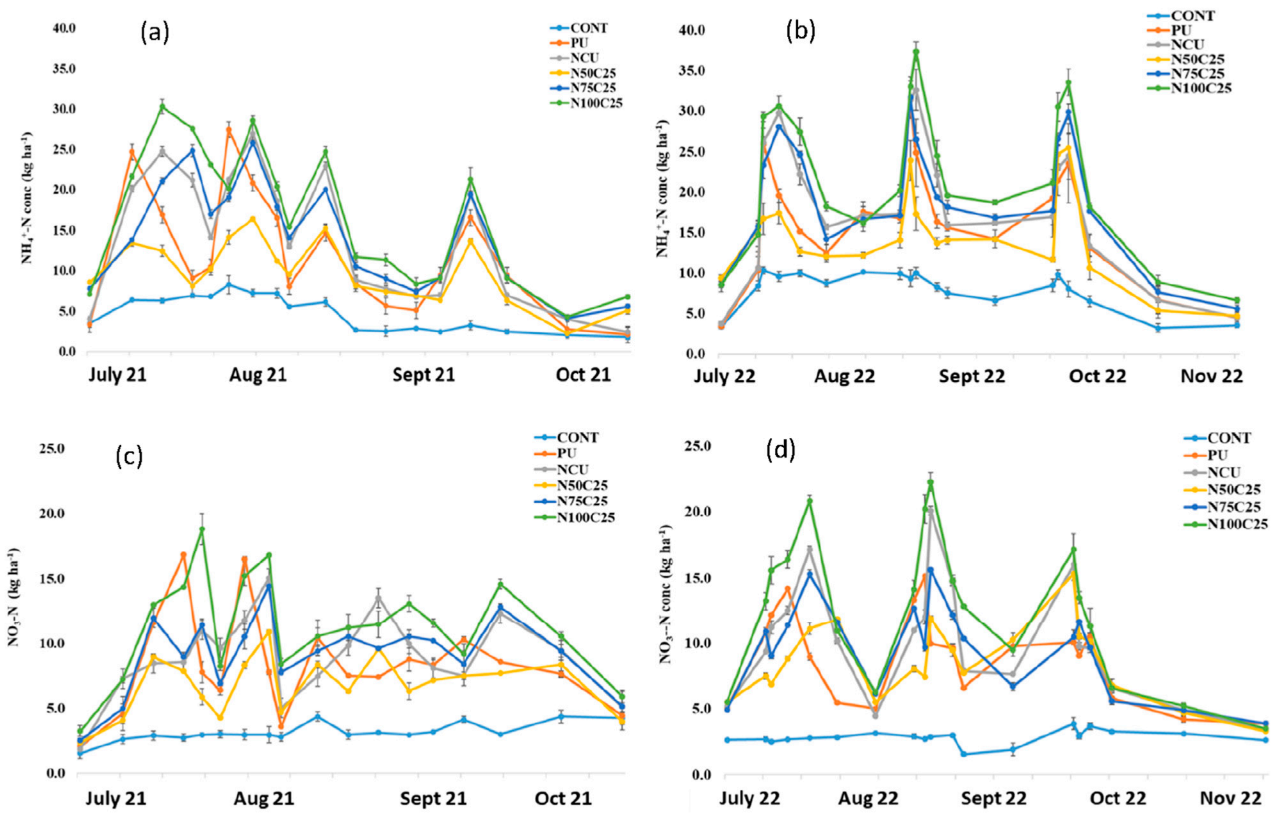

FIGURE 3
Temporal variation in soil NH_4^+-N levels in rice during **(a)** 2021; **(b)** 2022; temporal soil NO_3^--N levels in rice during **(c)** 2021; **(d)** 2022 (error bars represent standard error). PU: Prilled urea (PU); NCU: Neem coated urea 100%; N50C25: NCU 50% + 25% Compost; N75C25: NCU75% + 25%Compost; N100C25: NCU100% + 25%Compost.

The variation in the concentration of NH_4^+ and NO_3^- in soil during the crop growth period of rice and wheat under the different treatments during the two study years is shown in Figure 5. In rice, the maximum 2 year average NH_4^+ levels was observed in N100C25 treatment followed by NCU, N75C25, PU and N50C25. Similar trend among the treatments was observed for soil NO_3^--N concentration in rice. The mean soil NH_4^+ in rice was significantly ($p < 0.05$) higher in NCU and N75C25 as compared to PU during rice growth period. In wheat, the integrated treatment N75C25 treatment had higher mean NH_4^+ concentration as compared to NCU alone (100%) treatment, however the difference was not statistically different. The mean NO_3^- levels were similar in PU, NCU and N75C25 treatments during the 2 years in wheat crop. The NH_4^+ in the control plot during the two rice seasons ranged from 1.71 to 10.23 kg N ha^{-1} (Figure 5).

Percolation rate of water during rice and wheat cultivation

The percolation rate of water down the rice and wheat cropped soils under the different N treatments during 2021–22 and 2022–23 (Table 3), being almost double in wheat compared with rice. During the initial year, no significant treatment differences were observed in both rice and wheat crops. However, in the second year, the integrated compost treatments N100C25 had lower percolation than the PU and NCU alone treatments in both rice and wheat crop.

Ammonium and nitrate nitrogen leaching loss

Losses of both NH_4^+ and NO_3^- were observed in rice, whereas in wheat, NO_3^- losses predominated with only marginal NH_4^+ loss (Figures 5, 6). The different treatments had significant effects on NH_4^+ and NO_3^- leaching in rice, and on NO_3^- leaching in wheat (Table 4). In rice, the cumulative NH_4^+ in leachate ranged from 0.34 to 4.10 kg ha^{-1} in 2021, and 0.52–5.27 kg ha^{-1} in 2022 (Figure 6). The leaching of NH_4^+ in wheat was low, ranging from 0.19 to 1.34 kg ha^{-1} in 2021–22 and 0.08–1.25 kg ha^{-1} in 2022–23 season. Substituting 25% N with compost (N75C25) reduced NO_3^- leaching in wheat by 12.9% and NH_4^+ losses in rice by 16.9%, relative to the NCU (100%) treatment over the 2 years. The substitution of 25% N with compost in N75C25 in rice did not significantly reduce NO_3^- in the first year over NCU (100%), however, a reduction of 19.5% was observed during the second-year rice crop. The leaching losses of NH_4^+ were highest in N100C25, followed by NCU and PU, which were statistically at par ($p < 0.05$) in the 2 years. The leaching losses of NH_4^+ and NO_3^- were similar in both years and the treatment*year ($p > 0.05$) interactions was not significant in both crops (Table 4).

