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Co-application of biochar and compost with decreased N fertilizer reduced annual ammonia emissions in wetland rice

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Ammonia (NH_3) emission from rice fields is a dominant nitrogen (N) loss pathway causing negative impacts on farm profitability and the environment. Reducing N fertilizer application to compensate for N inputs in organic amendments was evaluated for effects on N loss *via* volatilization, rice yields and post-harvest soil properties in an annual irrigated rice (Boro) – pre-monsoon rice (Aus) – monsoon (Aman) rice sequence. That experiment was conducted using the integrated plant nutrition system (IPNS; nutrient contents in organic amendments were subtracted from the full recommended fertilizer dose i.e., RD of chemical fertilizers) where six treatments with four replications were applied in each season: (T_1) no fertilizer (control), (T_2) RD, (T_3) poultry manure biochar (3 t ha^{-1}; pyrolyzed at 450°C) + decreased dose of recommended fertilizer (DRD), (T_4) rice husk ash (3 t ha^{-1}) + DRD, (T_5) compost (3 t ha^{-1}) + DRD, and (T_6) compost (1.5 t ha^{-1})+ biochar (1.5 t ha^{-1}) + DRD. The N loss *via* volatilization varied twofold among seasons being 16% in irrigated rice and 29% in the pre-monsoon rice crop. In irrigated rice, T_6 had significantly lower NH_3 emissions than all other treatments, except the control while in pre-monsoon and monsoon seasons, T_6 and T_3 were alike. Pooling the three seasons together, biochar (T_3) or biochar plus compost (T_6) reduced NH_3 loss *via* volatilization by 36-37% while compost alone (T_5) reduced NH_3 loss by 23% relative to RD. Biochar (T_3) and biochar plus compost mixture (T_6) reduced yield-scaled NH_3 emissions by 40 and 47% relative to the RD of chemical fertilizer (T_2). The organic amendments with IPNS reduced the quantity of N fertilizer application by 65, 7, 24, and 45% in T_3, T_4, T_5, and T_6 treatments, respectively, while rice yields and soil chemical properties in all seasons were similar to the RD. This study suggests that incorporation of biochar alone or co-applied with compost and decrease of N fertilizer on an

IPNS basis in rice-based cropping systems can reduce N application rates and NH_3 emissions without harming yield or soil quality.

KEYWORDS

emission factor, NH_3 emissions, yield- rice yield, soil quality, scaled NH_3 emissions, ammonia emissions

1. Introduction

More than 90% of rice (*Oryza sativa*) in the world is grown in Asia, feeding more than 60% of the global population and it supports the livelihood of millions of small and marginal farm families in south Asia (Brolley, 2015). Bangladesh is the third largest rice producing country in the world where rice contributes about 4.5% to the country's gross domestic product. In this country, rice is grown in three seasons i.e., irrigated winter rice called Boro, pre-monsoon rice called Aus and monsoon rice called Aman. In 2020–21, gross annual production of 3-seasons' rice was 36.61 Mt (BBS, 2021). Despite large quantities of nitrogenous fertilizer being applied to maintain rice yields, there is low use efficiency (30–35%) of this fertilizer, and significant gaseous nitrogen (N) loss (Xia and Yan, 2012). In Bangladesh, N is applied at around 150 kg N ha^{-1} $season^{-1}$, which is almost double the rate of Japan (80 kg N ha^{-1} $season^{-1}$) and a little higher than in the United States (140 kg N ha^{-1} $season^{-1}$) (Linquist et al., 2015; Xia et al., 2016). Ammonia (NH_3) is one of the most important by-products of applied N in rice field and volatilization of NH_3 is the primary source of soil nitrogen loss (Pan et al., 2016; Xu et al., 2019; Kuttippurath et al., 2020; Wang et al., 2021).

