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Reducing ammonia volatilization in rice paddy: the importance of lower fertilizer rates and soil incorporation

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In rice paddies, which exhibit higher ammonia (NH_3) emission factors than upland soils, identifying key drivers of NH_3 flux intensity is crucial. Contrary to the commonly held view that NH_3 flux is primarily governed by soil ammonium (NH_4^+) concentrations, we found no significant relationship between NH_3 flux and NH_4^+ levels in the soil during rice cultivation. To pinpoint a primary factor influencing NH_3 flux intensity under conventional rice cropping practices, we conducted a 2-year field study applying four nitrogen (N) fertilization rates (0, 45, 90, and 180 kg N ha^{-1}) using urea [$(NH_2)_2CO$], the most common N fertilizer. NH_3 emissions were tracked using the ventilation method. Following N application, NH_3 flux sharply increased but rapidly returned to baseline. Half of the N applied as a basal fertilizer was incorporated within the soil, contributing only 10% of total NH_3 emissions. In contrast, top-dressed applications—20% of total N at the tillering stage and 30% at panicle initiation—accounted for approximately 90% of NH_3 loss. Seasonal NH_3 flux increased quadratically with rising N application rates, correlating strongly with NH_4^+ concentrations in floodwater rather than soil. Grain yield responded quadratically to N levels, peaking at 120 kg N ha^{-1} with a 37% increase over control yields. NH_3 flux intensity, defined as seasonal NH_3 flux per unit of grain yield, showed a quadratic response to N fertilization, decreasing with initial fertilizer additions (up to 38 kg N ha^{-1}) but then sharply increased with further N fertilization increase. Hence, reducing NH_4^+ concentrations in floodwater through moderated N application and deeper fertilizer placement could be essential for minimizing NH_3 volatilization in rice systems.

KEYWORDS

urea, ammonia emission intensity, ammonia emission factor, fertilizer incorporation, rice paddy

1 Introduction

The inevitable rise in global population necessitates a proportional increase in food production. The United Nations projects the population will reach 8.2 billion in 2025, increasing to 9.7 billion by 2050 (USDA, 2010). These trends indicate a continuous escalation in food demand. For instance, cereal production, needed for both human and animal consumption, is expected to reach 3 billion tons by 2050, up from the current 2.7 billion tons (Fao and AO, 2017). To meet these demands, crop production must intensify—an already challenging goal given the limited availability of arable land.

Among agricultural practices such as tillage, water management, and cultivar selection, fertilization remains the most effective for boosting crop productivity (Farooq F. et al., 2022). Of all nutrients applied, nitrogen (N) has the greatest impact on crop yields (Cagasan et al., 2020; He et al., 2024). For example, long-term studies in fertilized rice paddies in Korea showed that N fertilizer increased rice grain yields by an average of 45%, compared to yield increases of 9.8% and 5.1% with phosphorus (P) and potassium (K), respectively (Lee et al., 2008). However, this study also revealed that less than 30% of the applied N was absorbed by rice plants, leaving over 70% as a potential pollutant in the atmosphere, soil, and water (Cao et al., 2013). Soil N losses occur through leaching, runoff, denitrification, and volatilization (Cameron et al., 2013; Ma et al., 2019; Zeng et al., 2021). Notably, around 70% of the applied N is lost through NH_3 volatilization, with agriculture contributing approximately 80%–95% of atmospheric NH_3, stemming from N fertilization and livestock excretion (Sapek, 2013; Skorupka and Nosalewicz, 2021). Once emitted, NH_3 converts to ammonium (NH_4^+) and forms fine particulate matter ($PM_{2.5}$), which, when combined with anionic pollutants (SO_x and NO_x), can cause respiratory issues, including asthma and inflammation, impair lung function, and increase cancer risks (Xing et al., 2016; Yang L. et al., 2020).

In soils, NH_3 flux intensity is generally influenced by factors such as NH_4^+ concentration, pH, and oxygen (O_2) levels (Chua et al., 2019; Merl and Koren, 2020; Kim et al., 2021). Higher NH_3 emissions are observed under conditions of elevated NH_4^+ concentration, increased pH and temperature, and reduced O_2 (Rochette et al., 2013; Shen et al., 2020; Adegoke et al., 2022). Emissions are especially pronounced in flooded rice paddies compared to drier upland soils, due mainly to the lower O_2 levels in flooded soils (Li et al., 2017; Xu et al., 2020; Farooq F. et al., 2022). For example, in China, rice paddies exhibited a higher NH_3 emission factor (EF) of 0.179 kg NH_3-N per kg of applied N compared to 0.128 kg NH_3-N per kg in upland soils (Zhang et al., 2017; Farooq M. S. et al., 2022). Yet, many field studies have failed to establish clear relationships between NH_3 emission rates and these soil factors in flooded paddies (Wang et al., 2018), suggesting that additional factors may drive NH_3 flux intensity. While general factors affecting NH_3 emission are known, their specific impacts under varying N fertilization levels in rice paddies are less understood.

In this 2-year field study, we aimed to identify core factors affecting NH_3 flux intensity in flooded rice paddies. Using urea as the N source, we applied four different N levels across rice crops, monitoring NH_3 emissions alongside soil and water properties throughout the growing season to understand their role in NH_3 volatilization loss.