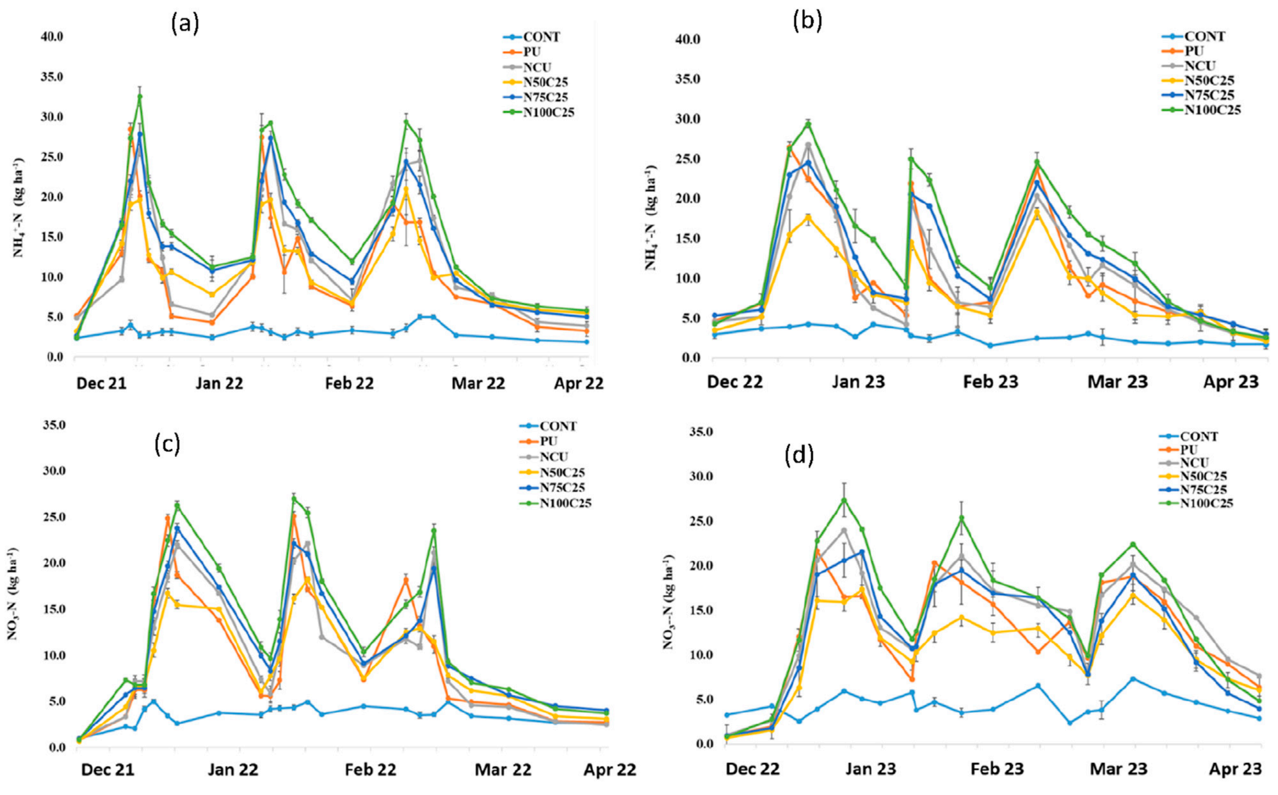

FIGURE 4
Temporal variation in soil NH_4^+ levels in wheat **(a)** 2021–22; **(b)** 2022–23; temporal NO_3^- concentrations in wheat **(c)** 2021–22; **(d)** 2022–23 (error bar represent standard error). PU: Prilled urea (PU); NCU: Neem coated urea 100%; N50C25: NCU 50% + 25% Compost; N75C25: NCU 75% + 25% Compost; N100C25: NCU 100% + 25% Compost.

The repeated measure of ANOVA indicates that the NH_4^+ and NO_3^- leached at the different crop stages differed significantly in time for both rice and wheat (Table 5). Different N treatments resulted in significantly different amount of NH_4^+ and NO_3^-leached in rice, and NO_3^-in wheat. In rice, the interaction (time*N treatment) was significant ($p < 0.05$) for NH_4^+ leached only. In wheat, the interaction (time *N treatment) was not significant for the leached amounts of both NH_4^+ and NO_3^-.

The cumulative NO_3^- and NH_4^+ leaching during the crop growth period of rice and wheat are given in Figures 6, 7, respectively. In rice crop, higher NH_4^+ loss was observed throughout the rice growth period in N100C25 during both the years, however, NO_3^- losses were similar in the PU and N100C25 treatments. In wheat crop too, the NO_3^- losses were similar for PU and N100C25 treatments throughout the crop growth period. The highest leaching losses of 7.72 kg ha^{-1} NO_3^--N was observed in the 125% integrated treatment (N100C25) in the second year in wheat crop.

Total nitrogen annual leaching loss

During both years, total leaching loss of N were higher in rice than in wheat (Table 4). The application of NCU reduced the leaching of both NH_4^+ and NO_3^- as compared to PU, however, the difference was not significant. Substitution of 25% N with compost in N75C25 had no significant effect on the total mineral N leaching in the first year, however the total N leaching reduced in the second year in N75C25 as compared to NCU alone, in both rice and wheat crops. The total annual N leaching loss was higher during the second year of experimentation, however the difference between the 2 years was not significantly different accept under N100C25 treatment (Table 6). In both crops, among the fertilized treatments the lowest annual N leaching losses were observed with 75% N application in N50C25 treatment. Total annual N losses were the highest in N100C25 treatment in both the years and were not significantly different from PU treatment in both the years.

Grain yield of rice and wheat crops

The substitution of 25% N with compost in N75C25 resulted in no significant difference in rice and wheat yields as compared to 100%NCU, accept in the first-year rice crop. The grain yield increased with application of NCU by 3.8%–7.7% than PU in both rice and wheat crops over the 2-year study period. The grain yield was significantly higher ($p < 0.01$) in N100C25 than PU and NCU treatments in rice crop (Table 7). The wheat crop also followed the same trend, maximum grain yield was observed in N100C25. With 25% less N application in N50C25, the grain yield of both rice and wheat reduced significantly ($p < 0.01$) than 100% N