In 2021, Bangladesh ranked first globally in air pollution due to elevated concentrations of CH_4 and NH_3 in the air (IQAir, 2021). Even though NH_3 is not a potential greenhouse gas (GHS), its emissions and re-deposition can have negative impacts on the environment (Zhang et al., 2020). Volatilized NH_3 is a secondary source of N_2O and NO (Mosier et al., 1998), and NH_3 volatilization is responsible for around 30% of N deposition (Wolfe and Patz, 2002). Ammonia has a negative impact on regional air quality and human health generating aerosols in the atmosphere, influencing the radiation balance by scattering light and changing the earth's reflectivity (Xu and Penner, 2012; Stokstad, 2014). In Asia, agricultural gaseous N losses including NH_3 volatilization may reach 18.8 Tg N yr^{-1} in 2030 (Zheng et al., 2002; Liu et al., 2021). The global estimate of NH_3 emissions from urea-fertilized soils ranges from 10 to 20%, although in warmer zones, it is substantially higher (Cantarella et al., 2018). Because of extensive rice cultivation, the Indo Gangetic Plain has been identified as a hotspot for NH_3 fluxes but estimates of the rates of loss are limited (Kuttippurath et al., 2020; Uddin et al., 2021; Jahangir et al., 2022).

Mitigating NH_3 emissions from agriculture will not only cut the cost of fertilizer N, but it will also improve air and water quality (Zhao et al., 2017). To limit N losses, various practices are proposed such as use of nitrification inhibitors, urease inhibitors (UI), elemental S, and polymers (He et al., 2018), crop residue removal management (Battaglia et al., 2018, 2021), and organic amendments (Saarnio et al., 2013; Malińska et al., 2014). The role of organic amendments like poultry manure, biochar, compost, etc. in mitigating NH_3 fluxes from wetland rice fields is unresolved since some researchers have reported positive effects (Saarnio et al., 2013; Malińska et al., 2014; Ali et al., 2019), while others reported negative effects (Feng et al., 2017; Chu et al., 2019; Rahaman et al., 2020). Ammonia emissions increase with the N fertilizer rate (Uddin et al., 2021; Jahangir et al., 2022) which suggests that with organic amendments the rate of N fertilizer application could be decreased to reduce both economic and environmental costs while maintaining soil quality. Biochar is a carbon-rich substance made from the pyrolysis of organic matter (Lehmann and Joseph, 2009). It has been reported to prevent NH_3 loss and improve soil health, crop output, and soil carbon sequestration, while also recycling organic waste (Diatta et al., 2020). Biochar and compost mixture can be utilized as fertilizer sources to increase soil nutrients and reduce nutrient losses (Banik et al., 2021).

Ammonia emissions are estimated by the IPCC Tier 1 method but only a single emission factor is scheduled (Bouwman, 1996). While a large amount of N loss as NH_3 can occur, the exact quantity is not known for accurate N balance calculations for many managed agricultural systems including the rice-based cropping patterns of South Asia. Previously, Uddin et al. (2021) evaluated the impact of Conservation Agriculture along with different N fertilization rates on NH_3 volatilization in winter rice (Boro rice). They reported that NH_3 volatilization accounted for 16–21% of the applied N. However, there is no baseline data of NH_3 volatilization in the other two rice growing seasons when temperature is higher (Aus and Aman rice), nor on the impacts of reduced N fertilizer application when co-applied with organic amendments (i.e., integrated plant nutrition system (IPNS) approach) on NH_3 volatilization. We hypothesize that co-application of organic fertilizer such as biochar, rice mill ash (RMA) and compost together with inorganic N fertilizers, which together provide the same amount of N as chemical fertilizer alone, would reduce

NH_3 volatilization loss without changing the soil N status. Thus, the study was conducted to evaluate the effects of rice husk ash, biochar alone or with compost (IPNS basis) on seasonal and annual NH_3 emissions, rice yields and soil quality.