2 Materials and method

2.1 Experimental field installation and rice cultivation

To identify key factors influencing NH_3 emission rates in a rice cropping system, a typical rice paddy was selected at the Gyeongsang National University experimental station in Jinju, Korea (35.15° N, 128.10° E) for a 2-year study. The site lies within a monsoon climate zone, with a 30-year average air temperature of 13.4°C and an annual precipitation of 1,518 mm (KMA, 2021). Mono-rice cultivation using conventional practices has been conducted on this field for over 50 years. The soil is a silt loam, classified as mixed, mesic Typic Endoaquepts (USDA, 2010), with an initial neutral pH of 6.0 (1:5 in H_2O) and low fertility, containing 19.4 g kg^{-1} organic C, 1.2 g kg^{-1} total N, and 31 mg kg^{-1} available P_2O_5.

Urea [$(NH_2)_2CO$] was chosen as the nitrogen (N) fertilizer. Based on the recommended fertilization rates for rice in Korea (N-P_2O_5-K_2O = 90–45–58 kg ha^{-1}; RDA, 2019), four levels of N fertilization (0, 45, 90, and 180 kg N ha^{-1}) were applied as treatments and maintained across both years of the study. The experimental design was a randomized complete block design (RCBD) with three replicates per treatment, resulting in 12 plots (10 m × 10 m each), separated by metal barriers. Nitrogen was applied in three split doses: 50% as a basal application, 20% at tillering, and 30% at panicle initiation. Basal fertilizers were incorporated mechanically into the surface layer (0–15 cm) 1 day before rice transplanting, while the tillering and panicle initiation applications were top-dressed at 15 and 45 days after transplanting, respectively. Phosphorus (P_2O_5, as superphosphate) and potassium (K_2O, as potassium chloride) were applied uniformly across all treatments.

Three-week-old rice seedlings (Sindongjin cultivar, Japonica type) were transplanted by hand at 15 cm × 30 cm spacing in late May, with harvest occurring in mid-October. The field was flooded to a depth of 5–7 cm, and water was drained 1 month before harvesting.

2.2 Ammonia flux measurement

Ammonia (NH_3) emission rates were measured using a ventilation method (Nommik and Vahtras, 1982). A transparent acrylic chamber (12 cm in diameter, 25 cm in height) was utilized to hold a sponge that served as the primary NH_3 absorbent during each sampling period. This chamber was placed between rice plants, partially embedded into the soil. Each chamber contained two identical sponges: the lower sponge was positioned 8 cm above the soil surface to trap NH_3 emitted from the soil, while the upper sponge was placed 6 cm above the lower sponge to capture NH_3 from any external sources. All sponges were moistened with a 2 M H_3PO_4 and 4% glycerin solution (Wang et al., 2004), with H_3PO_4 acting as the main NH_3-trapping acid and glycerin reducing water evaporation from the sponge.

To minimize NH_3 loss during the study, NH_3 gas was collected systematically at controlled intervals. Sampling occurred daily for 1 week following nitrogen application, then every 2–3 days during the second and third weeks, and finally weekly, totaling 36 sampling sessions (Figure 1). Since the primary focus was on NH_3 emissions from the soil, only the lower sponges were collected for analysis, while the upper sponges, used solely to protect the lower sponges, were discarded. To extract trapped NH_3, the sponges were immediately soaked in a 2 M KCl solution, shaken at 120 rpm for 1 hour, then hand-squeezed, and filtered using a vacuum filter with Whatman 40 filter paper. The resulting NH_4^+-N levels were measured by the indophenol blue method (Akao, 2023).

The NH_3 emission rate was then calculated based on the NH_3 concentration trapped per unit surface area over each specified sampling interval.

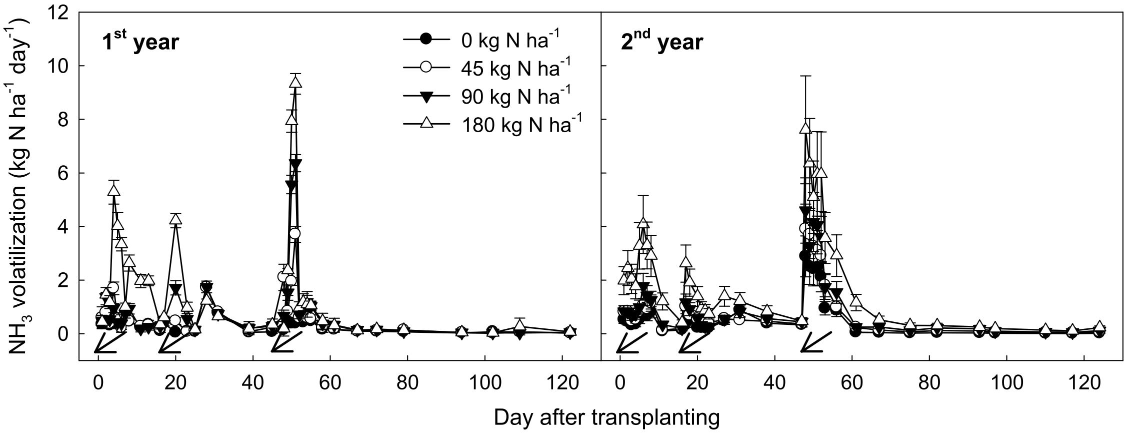

FIGURE 1
Changes in NH_3 emission rates under different levels of N fertilization in rice paddy soil. Vertical bars indicate standard deviations (n = 3). Arrows indicate fertilization day.