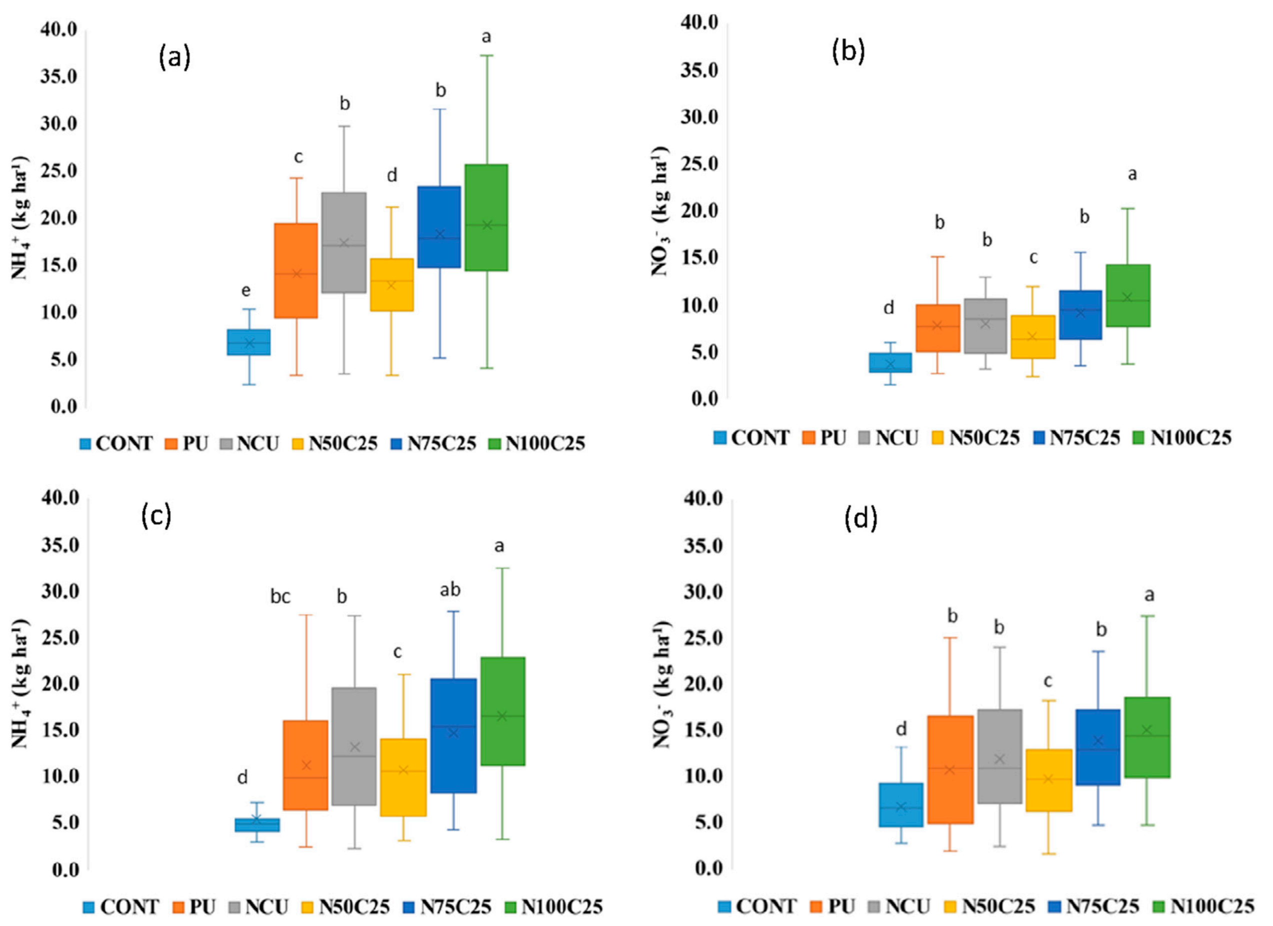

FIGURE 5
Variation in soil **(a)** NH_4^+ and **(b)** NO_3^- levels in rice; Variation in soil **(c)** NH_4^+ **(d)** NO_3^- levels in wheat under different treatments during the two-year crop growth period. Different symbol indicates significant difference ($p < 0.05$) in mean concentration. The horizontal line is the median (x) is the mean value, whiskers represent the minimum and maximum concentration, lower box and upper box represents 25 and 75 percentiles of data. PU: Prilled urea (PU); NCU: Neem coated urea 100%; N50C25: NCU 50% + 25% Compost; N75C25: NCU 75% + 25% Compost. Box plot show the variation across two study years.

TABLE 3 Percolation rate of water in rice and wheat cropped soils.

Treatment	Percolation rate (mm day^{-1})					
	Rice			Wheat		
	2021	2022	Mean	2021–2022	2022–2023	Mean
CONT	9.23 ± 0.09a	9.10 ± 0.15a	9.17 ± 0.08a	15.12 ± 0.21a	14.84 ± 0.10a	14.98 ± 0.12a
PU	9.32 ± 0.03a	9.06 ± 0.11 ab	9.19 ± 0.08a	15.25 ± 0.18a	14.66 ± 0.16 ab	14.96 ± 0.17a
NCU	9.36 ± 0.08a	9.04 ± 0.07 ab	9.20 ± 0.09a	15.29 ± 0.15a	14.68 ± 0.14 ab	14.99 ± 0.16a
N50C25	9.19 ± 0.17a	8.65 ± 0.13bc	8.92 ± 0.16 ab	15.03 ± 0.14a	14.21 ± 0.09bc	14.63 ± 0.20 ab
N75C25	9.17 ± 0.11a	8.59 ± 0.09c	8.88 ± 0.15 ab	14.92 ± 0.14a	13.96 ± 0.14c	14.44 ± 0.23b
N100C25	9.02 ± 0.16a	8.57 ± 0.05c	8.79 ± 0.13b	14.89 ± 0.08a	13.95 ± 0.20c	14.42 ± 0.23b
	Significance		Fertilizer	Year	Fertilizer*Year	
	Percolation rate in rice		**	***	ns	
	Percolation rate in wheat		***	***	ns	

*Mean ± Standard error (n = 3); Different lowercase letters in a column indicate significant differences ($p < 0.05$) among the treatments in each column. The *post hoc* analysis was done using Tukey's Honest Significant difference (HSD) Test. PU: Prilled urea (PU); NCU: Neem coated urea 100%; N50C25: NCU, 50% + 25% Compost; N75C25: NCU, 75% + 25% Compost; N100C25: NCU, 100% + 25% Compost; ns: non-significant $p > 0.05$; **$p \leq 0.01$; ***$p \leq 0.001$.