2. Materials and methods

2.1. Experimental site description

The study was carried out on the Soil Science Field Laboratory (24° 71.59′ N, 90° 42.50′ E) of Bangladesh Agricultural University (BAU) in Mymensingh, Bangladesh. The experiment was done with an annual irrigated rice– pre-monsoon rice – monsoon rice cropping sequence, which is a common cropping sequence followed by the farmers of this country. The irrigated rice season, pre- monsoon rice season and monsoon rice season were occupied by Boro, Transplanted Aus (T. Aus), and Transplanted Aman (T. Aman) rice growing seasons, respectively. The field site was characterized as a Non-calcareous Dark Gray Floodplain soil (Aeric Haplaquept in US Soil Taxonomy), and belongs to agro-ecological zone-9, Old Brahmaputra Floodplain soil (FAO/UNDP, 1988). The soil is moderately drained with a silt loam texture and near neutral pH (6.5). The region has a sub-tropical monsoon climate with a mean annual temperature of 26°C, average annual rainfall of 1,800 mm, and relative humidity of 85% (Uddin et al., 2021, Supplementary Data 1).

2.2. Experimental design and crop management

The experiment was conducted with the same treatment combinations for Boro – T. Aus – T. Aman rice crops in sequence, but with different levels of a nutrient based on the requirements of individual crop and their target yields. That experiment was conducted under integrated plant nutrition system (IPNS; nutrient contents in organic amendments were subtracted from the full recommended fertilizer dose, i.e., RD of chemical fertilizers) where six treatments with four replications were applied in each season. The treatments were: (T_1) no fertilizer (control), (T_2) RD, (T_3) poultry manure biochar + decreased dose of recommended fertilizer (DRD), (T_4) rice husk ash + DRD, (T_5) compost + DRD, and (T_6) compost + biochar + DRD, laid out in a randomized complete block design (RCBD) with four replications. Total plot number was twenty-four for each season and the same plots were used for consecutive rice growing seasons and the unit plot size was 5 m × 4 m, with a 0.75 m inter-plot space, and 1 m inter-block space. The varieties were BRRI dhan28 for Boro, BINA dhan19 for T. Aus and BRRI dhan49 for T. Aman rice, respectively. Boro rice was grown during January–April (winter season), followed by T. Aus rice as a rainfed crop from May to August (pre-monsoon), and then T. Aman rice from August to November (monsoon).

The rate of chemical fertilizer application was based on Fertilizer Recommendation Guide (FRG, 2018) for the test crops. The nutrient contents of used organic amendments are presented in Table 1 while the recommended doses of nutrients for three seasons were presented in Table 2. Urea, triple super phosphate, muriate of potash, gypsum and zinc sulfate were used for N, phosphorus (P), potassium (K), sulfur (S) and zinc (Zn) sources, respectively. Except urea all the nutrients were applied during land preparation. For both Boro and T. Aman rice nitrogenous fertilizer (urea) was applied in equal three splits, followed interval for Boro rice was at 10, 31, and 53 Days After Transplanting (DAT) and for T. Aman that interval was at 9, 24, and 39 DAT. In T. Aus rice two splits of urea application were followed, at 11 and 29 DAT. Compost was collected from Mazim Agro Industries Ltd and rice husk ash from a local rice mill. Biochar was produced using poultry manure by an anaerobic pyrolysis process at 450°C for 4 hr. The organic materials were air dried to 15% moisture content, pulverized and sieved with a 2 mm mesh. In T_3, T_4, and T_5 treatments organic materials were applied at the rate of 3 t ha^{-1} where T_6 was balanced by applying 1.5 t ha^{-1} compost and 1.5 t ha^{-1} biochar, the remaining nutrients were applied from chemical fertilizer based on FRG under IPNS approach. Glyphosate (Round up®) was sprayed over the field at a rate of 1.85 kg ha^{-1} 3 days before final land preparation. The field was irrigated to maintain 3 cm standing water throughout rice growing seasons.