$$R\ (kg\,N\,ha^{-1}\,day^{-1}) = \frac{M}{A\,x\,D}$$

where R: daily NH_3 emission rate, *M* (kg): NH_3-N collected via sponge in the chamber, *A* (m^2): cross-sectional area of the chamber, and *D* (day): sampling day interval.

The seasonal NH_3 flux was computed by integrating the daily NH_3 flux rate and sampling day interval:

$$Seasonal\ NH_3\ flux\ (kg\,N\,ha^{-1}) = \sum_i^n (R_i \times D_i)$$

where R_i: daily NH_3 emission rate (kg N ha^{-1} d^{-1}) of the i^{th} sampling interval, D_i: days between the i^{th} and $(i\text{-}1)^{th}$ sampling interval, and *n*: number of samplings.

The NH_3 emission factor (EF) was calculated by dividing the cumulative NH_3 emissions by the total nitrogen applied.

$$NH_3\,EF\,(\%) = \frac{Fluxes\,WNT - Fluxes\,WoNT}{Total\ N\ Applied}$$

where EF: emission factor (%), Fluxes WNT: fluxes with N treatment (kg NH_3-N ha^{-1}), Fluxes WoNT: fluxes without N treatment (kg NH_3-N ha^{-1}) and total N applied (kg N ha^{-1}).

The NH_3 flux intensity was calculated by dividing the cumulative NH_3 emissions by the grain yield.

$$NH_3\,flux\,intensity\ (kg\,NH_3 - N\,Mg^{-1}\,grain) = \frac{Seasonal\ NH_3\ flux}{Grain\,Yield}$$

2.3 Characterizing soil and water properties and rice yield components

Soil temperature and redox potential were continuously monitored in the field throughout rice cultivation using automatic sensors and electrodes. These devices were installed at a soil depth of 5–10 cm and connected to a battery-powered data logger and an Eh meter, respectively. After harvesting, surface soil samples were collected for chemical analysis, including measurements of pH (1:5 with H_2O), organic carbon (using the Walkley-Black method), total N (via Kjeldahl digestion), available P_2O_5 (Lancaster method), and exchangeable cations—Ca^{2+}, Mg^{2+}, and K^+—measured by ICP-OES following extraction with a 1 N ammonium acetate solution at pH 7.0.

Floodwater and soil samples were periodically collected during rice cultivation to monitor pH changes and NH_4^+ concentrations. Floodwater samples were collected concurrently with NH_3 gas samples, while soil samples were taken at monthly intervals. To measure inorganic NH_4^+ concentrations, floodwater was filtered through filter paper, and soils were extracted using a 2 M KCl solution. NH_4^+-N concentrations were then quantified by the indophenol blue method (Tzollas et al., 2010).

At the rice maturation stage, ten representative plants were sampled manually from each plot. According to the Korean standards for rice yield assessment (RDA, 2019), grains and straw were separated using a thresher. Yield components, such as tiller number, panicles per tiller, 1000-grain weight, and ripening ratio, were measured. Finally, grain yield was standardized to a 14% moisture level, and the harvest index was calculated as the ratio of grain yield to total biomass.

2.4 Statistical analysis

Statistical analyses were carried out using the Statical Tool for Agricultural Research (STAR). The data were analyzed using analysis of variance (ANOVA) for RCBD. Separation of treatment effects was carried out using Tukey's test at 5% level of significance. Regression analyses between N fertilizer level and seasonal NH_3 flux, grain yield, and NH_3 flux intensity were done using SigmaPlot10.

3 Results

3.1 Changes in temperature and Eh values

Soil temperature fluctuated similarly with changes in air temperature (Supplementary Figure S1), though no significant