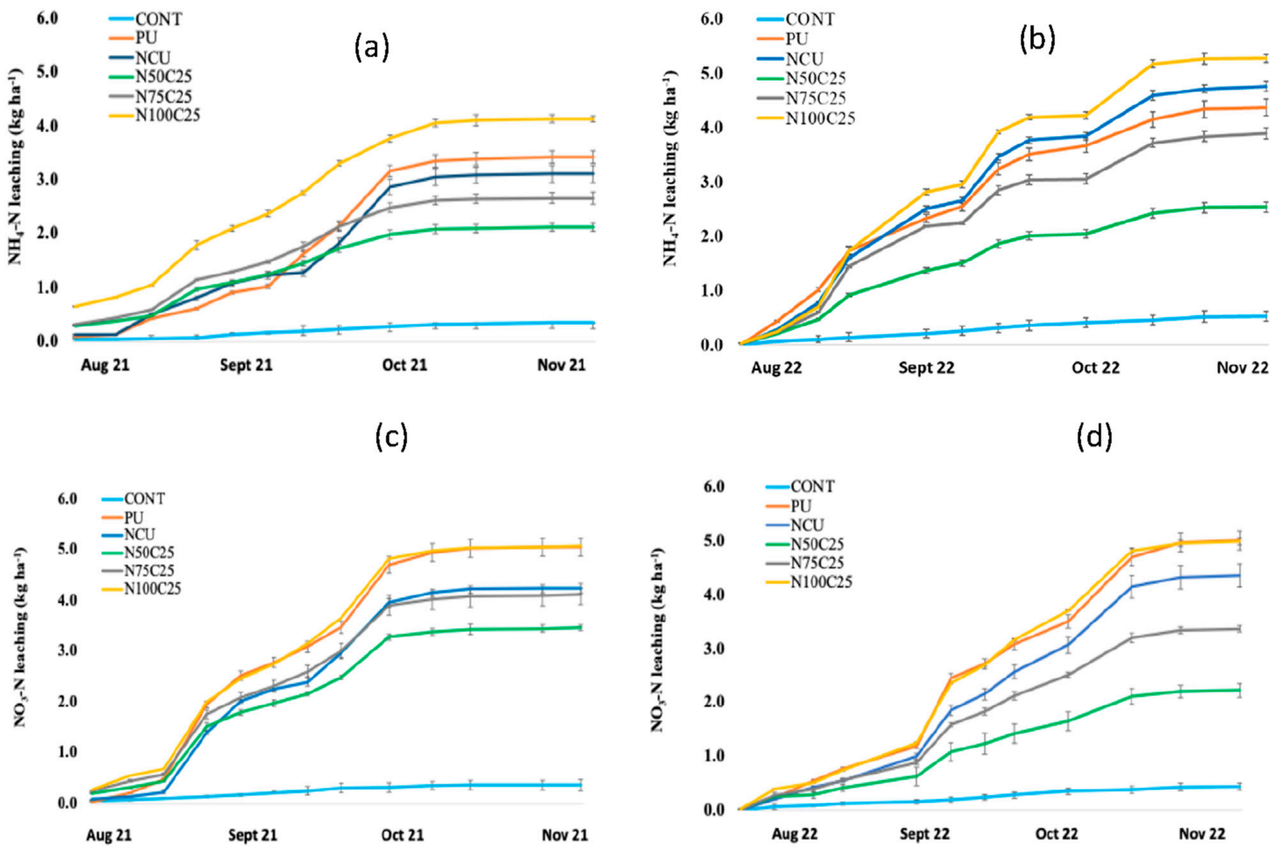

FIGURE 6
Cumulative Leaching loss of NH_4^{+-} in rice **(a)** 2021–22; **(b)** 2022–23; Cumulative Leaching loss of NO_3^- in rice **(c)** 2021–22; **(d)** 2022–23 (error bars represent the standard deviation between replicates for each cumulative measurement); PU: Prilled urea (PU); NCU: Neem coated urea 100%; N50C25: NCU 50% + 25% Compost; N75C25: NCU 75% + 25% Compost; N100C25: NCU 100% + 25% Compost.

treatments. During the second year of rice in 2022, at the ripening stage, high winds along with rain impacted the crop and this led to a significant decline in yield between the two rice seasons (Table 7). The highest grain and straw yield (results not shown) of rice and wheat were in N100C25 treatment in both the years.

Nitrogen uptake in rice and wheat

The N uptake was higher in wheat than rice in all the fertilized treatments. The N uptake increased significantly with NCU (100%) as compared to PU in rice during first year and wheat crop during both years. The N uptake in the integrated NCU + compost (N75C25) was comparable with NCU (100%), but higher than PU in both rice and wheat crops during the 2 years. The N uptake increased ($p < 0.05$) with additional 25% N application in both crops in N100C25 treatment (Figure 8). In rice crop, with reduction of 25% N application in the N50C25 treatment, the N uptake reduced significantly ($p < 0.01$) by 7.5% and 18%, over NCU (100%) and N75C25, respectively. Similar pattern of N uptake in the different treatments was observed in the wheat crop during both the years (Figure 8). Lodging of the crop during the second-year rice resulted in lower grain yields, thus total N uptake in rice reduced significantly in all the N treatments in the second year (Table 7; Figure 8).

Discussion

Soil ammonium and nitrate concentration under different treatments

The application of urea coated with nitrification inhibitor neem oil significantly influenced the soil NH_4^+ and NO_3^- levels, and these effects differed between the rice and wheat crops in this study. The differences in soil available nitrogen are primarily due to the contrasting soil and physiological conditions found in rice and wheat crops. Rice is adapted to anaerobic soil conditions with a compacted subsoil and has specialized roots that transport oxygen, while wheat, requires aerobic soil conditions (Pathak et al., 2002). In the PU treatment, the peak flux of NH_4^+ was observed on the 2–3 days after each N fertilizer application event. Whereas, in NCU and the integrated treatments (N50C25, N75C25 and N100C25) treatments, the slow-release effect of neem oil on urea hydrolysis led to peak NH_4^+ levels in NCU delayed by 2–3 days than PU, after each fertilizer application event. The coating of neem oil on the urea granules slowed down the dissolution of nitrogen, leading to a gradual release of NH_4^+ into the soil, maintaining higher levels of NH_4^+ over an extended period than PU (Figure 5A). Neem oil having nitrification inhibitory activity, impedes the activity of ammonia-oxidizing bacteria (Kawakami et al., 2012) responsible

TABLE 4 Total N leaching losses in rice and wheat during 2021–22 and 2022–23.

Treatment	N leaching (kg ha^{-1})						Annual N leaching loss (kg ha^{-1})		
	Rice			Wheat			2021–2022	2022–2023	Mean
	2021	2022	Mean	2021–2022	2022–2023	Mean			
CONT	0.71 ± 0.24d	0.97 ± 0.09e	0.82 ± 0.09f	0.49 ± 0.41e	1.19 ± 0.36e	0.83 ± 0.16f	1.21 ± 0.15e	2.16 ± 0.06e	1.65 ± 0.24f
PU	8.42 ± 0.32 ab	9.37 ± 0.23b	8.88 ± 0.23b	6.61 ± 0.45 ab	8.23 ± 0.41 ab	7.42 ± 0.37b	15.03 ± 0.07a	17.60 ± 0.24 ab	16.30 ± 0.59b
NCU	7.3 ± 0.45b	9.01 ± 0.38b	8.15 ± 0.44c	6.13 ± 0.34bc	7.45 ± 0.29b	6.73 ± 0.32c	13.33 ± 0.15b	15.35 ± 0.12b	14.88 ± 0.74c
N50C25	5.53 ± 0.36c	4.73 ± 0.09d	5.08 ± 0.19e	4.25 ± 0.22d	4.94 ± 0.17d	4.60 ± 0.17e	9.79 ± 0.39d	9.66 ± 0.07d	9.68 ± 0.18e
N75C25	6.72 ± 0.21b	7.25 ± 0.16c	6.97 ± 0.14d	5.39 ± 0.28c	6.61 ± 0.35c	5.99 ± 0.27d	12.10 ± 0.14c	13.85 ± 0.18c	12.95 ± 0.41d
N100C25	9.13 ± 0.12a	10.23 ± 0.27a	9.69 ± 0.26a	7.25 ± 0.31a	8.96 ± 0.58a	7.91 ± 0.23a	16.38 ± 0.07a	19.19 ± 0.15a	17.60 ± 0.74a
		Significance		Fertilizer	Year	Fertilizer*Year			
		N leaching in rice		***	*	**			
		N leaching in wheat		***	ns	ns			
		Annual N leaching loss		***	ns	ns			

ns, non-significant $p > 0.05$; *$p < 0.05$; **$p \leq 0.01$; ***$p \leq 0.001$.
Mean ± Standard error (n = 3); Different lowercase letters in a column indicate significant differences ($p < 0.05$) among the values in each column.