2.3. NH_3 gas sampling and analysis

Field measurements of NH_3 were conducted during January 2020–November 2021 in the rice field. A low-cost chamber was deployed in field conditions for NH_3 volatilization measurements (Nichols et al., 2018) and used for monitoring NH_3 fluxes in crop fields (Martins et al., 2021a,b; Zaman et al., 2021). The open chamber method was used to measure NH_3 fluxes in the field site on a daily basis. In the laboratory, the amount of NH_3 trapped in acid solution was estimated using the Kjeldahl principle (Keeney and Nelson, 1982). Measurements were done on the soil shortly after urea application and it was carried out until the fluxes were below the detection limit in each case.

2.4. NH_3 fluxes and emission factor calculation

The NH_3 fluxes were calculated following Equation 1.

$$NH_3 \text{ fluxes } \left(\text{mg N m}^{-2}\text{ d}^{-1}\right) = \frac{(\text{FBR} - \text{IBR}) \times 14.01 \times 0.01 \times 1000}{\text{Surface Area } (\text{m}^2) \times 1000} \quad (1)$$

TABLE 1 Chemical properties of organic amendments (poultry manure biochar, cattle compost, rice husk ash) used in three rice growing seasons.

Organic amendments	Soil organic carbon (%)	Total N (%)	Total P (mg kg^{-1})	Total S (mg kg^{-1})
Biochar	33.1	2.66	54.9	1990
Compost	25.3	0.98	14.4	770
Rice husk ash	3.10%	0.14%	3.9	126

TABLE 2 Amounts of nutrients added from each source of organic amendments used in three rice growing seasons.

	Treatment	N (kg ha^{-1})	P (kg ha^{-1})	K (kg ha^{-1})	S (kg ha^{-1})
Boro rice	Control	0	0	0	0
	Chemical fertilizer	144	21	60	8
	Biochar	66.5	3.43	58	4.97
	Rice husk ash	7	0.49	94	0.63
	Compost	24.5	0.9	23	1.93
	Compost + Biochar	45.5	2.17	40	3.45
T. Aus rice	Control	0	0	0	0
	Chemical fertilizer	72	7	40	3
	Biochar	66.5	3.43	58	4.97
	Rice husk ash	7	0.49	94	0.63
	Compost	24.5	0.9	23	1.93
	Compost + Biochar	45.5	2.17	40	3.45
T. Aman rice	Control	0	0	0	0
	Chemical fertilizer	90	8.5	50	4
	Biochar	66.5	3.43	58	4.97
	Rice husk ash	7	0.49	94	0.63
	Compost	24.5	0.9	23	1.93
	Compost + Biochar	45.5	2.17	40	3.45

Where, NH_3 flux was measured as mg N m^{-2} d^{-1}; FBR, Final Burette Reading (ml); IBR, Initial Burette Reading (ml); molecular weight of $N = 14.01$ g; normality of $H_2SO_4 = 0.01$ N; and 1000 = unit conversion factor. The sum of NH_3 fluxes on sampling days across the whole sampling period was used to estimate cumulative NH_3 fluxes.

We derived EF (%) according to Equation 2 (Mazzetto et al., 2020).

$$EF(\%) = \frac{\text{Fluxes FT} - \text{Fluxes C}}{\text{Applied Fert}} \times 100 \quad (2)$$

Where EF (%) = Emission Factor, in%; Fluxes FT, Fluxes from fertilizer treatment (in kg N ha^{-1}); Fluxes C, Fluxes from control treatment (in kg N ha^{-1}); Applied Fert, Amount of fertilizer applied (in kg N ha^{-1}).

Yield-scaled NH_3 fluxes were determined following the Equation 3.

$$\text{Yield-scaled } NH_3\text{fluxes}(\text{kg N t grain}^{-1}) = \frac{\text{Total fluxes from a plot (kg)}}{\text{Yield obtained from the plot (t)}} \quad (3)$$

2.5. Measurement of grain yield

Before the final harvest of each rice growing season, plants from 1 m^2 area were collected from each plot, weighed and then oven dried to determine yield and system productivity i.e., pooling together the grain yields of the three rice seasons. For oven drying, 1000 grain samples of each plot were placed in an oven at 65°C until it reached constant weight to determine moisture content. After drying, rice grain samples were weighed and yields were estimated as tonne per hectare.