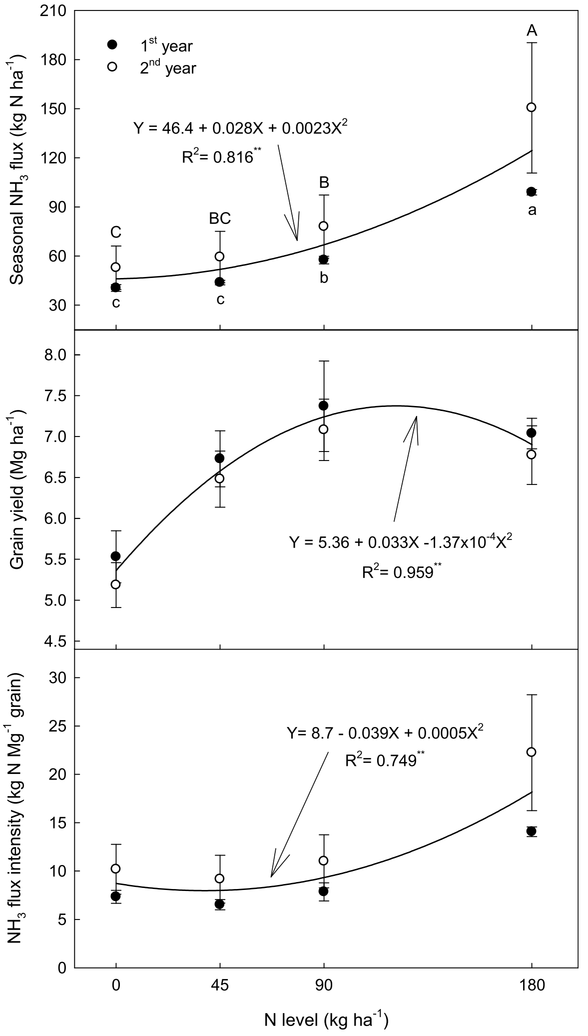

FIGURE 2
Cumulative NH_3 emission, grain yield and NH_3 flux intensity under different levels of N fertilization during rice cultivation. Vertical bars indicate standard deviations (n = 3).

differences were observed among the various N fertilization treatments. Soil temperature gradually increased after rice transplanting, peaked at the reproductive stage (60–70 days post-transplanting), and then gradually declined. Both air and soil temperatures were slightly higher in the second year than in the first year of investigation, with cumulative air temperatures of 2,913°C and 2,942°C, respectively. The higher temperatures in the second year may have contributed to improved rice development and increased productivity.

Soil Eh values followed a typical pattern seen in rice cropping environments. Eh values dropped sharply from over 150 mV to between −150 and −260 mV within 2 weeks after flooding (Supplementary Figure S1). This highly reduced soil condition, with Eh values below −200 mV, was sustained until drainage in preparation for rice harvesting. Like soil temperature, soil Eh values showed no significant variation across different levels of N fertilization.

3.2 Changes in ammonia (NH_3) emission rates

Similar NH_3 emission patterns were observed across both cropping years, regardless of N fertilization levels (Figure 1). Right after the application of chemical N fertilizer, NH_3 emission rates spiked sharply, peaking within 2–3 days, then rapidly declining to background levels. In this study, N fertilizer was applied in three stages: as a basal fertilizer (50% of total N) before transplanting, a tillering fertilizer (20%) on the 15th day after transplanting, and a panicle-initiating fertilizer (30%) on the 45th day after transplanting. Each N application triggered an increase in NH_3 emissions, with emission rates rising in proportion to the N fertilization level.

Seasonal NH_3 fluxes (Y, kg NH_3-N ha^{-1}) increased significantly with higher N fertilization levels (X, kg N ha^{-1}), following a quadratic relationship ($Y = 46.4 + 0.028X + 0.0023X^2$, $R^2 = 0.816^{**}$) (Figure 2). In control plots (0 kg N ha^{-1}), an average of 46.4 kg NH_3-N ha^{-1} was emitted, while adding 45, 90, and 180 kg N ha^{-1} of urea increased this flux by an average of 13%, 46%, and 171%, respectively. The ammonia emission factor (EF) (kg NH_3-N kg^{-1} N), which indicates net NH_3 emission losses from applied N fertilizer (Xu et al., 2019; Pan et al., 2022; Zhang et al., 2022), also showed a quadratic increase with higher N levels. For 45 kg N ha^{-1} of urea, the NH_3 EF averaged 0.13 kg NH_3-N kg^{-1} N, rising to approximately 0.23 and 0.44 kg NH_3-N kg^{-1} N for 90 and 180 kg N ha^{-1}, respectively.

The basal N fertilizer, incorporated into the surface soil layer 1 day before transplanting, accounted for only 8%–13% of total NH_3 emissions. In contrast, the tillering fertilizer (20% of total N), top-dressed at the tillering stage, contributed about 10%–15% of total NH_3 emissions. During the panicle initiation stage—typically the hottest period, around 45 days after transplanting—the remaining 30% of N fertilizer was broadcasted over the soil surface, accounting for 70%–80% of total NH_3 loss. This suggests that NH_3 flux intensity is strongly influenced by soil temperature and the method of fertilizer incorporation (Feng et al., 2017).

3.3 Changes in pH and ammonium (NH_4^+) concentration in floodwater and soil

During rice cultivation, pH and NH_4^+ concentrations, which directly influence NH_3 flux intensity (Rochette et al., 2013; Yu et al., 2020; Farooq M. S. et al., 2022), were monitored in both floodwater and soil. In floodwater, pH and NH_4^+ concentrations fluctuated in parallel with NH_3 emission rates. While floodwater pH did not correlate precisely with urea application levels, it increased consistently following urea applications. In contrast, NH_4^+ concentrations in floodwater showed a direct increase with higher urea application levels.

In comparison to the frequent floodwater monitoring, soil properties were analyzed only at monthly intervals rather than at each gas sampling. Due to this limited sampling frequency, no distinct response in soil pH and NH_4^+ concentration to urea application levels was observed (Figure 3). Soil pH showed minimal sensitivity to urea-N fertilization levels, but NH_4^+ concentrations increased proportionally with higher urea additions.