TABLE 5 p values of the repeated measures ANOVA to test the effect of fertilizer N split application, N treatments, and their interaction on soil NH_4^+ and NO_3- leaching (n = 3) in rice and wheat.

Crop	Parameter	NH_4^+-N leaching		NO_3^- leaching	
		1st year	2nd year	1st year	2nd year
Rice	Time	0.007	0.042	0.002	0.005
	N treatment	0.011	0.009	0.024	0.031
	Time * treatment	0.025	0.031	0.053	0.127
Wheat	Time	0.027	0.014	0.018	0.011
	N treatment	0.056	0.073	0.039	0.022
	Time * treatment	0.113	0.061	0.072	0.058

for the conversion of NH_4^+ to nitrite (NO_2^-) and subsequently to NO_3^-, leading to higher levels of NH_4^+ in the soil over a longer duration (Figure 5A). The application of DCD nitrification inhibitor in rice soils has been reported to increase the soil NH_4^+ levels by retaining the NH_4^+ form in soil for longer duration (Banerjee et al., 2002). By inhibiting nitrification, NCU application in wheat reduced the rapid conversion of NH_4^+ to NO_3^- (Figure 5D), which resulted in better synchronization with crop N demand (Qi et al., 2021).

The application of organic manure such as compost in the integrated treatments affected the availability of N in soil by the gradual conversion of organic N to plant-available forms of NH_4^+ and NO_3^- through microbial activity (Lopez and lopez, 2001). The applied compost was low in N having only 1% N, and a near neutral pH ranging from 7.2–7.4. Composts release organic N slowly and intermittently through mineralization into NH_4^+, a process dependent on soil temperature and moisture (Sierra et al., 2015; Machado et al., 2020). This slow release gradually increases soil nutrient content for plant uptake (Boldrin et al., 2009), resulting in higher soil NH_4^+ and NO_3^- levels in the 100% and 125% integrated compost treatments for both crops (Figure 5). The gradual decomposition of compost released nutrients slowly, synchronizing nutrient availability with plant uptake and reducing the build-up of excess mineral N that could be leached (Huang et al., 2017). Higher soil NH_4^+ and NO_3^- concentrations were observed in the integrated treatments during the second rice season, likely due to the mineralization of compost applied in the current and preceding crops, as well as previous crop's below-ground residues. (Perego et al., 2012).

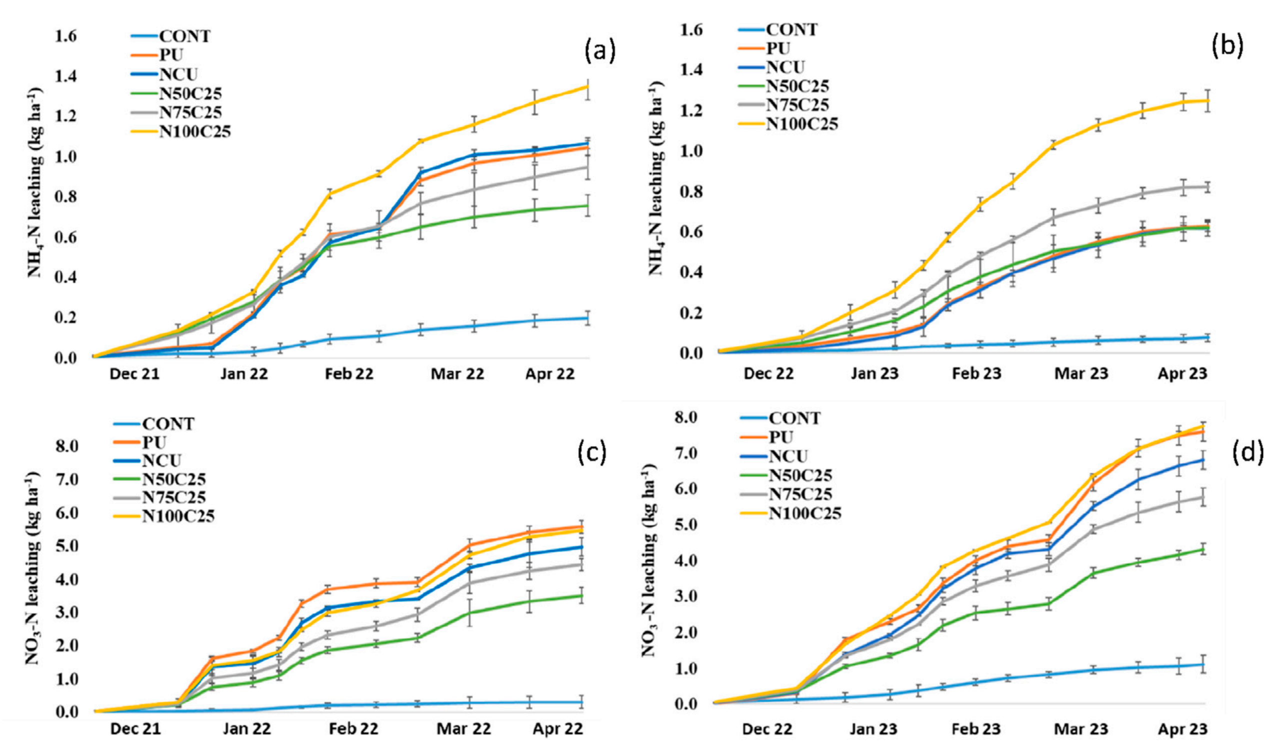

FIGURE 7
Cumulative Leaching loss of NH_4^+-N in wheat **(a)** 2021–22 **(b)** 2022–23; Cumulative Leaching loss of NO_3^--N in wheat **(c)** 2021–22 **(d)** 2022–23 (error bars represent the standard deviation between replicates for each cumulative measurement); PU: Prilled urea (PU); NCU: Neem coated urea 100%; N50C25: NCU 50% + 25% Compost; N75C25: NCU 75% + 25% Compost; N100C25: NCU 100% + 25% Compost. Mention it is in wheat crop.

TABLE 6 The F ratios significance level for annual N leaching, crop yields and N uptake under different N treatments during the two study years.