2.6. Soil sample collection and laboratory analysis

Composite soil samples were collected with an auger at 0–15 cm soil depth from the sites next to each NH_3 gas sampling chamber and preserved in sealable plastic bags in a cooler box. The field-moist soil was air-dried for 2 weeks in the shade at room temperature (25°C) and processed (2 mm sieved) for analysis of major soil physico-chemical parameters. During the NH_3 loss measurement, the pH of the soil was monitored in the field every seven days using a portable pH meter (HI12923; Hanna Instruments). The Kjeldahl method was used to determine total nitrogen (TN) content in the soil (Fawcett, 1954) and the wet oxidation method (Walkley and Black, 1934) was used for soil organic carbon (SOC) determination. Soil samples were extracted with 2 M KCl (1: 2.5; w/w) and NH_4^+ and NO_3^- contents were measured using the method described by Keeney and Nelson (1982).

2.7. Statistical analysis

One-way ANOVA was performed using treatments as fixed factors. The normality test on the NH_3 data was checked before analysis. *Post-hoc* tests were performed to separate differences among the treatments using the Tukey-Kramer multiple comparison Test. All statistical analyses were considered significant at $p \leq 0.05$, unless otherwise mentioned. All the statistical analyses were performed on Statistics 10 and Jamovi1.0.0.0 (R Package). Correlation among the parameters studied was tested by using Pearson's correlation coefficient comparison test.

3. Results

3.1. Time course of NH_3 fluxes after urea application

Ammonia fluxes reached their peaks at 2–3 days after each split of urea application in all seasons. The highest NH_3 fluxes were recorded during the second split application of urea in boro season but that was higher from first split application in both T. Aus and T. Aman seasons (Figure 1). In T. Aman rice, the NH_3 fluxes were 1.5–2.0 times higher in the first split compared to the second and third splits, while the latter two results were almost the same. The NH_3 flux peaks returned to background level at 7–10 days after each split urea application (Figure 1). The highest peak in all splits at each season ranked in the order of chemical fertilizer > RMA > compost > compost + biochar > biochar > control (Figure 1B). On the peak period at 1st, 2nd, and 3rd splits of urea fertilization the NH_3 fluxes from RD treatment were 117, 305, 160 mg N $m^{-2}d^{-1}$ in Boro season and that were 193, 165 mg N $m^{-2}d^{-1}$ in T. Aus and 289, 138 and 136 mg N $m^{-2}d^{-1}$ in T. Aman season, respectively.

3.2. Effects on mean and cumulative ammonia fluxes

The effect of organic and inorganic fertilizers on mean and cumulative ammonia fluxes of all three rice crops was significant. In Boro rice, the highest mean and cumulative NH_3 fluxes were observed in chemical fertilizer treated plot, which was statistically similar to RMA, and the lowest emission was observed in control (Table 3). Integrated use of organic and inorganic fertilizers reduced NH_3 emissions by 6–23% compared to the RD treatment. Either biochar or biochar plus compost reduced N loss *via* volatilization by 16–23%, while compost alone reduced it by 13%. Likewise, organic and inorganic fertilization also significantly influenced mean and cumulative NH_3 fluxes in T. Aus rice. Mean and cumulative NH_3 fluxes were higher in RD than in other treatments. Reduction in NH_3 fluxes ranged from 10% in rice husk ash to 52% in biochar. Disregarding the control, the highest mean and cumulative NH_3 fluxes were measured in chemical fertilizer treated plots, whereas the lowest emissions were measured in compost plus biochar treated plots. Combined application of organic and inorganic fertilizers reduced NH_3 volatilization by 20–45% compared to the RD application. Pooling the three rice growing seasons together, treatments comprised of biochar or biochar plus compost under IPNS basis reduced N loss *via* volatilization by 36–37% while biochar alone reduced it by 23% over sole application of full dose of recommended fertilizer as a treatment.