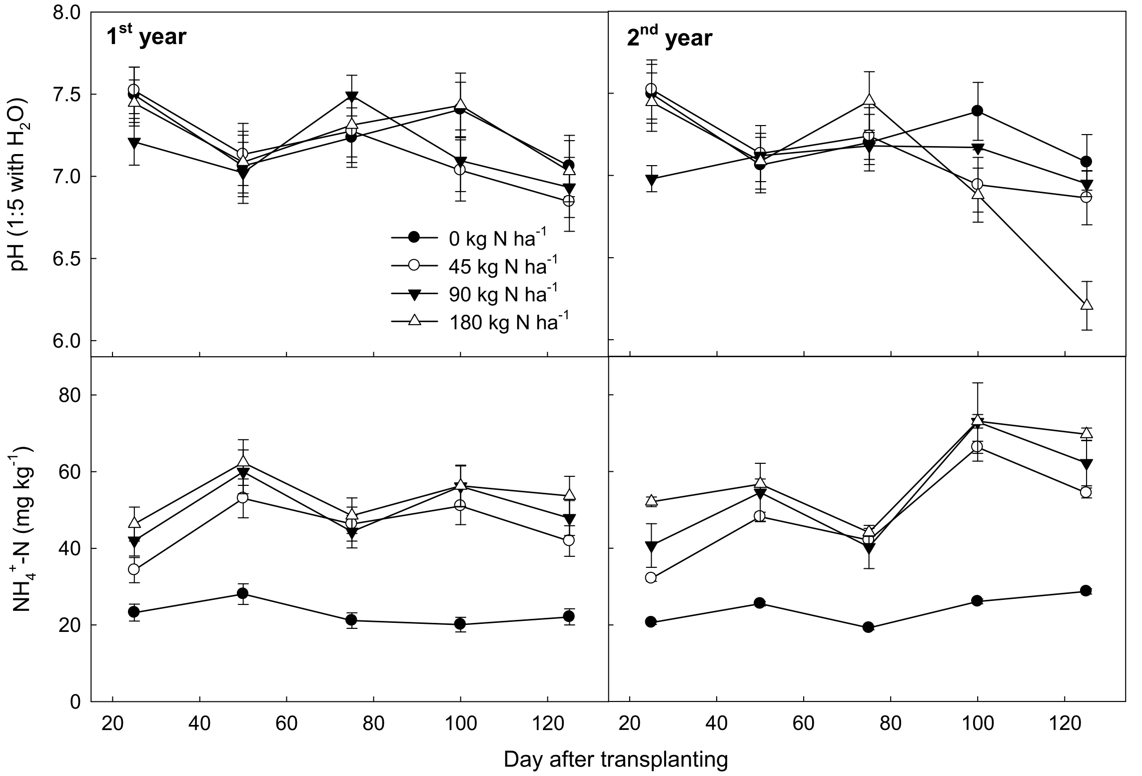

FIGURE 3
Changes in pH and NH_4^+ concentration in soil under different levels of N fertilization during rice cultivation. Vertical bars indicate standard deviations (n = 3).

3.4 Rice productivity and ammonia (NH_3) flux intensity

Rice grain yield (Y, Mg ha^{-1}) was significantly influenced by the level of N fertilization (X, kg N ha^{-1}), following a negative-quadratic trend ($Y = 5.36 + 0.033X - 1.37 \times 10^{-4}X^2$, $R^2 = 0.959^{**}$) (Figure 2). Grain productivity increased with higher N fertilization, reaching a maximum at approximately 120 kg N ha^{-1}—about a 37% increase compared to the control (no N fertilization). Beyond this level, grain productivity decreased notably with further increases in N fertilization (Supplementary Table S1).

The NH_3 flux intensity, defined as seasonal NH_3 flux per unit of grain yield (Wang et al., 2018; Sun et al., 2019; Cai et al., 2023), was measured at 8.7 kg NH_3-N Mg^{-1} grain in the control treatment. This intensity (Y, kg NH_3-N Mg^{-1} grain) varied with N fertilization level (X, kg N ha^{-1}) following a positive-quadratic response ($Y = 8.7 - 0.039X + 0.0005X^2$, $R^2 = 0.749^{**}$) (Figure 2). While NH_3 flux intensity initially decreased slightly with N application up to approximately 38 kg N ha^{-1}, it then increased sharply with higher levels of N fertilization.