Parameter	N treatment	Year	(Treatment*Year)
Annual N leaching in rice-wheat	3.32*	1.08^{ns}	0.34^{ns}
Rice yield	5.24**	8.99**	4.02*
Wheat yield	1.45^{ns}	1.78^{ns}	0.54^{ns}
N uptake Rice	4.11**	6.59*	2.78*
N uptake wheat	1.86^{ns}	2.13^{ns}	0.28^{ns}

Level of significance: *$p < 0.05$; **$p < 0.01$; ***$p < 0.001$; ns: not significant.

The soil NH_4^+ concentrations remained higher for a longer duration with the compost treatments than with PU and NCU alone, where a sharp decline in NH_4^+ concentration was observed, a few days after each fertilization event. The peak concentrations of NH_4^+ and NO_3^- in soil were lower in the integrated N75C25 than NCU alone, however, the average levels during crop growth period were similar in rice crop (Figure 5). The observed effects were attributed to the slow but continuous decomposition of organic fertilizer and the soil's limited NH_4^+ adsorption capacity (Meng et al., 2014). Organic fertilizers like compost contain both easily mineralizable and organically bound N, which slowly mineralize to NH_4^+ and NO_3^- for plant uptake throughout the crop growth period (Abeka et al., 2022).

In the integrated treatments, the application of compost may have promoted the formation of stable soil aggregates, thereby improving the soil structure (Diacono and Montemurro, 2011) and the ability of soil to retain water (Zemánek, 2011), thus irrigation water was held within rootzone for longer duration, reducing the amount of water percolation below rootzone in the compost treatments during the second year in both rice and wheat crops (Table 3).

Ammonium and nitrate N leaching losses in rice and wheat

The leaching losses of NH_4^+ have not been frequently reported in literature. However, at this study site, leaching loss of both NH_4^+ and NO_3^- was observed in rice, whereas in wheat, significantly higher NO_3^- leaching losses were observed as

TABLE 7 Grain yield of rice and wheat under different N treatments.

Treatment	Yield (kg ha^{-1})					
	Rice			Wheat		
	2021	2022	Mean	2021–2022	2022–2023	Mean
CONT	3253 ± 41e	2393 ± 35e	2785 ± 190e	3150 ± 103e	3269 ± 79d	3109.95 ± 59e
PU	5075 ± 50c	3823 ± 44c	4508.33 ± 270d	4600 ± 21c	4670 ± 33c	4761.18 ± 77c
NCU	5465 ± 76b	4149 ± 55b	4803.50 ± 290c	4932 ± 50b	4889 ± 30b	5106.88 ± 90b
N50C25	4708 ± 108d	3401 ± 61d	5450.75 ± 298b	4373 ± 58d	4485 ± 48d	4362.63 ± 39d
N75C25	5195 ± 72c	4012 ± 59bc	6379.33 ± 536a	4807 ± 69b	4858 ± 42b	5043.77 ± 49b
N100C25	5925 ± 43a	4459 ± 88a	5170.83 ± 346b	5363 ± 67a	5434 ± 22a	5435.27 ± 34a
Significance		Fertilizer	Year	Fertilizer*Year		
Rice yield		***	**	***		
Wheat yield		***	ns	ns		

ns: non-significant p > 0.05; **p ≤ 0.01; ***p ≤ 0.001.
Mean ± standard error (n = 4); Different small letters indicate significant difference (p < 0.05) between the means in same column indicate significant differences between means of Rice yield and wheat yields.

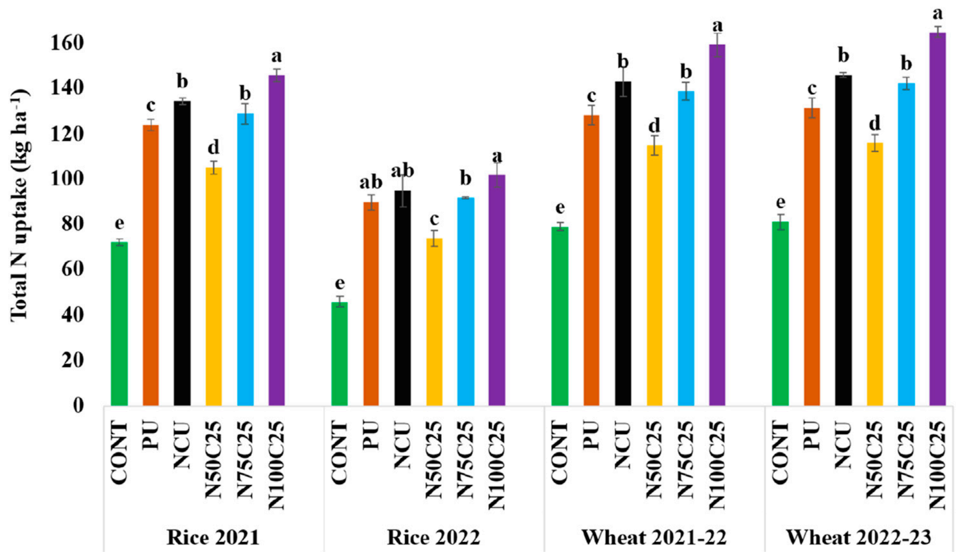

FIGURE 8
Total N uptake by rice and wheat during 2021–22 and 2022–23 (error bar representing the standard error n = 3). Different symbol indicates significant differences (p < 0.05) in mean N uptake.

compared to NH_4^+. Nitrogen leaching in arable soils is a complex process influenced by soil properties, climatic conditions, and management practices (Kabala et al., 2017; Meisinger and Delgado, 2002). Ammonium is a positive-charged cation, whereas NO_3^- is a negatively charged anion and negatively charged NO_3^- ions are more mobile and less strongly adsorbed to negatively charged soil particles, making them more likely to travel through the soil profile (Sahrawat, 2008). The cation exchange capacity (CEC) influences the leaching of NH_4^+ in the soil. Soil with lower CEC (<10 cmol (C)kg^{-1}) has fewer exchange sites available to retain NH_4^+ ions, increasing the risk of leaching (Mengel, 1993). The CEC of our study site soils was only 4.8 cmol (C)kg^{-1}, thus leaching of NH_4^+ was observed in both rice and wheat crops. The concentrations of NH_4^+ and NO_3^- ions in soil solutions, exhibit considerable variability depending on soil type (Kabala et al., 2017). While NH_4^+ is less mobile in soil compared to NO_3^-, it can still be susceptible to leaching under conditions where it is not taken up by plants or retained by soil colloids (Sarkar and Haldar, 2009). In general, NO_3^- tends to leach more extensively than NH_4^+ due to its higher mobility in soils. In contrast, NH_4^+ remains relatively stable, as it is readily adsorbed onto the clay particles in the soil, reducing its susceptibility to leaching in rice (Zhang et al., 2021). However, due to alternating anerobic and aerobic conditions prevailing during the rice growth period at this experimental site, the NH_4^+ was oxidized to NO_3^-, thus leaching of both NH_4^+ and NO_3^- was recorded. Since NO_3^- is an anion, it is more likely to move through the soil profile with percolating water.