3.3. Effects on NH_3 emission factor and yield scaled NH_3 emissions

The NH_3 emission factor (EF) was significantly influenced by the application of organic and inorganic fertilizers. The NH_3 EF ranged from 12% in compost + biochar to 16% in chemical fertilizer-treated plots in Boro rice, from 21% in biochar to 29% in sole chemical fertilizer treated plots in T. Aus rice, and from 22% in biochar to 28% in chemical fertilizer-treated plots in T. Aman rice (Table 4). Yield-scaled NH_3 emissions in Boro rice varied from 0.17 kg t^{-1} in control to 2.88 kg t^{-1} in chemical fertilizer treated plots (Table 4). Except for the control treatment, yield scaled NH_3 emissions were similar among treatments in Boro rice. Mixture of biochar and compost reduced the NH_3 EF and yield-scaled NH_3 emission in all rice fields. Similarly, yield-scaled NH_3 emissions in T. Aus rice varied between 1.04 kg t^{-1} in control and 5.83 kg t^{-1} in chemical fertilizer treated

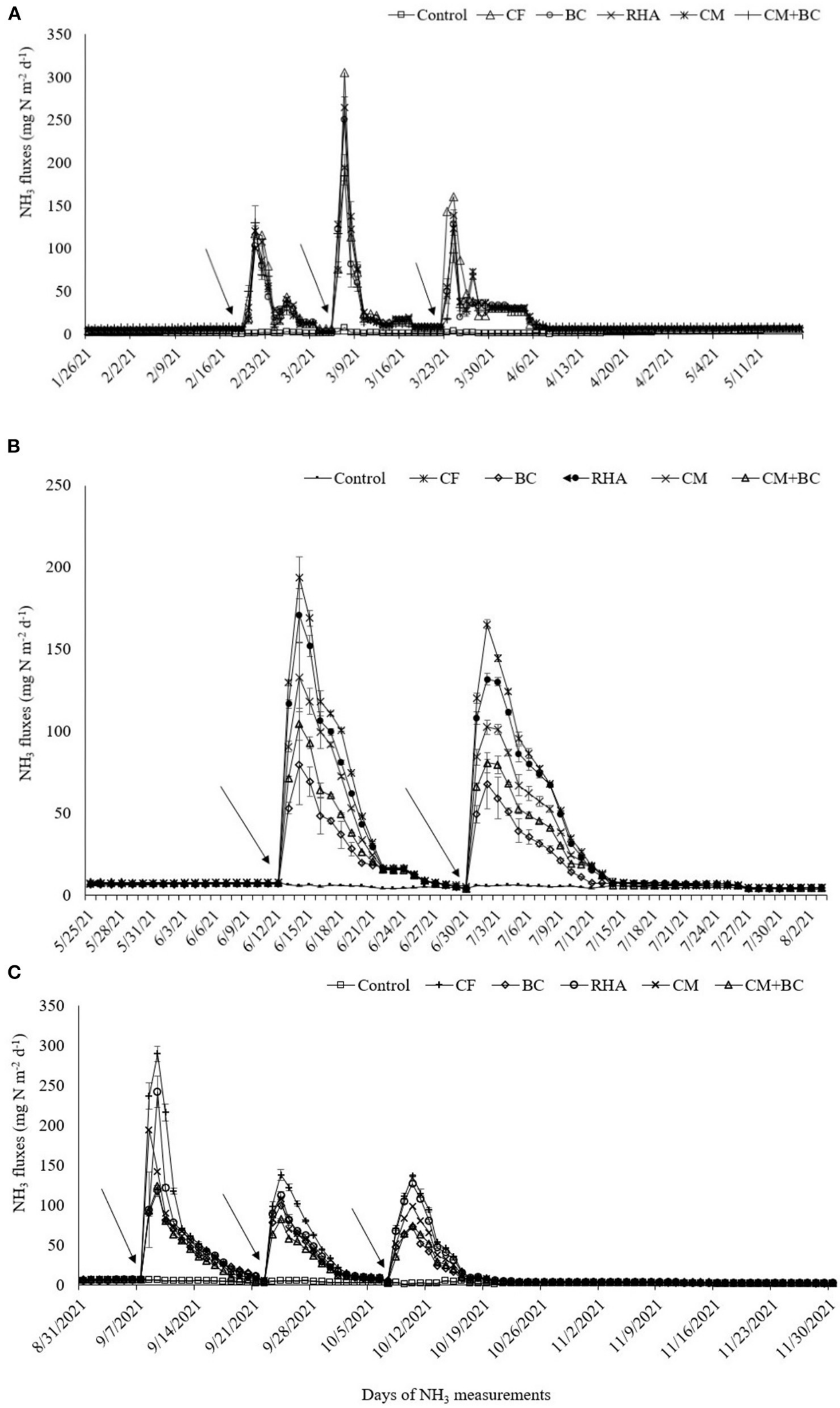

FIGURE 1
Daily NH_3 fluxes (mean ± SE; $R = 4$) from different plots treated with organic and inorganic fertilizers throughout the year [**(A)** Boro, **(B)** T. Aus, **(C)** T. Aman]. Arrows indicate the day of split urea application.

TABLE 3 Effects of organic and inorganic fertilizers on mean and cumulative ammonia fluxes in the Boro - T. Aus - T. Aman rice cropping pattern.

Treatment	Boro rice		Aus rice		Aman rice		Year round	