4 Discussion

Among the member countries of the Organization for Economic Cooperation and Development (OECD), Korea has the highest agricultural NH_3 flux intensity (Figure 4). In 2019, Korea emitted approximately 150 kg NH_3 ha^{-1} annually, which is 6.1 times higher than the OECD average of 24.7 kg ha^{-1} from the agricultural sector. Total NH_3 emissions in Korea increased by 37% over nearly 2 decades, from 231,000 tons in 2001 to 316,000 tons in 2019, primarily due to a significant rise in agricultural emissions (Figure 5). The agricultural sector contributed an average of 77% to total NH_3 emissions, closely aligned with the global agricultural

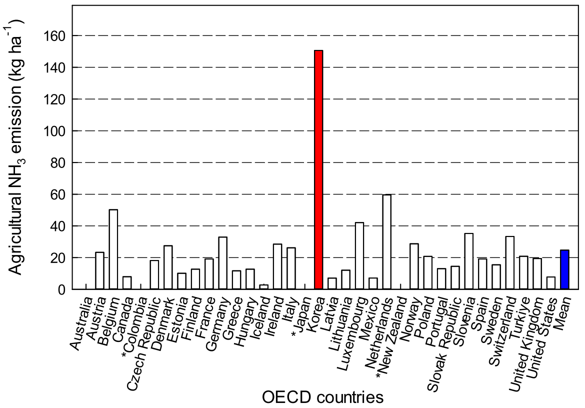

FIGURE 4
Comparison of agricultural NH_3 emissions among the OECD countries in recent (2014–2019). The data of Columbia, Japan, and New Zealand were not available in the OECD statistics.

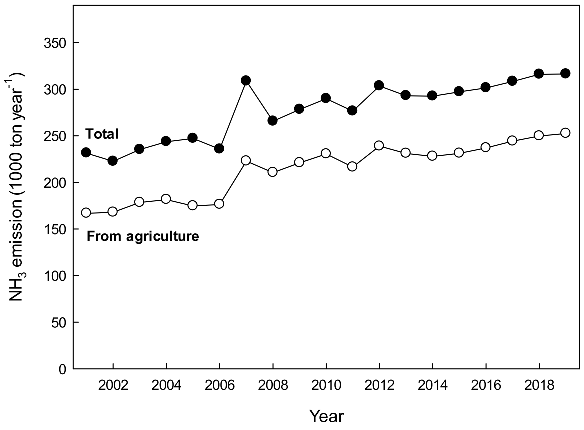

FIGURE 5
Changes in total and agricultural NH_3 fluxes in Korea.

contribution of 81% to NH_3 emissions (Van Damme et al., 2021). Agricultural NH_3 emissions in Korea rose by around 51% over the past 20 years, surpassing the 37% growth in overall NH_3 flux.

The main sources of agricultural NH_3 emissions are N-fertilized croplands and the livestock sector (Basosi et al., 2014; Zhang et al., 2018). Korea has the highest agricultural N balance among OECD countries, leading to considerable environmental impacts due to nitrogen release, including NH_3 emissions (Lim et al., 2021). This high N balance is attributed to intensive N input, primarily from chemical fertilizers and livestock manure. While chemical N fertilizer use decreased by 55% from 562,000 tons in 1990 to 251,000 tons in 2019, manure N production rose by 47%, from 206,000 tons in 1990 to 304,000 tons in 2019 (https://stats.oecd.org). Although chemical N fertilizer was the main source of NH_3 emissions in the 1990s, livestock manure has become the more significant contributor in recent years.

NH_3 emission losses are mainly influenced by NH_4^+ concentration, soil pH, and oxygen levels (Wang et al., 2018; Yang L. et al., 2020). The rapid hydrolysis of urea fertilizer, driven by soil moisture, converts urea into NH_4^+ and hydroxide ions (OH^-), increasing NH_4^+ concentrations in soil and thereby accelerating NH_3 volatilization (Yao et al., 2018; Li et al., 2023). Environmental factors, such as light intensity and air temperature, also affect NH_3 volatilization, as these conditions impact surface water temperature (Chen et al., 2015). Changes in solar radiation and temperature elevate NH_3 emission rates by increasing the surface compensation point and altering resistance dynamics (Loubet et al., 2018). Soil moisture further affects the NH_4^+/NH_3 balance; higher soil water potential increases NH_4^+ concentrations when NH_4^+ supply exceeds NH_3 oxidation. Above field capacity, however, this balance shifts, impacting nitrification rates (Cameron et al., 2013; Yun and Ro, 2014).

The Intergovernmental Panel on Climate Change (IPCC) has proposed a global ammonia (NH_3) emission factor (EF) of 10% of nitrogen (N) applied to cropping lands, with an uncertainty range of 3%–30%. In 2019, the IPCC updated the NH_3 EF for various N fertilizer types, spanning from 0.2% to 14.2% (Hergoualc'h et al., 2019). A recent meta-analysis by Ma et al. (2021) estimated global NH_3 EF values of 12.56% for synthetic N fertilizers and 13.95% specifically for rice fields. However, in our study of the selected rice paddy, NH_3 EF increased exponentially with rising N fertilization levels, from approximately 13% at 45 kg N ha^{-1} of urea application to 23% and 44% at 90 and 180 kg N ha^{-1}, respectively (Figure 2). This suggests that NH_3 EF should be adjusted based on N fertilizer input level (Ma et al., 2021; Wang et al., 2021), emphasizing the need for lower N fertilization to reduce NH_3 emissions in flooded rice paddies (Fan et al., 2011; Shan et al., 2015). In Korea, 90 kg ha^{-1} of N fertilization is recommended for rice, with urea as the primary N source, resulting in an estimated NH_3-N EF of around 23%.