Leaching happens when drainage exceeds evapotranspiration resulting in the downward movement through the soil of water and solutes such as NH_4^+ and NO_3^- ions. Percolation is an important factor in controlling the transport of NH_4^+ and NO_3^- to deeper layers of soil and groundwater through soil pores and gravity (LaHue and Linquist, 2021). In rice, the percolation rate was almost half than in wheat (Table 3), mainly due to the puddling of the rice field (Kukal and Aggarwal, 2003). Puddled transplanted rice under wet tillage increases soil bulk density and creates a hard pan in the soil plough (7–10 cm) layer thereby reducing water percolation losses significantly (Bhatt et al., 2021). Puddling can reduce the percolation rate from 30 to 13 mm day^{-1} in flooded sandy loam soils by decreasing hydraulic conductivity of puddled soil (Kukal and Aggarwal, 2003). Hatiye et al. (2017) observed percolation rates ranging from 0.01–6.12 cm d^{-1} resulting in deep percolation of 79%–87% of the total water inputs in an un-puddled rice field. The settling of the finer fraction of sediments in suspension after puddling in rice decreased the percolation losses by creating a semi-permeable layer at the top of the puddled layer in rice as compared to the wheat (Kukal and Aggarwal, 2002). The percolation losses were higher during the early growth period of the rice but decreased during the later crop growth stages in the puddled rice soils, probably due to small root volumes in the early growth stage of rice crop. In wheat, no significant decrease in percolation losses of water with time were recorded. Soil type significantly impacts percolation losses, with percolation rate varying from 1–5 mm day^{-1} in heavy clay soils and 25–30 mm day^{-1} in sandy and sandy loam rice soils (Bouman et al., 2007). Anaerobic conditions in rice also encourage the development of reduced compounds, such as ferrous iron, which can clog soil pores and slow percolation rates (Kögel-Knabner et al., 2010).

The higher proportion of sand (46%) compared to clay and silt was responsible for higher percolation rate in our study soil. Kukal and Aggarwal (2003) investigated the percolation rates in puddled rice fields, which ranged from 1.6 to 3.8 mm day^{-1}, while in well-drained wheat fields, the rates were significantly higher, ranging from 10 to 25 mm day^{-1} in northern India. In this study site the percolation losses ranged from 8–9 mm day^{-1} in rice to 14–15 mm day^{-1} in wheat. Humphreys et al. (2005) reported seasonal percolation losses of 57%–83% of total water input in the Indo-Gangetic Plains on sandy and sandy loam soils, with the lowest losses occurring on loams and clay loams in rice. Among the different treatments, there were no significant differences in water percolation rates in both rice and wheat during the first year, however, the percolation rates reduced under the NCU + compost (N50C25, N75C25 and N100C25) treatments in both rice and wheat in the second year. The increase in soil organic matter content with compost application may result in an improvement in soil physical properties and its water holding capacity, resulting in lower percolation losses (Savabi et al., 2003).

Flooded rice conditions accumulate NH_4^+ in soil, however as water levels reduce due to percolation in soil, resulting aerobic conditions increase NO_3^- leaching potential (Kumar et al., 2017). The alternate aerobic and anaerobic cycles in the study site's rice soil led to NH_4^+ nitrification to NO_3^-, causing similar leaching losses of both NH_4^+ and NO_3^- (2–5 kg N ha^{-1} across treatments). Conversely, in wheat, NH_4^+ leaching losses were significantly lower than NO_3^- over both years due to rapid NH_4^+ nitrification under aerobic soil conditions (Sahrawat, 2008). Additionally, in winters, especially in wheat, low microbial activities in the soil may also increase nitrate leaching (Kabala et al., 2017). Significant leaching losses of N as NO_3^- have been reported in rice grown in coarse-textured soils of the north-western IGP region, with Rana et al. (2020) noting higher NO_3^- leaching from rice than wheat. Lu et al. (2019) found that wheat NO_3^- leaching increased by 0.058 kg NO_3^--N ha^{-1} per season for every 1 kg ha^{-1} increase in NO_3^-N accumulation in 0–100 cm soil.

Contrasting soil environmental and management conditions in rice and wheat resulted in significant variations in soil NH_4^+ and NO_3^- concentrations. Soil aeration, moisture, temperature, crop growth stages, and water management are crucial factors determining the relative N concentrations (Bhatia et al., 2012). In rice, significantly higher NH_4^+ concentrations were observed due to waterlogging inhibiting nitrification, favoring NH_4^+ stability (Schneiders and Scherer, 1998). Nevertheless, NH_4^+ rapidly nitrified to NO_3^- during drier periods, followed by denitrification during alternating anaerobic-aerobic cycles (Jadczyszyn et al., 2010). While rice primarily uptakes 60%–90% N as NH_4^+ and 10%–40% as NO_3^- (Wang et al., 1993), these proportions vary with fertilizer type, crop, weather, and microbial activities (Kuypers et al., 2018).

The peak concentration of NO_3^- in rice was observed three to 4 days after the peak of NH_4^+ (Figure 3), whereas in wheat crop, the peak NO_3^- was observed after one to 2 days only (Figure 4). Following application of urea to soil, the urease enzyme hydrolyses urea to NH_4^+, however, the simultaneous increase in soil pH may lead to ammonia volatilization (Cowan et al., 2021; Ma et al., 2019). The NH_4^+ in soil may be taken up by the plant (in rice), may be leached down if not adsorbed on to the soil colloids, or may be oxidized to NO_3^- depending on soil redox potential (Song et al., 2021). When the soils are saturated as in rice soils, the nitrate may be reduced to nitrous oxide by the denitrification process (Pathak et al., 2002), or NO_3^- may be leached (Chaterjee et al., 2024), however in wheat, the aerobic soil conditions and lower moisture levels favor rapid conversion of soil NH_4^+ to NO_3^- (Cramer and Lewis, 1993; Raun and Johnson, 1999).

Leaching losses under NCU and integrated treatments

In current agricultural systems, N losses ranging from less than 10%–30% of the total applied N have been reported (IPCC, 2006). Our results showed that application of prilled urea (PU) caused slightly higher total N leaching losses (6.9% of applied N) than the NCU (6.2%) on an annual basis (Table 4). There were no significant differences in the leaching of NH_4^+ between PU and NCU in rice, whereas there was significantly lower NO_3^- leaching with NCU in rice crop. This was due to the slow-release properties of NCU and the nitrification inhibition by neem oil (Malla et al., 2005), which led to slower availability of the NO_3^- in soil. Nitrification inhibitors delay the transformation of NH_4^+ to NO_3^- by inactivating the ammonia monooxygenase (AMO) enzyme, which is the key enzyme for the first rate-limiting step of nitrification (Cui et al., 2021). Chen et al. (2021) reported leaching losses of 3.94–9.63 kg ha^{-1} of NO_3^-, and 0.64–0.93 kg ha^{-1} of NH_4^+ in paddy rice, and the application of coated urea fertilizers reduced the leaching losses by 21%.