Rice cropping is known to have a higher NH_3 EF than upland crops, largely due to lower oxygen (O_2) levels in paddy soils (Lee et al., 2024). The limited O_2 in waterlogged conditions inhibits nitrification, the process converting NH_4^+-N to NO_3^--N, which leads to increased NH_3 emissions (Nurulhuda et al., 2018; Yang W. et al., 2020). In our mono-rice paddy field, which has a rice-growing period of 100–140 days followed by over 200 days of fallow period, soil Eh dropped from 150 mV to −200 mV shortly after flooding for rice cultivation (Supplementary Figure S1). This reduction process raised soil pH to between 7.5 and 9.0, further enhancing NH_3 emissions (Feng et al., 2017; Kim et al., 2021). Elevated pH levels were sustained throughout the flooded period (Figure 3) (Guo et al., 2018; Ding et al., 2019).

Among synthetic N fertilizers, urea leads to the highest NH_3 EF due to its rapid hydrolysis, which creates localized increases in soil pH that promote NH_3 volatilization (Bittman et al., 2014). Regardless of urea-N fertilization levels, NH_3 emissions spike shortly after N fertilizer application and quickly return to baseline (Figure 1). However, NH_3 EFs for N fertilizers can vary significantly depending on soil, climate, and site-specific management practices (Pan et al., 2016; Sommer et al., 2004). In this study, half of the urea was incorporated as basal fertilizer before rice transplanting, resulting in only 10% of the total NH_3 flux, whereas top-dressing 20% and 30% of urea-N at tillering and panicle initiation stages contributed 10%–15% and 70%–80% of total NH_3 fluxes, respectively. The basal fertilizer mixed into the plow layer likely led to lower NH_3 emissions due to NH_4^+ adsorption onto clay particles (Xia et al., 2020; Mirkhani et al., 2023), in contrast to top-dressing at tillering and panicle initiation. Similar reductions in NH_3 volatilization and runoff losses were observed with mechanical side deep fertilization (MSDF) (Min et al., 2021). Moreover, a field investigation in China revealed that deep placement of urea-N fertilizer has indicated effective reduction in NH_3 volatilization to 1%–2% of the applied N, achieving a 91% reduction compared to surface broadcasting (Yao et al., 2018). Our data showed that NH_4^+ concentration and pH in floodwater significantly increased after top-dressing at these stages (Figure 6), underscoring the importance of incorporating N fertilizer into the soil layer to reduce NH_3 emissions (Rochette et al., 2013; Huang et al., 2016).

In this study, NH_3 emissions correlated more strongly with NH_4^+ concentrations in floodwater than in soil (Figure 7). While NH_3 flux is typically linked to soil NH_4^+ levels, floodwater NH_4^+ concentration was the primary determinant of NH_3 emissions in this rice paddy (Li et al., 2008; Yao et al., 2018; Canatoy et al., 2024). These findings suggest that incorporating chemical N fertilizers below the surface, rather than surface application, could effectively reduce NH_4^+ concentration in floodwater (Li et al., 2014; Gaihre et al., 2015), thus limiting NH_3 volatilization during rice growth (Zhang et al.,

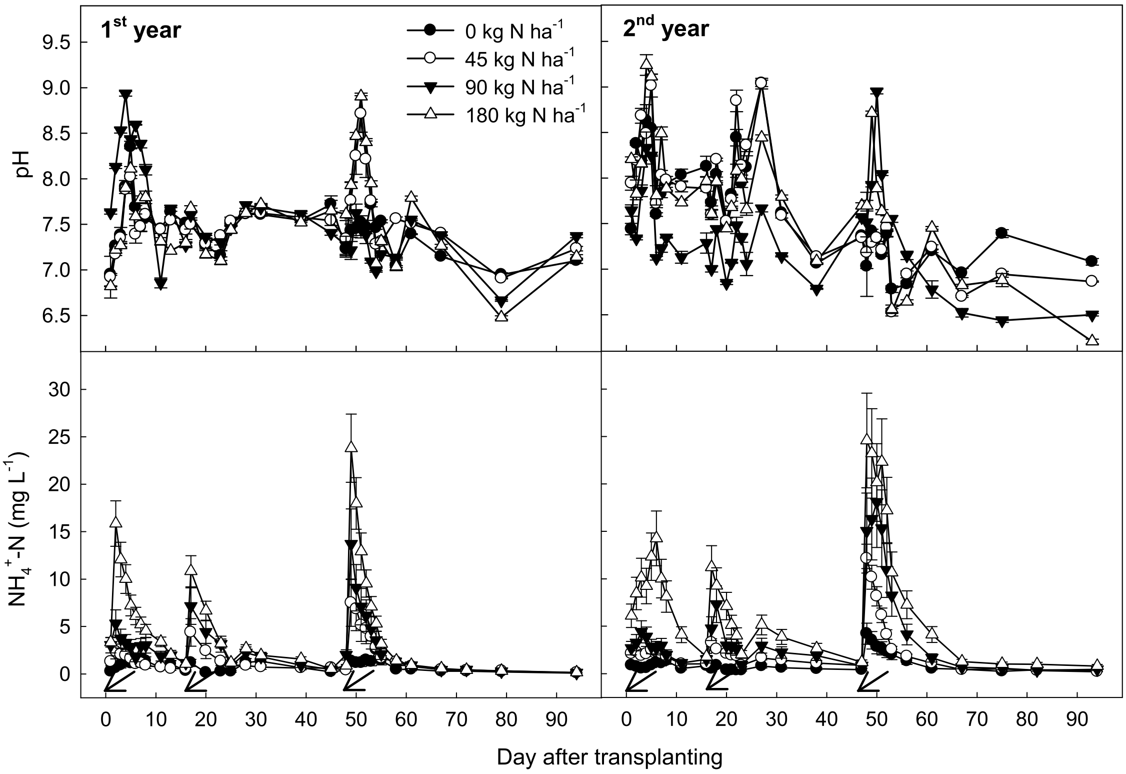

FIGURE 6
Changes in pH and NH_4^+ concentration in floodwater under different levels of N fertilization during rice cultivation. Vertical bars indicate standard deviations (n = 3). Arrows indicate fertilization day.

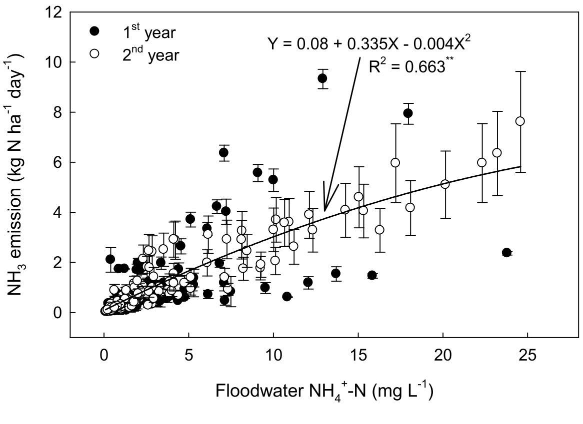

FIGURE 7
Relationship between NH_3 emission rates to NH_4^+ concentration in floodwater under different levels of N fertilization during rice cultivation. Vertical bars indicate standard deviations (n = 3).

2017; Yao et al., 2018). Moreover, the depth of N fertilizer placement should be selected with caution, as the upward movement of NH_4^+-N can result in its entry into floodwater. In the absence of site-specific data, a placement depth of 10 cm is recommended. However, for sandy loam soils, deeper placement may be required to mitigate potential nitrogen losses (Liu et al., 2015). Controlled-release N fertilizers have similarly been shown to decrease NH_3 losses by reducing NH_4^+ levels in surface water (Xu et al., 2012).

NH_3 flux intensity, defined as total NH_3 flux per unit of grain yield (Wang et al., 2018), was 8.7 kg NH_3-N Mg^{-1} grain in the control treatment and showed a quadratic relationship with N fertilization level (Figure 2). While NH_3 flux intensity decreased slightly with a 38 kg N ha^{-1} urea application to 7.9 kg N Mg^{-1} grain, it increased sharply at higher N levels. At 120 kg N ha^{-1}—the application rate for peak grain yield—the NH_3 flux intensity was 11.4 kg N Mg^{-1} grain, whereas the recommended 90 kg N ha^{-1} reduced this intensity by 2.1 kg N Mg^{-1} grain.

Rice grain yields differed by only 1.7% between the 120 and 90 kg N ha^{-1} applications, indicating that reduced N fertilization may be a viable strategy to mitigate NH_3 emissions without compromising yield (Subbarao and Searchinger, 2021). Additionally, alternative fertilizers like ammonium sulfate could further reduce NH_3 volatilization, though the specific reaction mechanisms warrant further investigation.

5 Conclusion

During rice cultivation, the majority of NH_3 emissions occurred shortly after the application of chemical N fertilizer. Total NH_3 flux exhibited a quadratic increase with rising N application levels. Basal N fertilization (50% of total N) was incorporated into the surface soil layer, slightly impacting total NH_3 flux. In contrast, the remaining urea-N was broadcasted on the soil surface during the tillering (20% of total N) and panicle initiation stages (30% of total N), contributing to 87%–92% of total NH_3 flux. NH_3 emission rates were strongly correlated with dissolved NH_4^+-N concentration in floodwater rather than soil concentration. Incorporating N fertilizer into soil layers instead of broadcasting it on the surface effectively reduced NH_4^+-N concentration in floodwater, thereby lowering NH_3 volatilization losses. While NH_3 flux intensity initially decreased with an additional 38 kg N ha^{-1} application, it increased significantly with higher N rates. In conclusion, to mitigate NH_3 volatilization losses in rice paddies, reducing N fertilization and incorporating fertilizer within the soil layer, rather than surface broadcasting, are essential strategies.

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 authors.

Author contributions

RC: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Project administration, Software, Writing–original draft, Writing–review and editing. SC: Investigation, Project administration, Resources, Writing–review and editing. SG: Formal Analysis, Investigation, Writing–review and editing. PK: Conceptualization, Funding acquisition, Project administration, Resources, Supervision, Writing–original draft, Writing–review and editing. GK: Project administration, Supervision, Writing–review and editing.

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Conflict of interest

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

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2024.1479712/full#supplementary-material

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