The N leaching losses reduced with integrated application of compost, as firstly the amount of chemical N fertilizer reduced and secondly there was higher retention of N fertilizer in the rhizosphere due to microbial immobilization which later slowly became available as the microbes decomposed (Song et al., 2021). In a lysimeter study in a sandy-loam soil planted with rice, leaching losses of N (NH_4^+, and NO_3^-) beyond 30 cm depth were 6% of the total urea-N applied in three equal split doses, and 13% when applied as a single dose (Bijay Singh et al., 1991). In this study the leaching loss was not significantly different during the 2 years in rice crop, even though the chemical N fertilizer was applied in four and three splits in the first and second year, respectively.

The integrated treatment NCU + compost (100%, N75C25) showed lower leaching losses compared to NCU alone and PU treatments, which was mainly due to the slower decomposition of organic matter into NH_4^+ and then further to NO_3^-. When compared on a large scale, organic fertilizers often have 30%–40% lower leaching losses (Hina, 2024) due to slower nutrient release. The average NH_4^+ and NO_3^- levels in soils were slightly higher in the integrated N75C25 than NCU alone in the wheat (Figure 5), however, no significant differences were observed in case of rice. N leaching losses from organic manures are generally lower than those from mineral N fertilizers except for when they contain high proportion of mineral N as in pig slurry (Di and Cameron, 2002). Organic nutrient sources alone may not meet plant demand during critical stages, while integration with chemical fertilizers provide quick mineralization, and reduce reactive N losses through leaching, volatilization, and N_2O emission (Bhardwaj et al., 2021; Cowan et al., 2021). However, when organic manures are applied on a long-term basis, the N leaching may or may not be lower than those from mineral N fertilizers as there may be gradual build-up of soil N which may be prone to leaching. As the organic matter decomposes and releases nitrogen gradually, and if the crop uptake does not match this release rate, excess nitrogen can accumulate in the soil and be lost through leaching (Frick et al., 2022).

Grain yield and N uptake under different N treatments in rice and wheat

Farmers prioritize crop growth and yield when managing field nutrients. In this experiment, PU, NCU, and integrated NCU + compost treatments significantly ($p < 0.05$) increased both rice and wheat grain and straw yields. NCU alone, with its slow-release and nitrification inhibition properties, led to higher yields than PU. The maximum yields in both crops over 2 years were observed in the integrated treatment of 125% N (N100C25) due to additional N from compost. The gradual N release from NCU and compost enhanced its availability and increased yields (Nagabhushanam and Bhatt, 2020). Organic manure, like compost, improves soil health, nutrient availability, and water-holding capacity, boosting crop growth (Machado et al., 2020; Mohanty et al., 2023). While fully organic systems can have low NUE due to poor demand-supply synchronization and delayed mineralization (Musyoka et al., 2017), integrated nitrogen management (INM) approaches are suggested to improve NUE (Dwivedi et al., 2016). Compost co-application also reduced deep percolation (Table 3), explaining lower mineral N (especially NO_3^-) leaching. The synergistic effects of NCU and compost contribute to better nutrient use efficiency, resulting in higher rice and wheat yields (Rehman et al., 2021; Deepika et al., 2017). Overall, INM increased crop yields by 1.3%–66.5% in tested cropping systems (rice, wheat, soybean) compared to conventional nutrient management (Kabato et al., 2022; Paramesh et al., 2023).

Nitrogen is a most essential and the main limiting factor for rice and wheat productivity, thus, crop N uptake plays a vital role for crop biomass and grain yield. Wheat showed higher N uptake than rice across both years due to greater N content in its grain (results not shown). While no significant change in wheat N uptake was observed over 2 years, lower rice yields and N uptake in the second year were attributed to lodging during the ripening phase due to heavy rainfall and high winds. NCU, alone and with compost, enhanced slow and long-term N availability in the soil, improving N uptake efficiency. Both rice and wheat exhibit unique sigmoidal N uptake patterns, with slow initial uptake, a high uptake phase during vegetative and reproductive stages, and a decline towards maturity (Ercoli et al., 2009; Shukla et al., 2004). This non-linear uptake means a large proportion of applied chemical N can be lost as NO_3^- and NH_4^+ through leaching if application does not synchronize with plant demand (Coskun et al., 2017). The slow and prolonged availability of NH_4^+ and NO_3^- from compost's gradual mineralization in the 100% N integrated treatment (N75C25) ensured improved synchrony between N release and plant uptake, thereby reducing mineral N losses.

Conclusion and prospects

Significant leaching losses of both NH_4^+ and NO_3^- were measured in rice, while only NO_3^- leaching was significant in wheat. Annually, the rice-wheat system experienced leaching losses ranging from 6.2% to 7% of applied N fertilizer. Total mineral N leaching was 15.9% higher in rice than in wheat across different N treatments. Compared to Neem coated urea (NCU), prilled urea (PU) resulted in 8% and 10% higher total mineral N loss in rice and wheat, respectively. Substituting 25% N with compost further reduced total N leaching by 10%–15% in rice and wheat, respectively. The extended N availability from NCU and integrated NCU + compost led to higher rice and wheat yields and improved N uptake efficiency. Compost application also lowered the leachate percolation rate, thereby reducing leaching losses. Reducing fertilizer N application through integrated N management and using nitrification inhibitor-coated slow-release fertilizers are promising strategies to regulate mineral N leaching losses and mitigate environmental impact. However, repeated compost application may alter leaching losses, necessitating further research into the long-term impact of integrated NCU and compost on leaching and N use efficiency.

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

SK: Validation, Writing – review and editing, Visualization, Methodology, Writing – original draft, Investigation, Formal Analysis. AB: Conceptualization, Methodology, Supervision, Project administration, Data curation, Visualization, Writing – original draft, Software, Writing – review and editing, Resources, Validation, Funding acquisition. JD: Conceptualization, Writing – original draft, Methodology, Visualization, Writing – review and editing. RR: Writing – review and editing, Methodology, Conceptualization, Funding acquisition. SS: Validation, Writing – original draft, Formal Analysis. VK: Investigation, Validation, Supervision, Writing – original draft. RT: Writing – original draft, Formal Analysis, Investigation. MR: Methodology, Validation, Writing – review and editing. MS: Writing – review and editing, Conceptualization, Funding acquisition, Project administration, Methodology.

Funding

The author(s) declare that financial support was received for the research and/or publication of this article. The work was funded by the UKRI, United Kingdom funded GCRF-SANH project. Partial funding support was also provided by ICAR-NICRA (12-115) project.

Acknowledgments

We acknowledge with gratitude the support of the United Kingdom Research and Innovation (UKRI) for funding this research under the Global Challenge Research Fund-South Asian Nitrogen Hub (SANH) (Project Number 24-754). We are also thankful to ICAR-NICRA project (IARI 12-115) for partial funding support. We also thank the Director of the ICAR-Indian Agricultural Research Institute, New Delhi, for providing the necessary facilities for conducting this research smoothly.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2025.1656231/full#supplementary-material

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