	Mean NH_3 fluxes (mg N m^{-2} d^{-1})	Cumulative NH_3 fluxes (mg N m^{-2})	Mean NH_3 fluxes (mg N m^{-2} d^{-1})	Cumulative NH_3 fluxes (mg N m^{-2})	Mean NH_3 fluxes (mg N m^{-2} d^{-1})	Cumulative NH_3 fluxes (mg N m^{-2})	Mean NH_3 fluxes (mg N m^{-2} d^{-1})	Cumulative NH_3 fluxes (mg N m^{-2})
Control	1.4 ± 0.4e	69 ± 1.7e	4.8 ± 0.1f	292 ± 3.0f	3.5 ± 0.1e	164 ± 3.3e	2.9 ± 0.1e	1055 ± 14.0e
Chemical fertilizer	41.0 ± 1.0a	1966 ± 47.5a	37.1 ± 0.9a	2262 ± 56.4a	56.8 ± 0.6a	2670 ± 29.3a	21.4 ± 0.4a	7822 ± 128.2a
Biochar	34.6 ± 0.5c	1660 ± 25.1c	17.7 ± 0.2e	1082 ± 14.2e	33.5 ± 0.4d	1575 ± 19.2d	14.4 ± 0.1d	5238 ± 33.4d
Rice husk ash	38.4 ± 0.7ab	1844 ± 32.0ab	33.5 ± 0.5b	2045 ± 27.4b	45.4 ± 1.0b	2133 ± 45.5b	19.3 ± 0.3b	7057 ± 93.6b
Compost	35.5 ± 1.0bc	1703 ± 47.1bc	27.9 ± 0.3c	1703 ± 18.4c	40.6 ± 1.2c	1909 ± 57.3c	17.2 ± 0.2c	6281 ± 82.7c
Compost + Biochar	31.4 ± 0.3d	1506 ± 12.8d	22.2 ± 0.3d	1357 ± 18.4d	31.2 ± 0.5d	1465 ± 25.2d	15.2 ± 0.4d	5530 ± 136.9d
CV (%)	4.43	4.43	2.67	2.67	3.50	3.50	3.23	3.23
Level of significance	***	***	***	***	***	***	***	***

***p < 0.001. Columns (Mean ± SE) with different letters vary significantly.

plots (Table 4). Ignoring the control treatment, the highest yield-scaled NH_3 emissions were noted in chemical fertilizer, which was similar to RMA, and the lowest value was in biochar with or without compost treatment. Yield-scaled NH_3 emissions in T. Aus rice were 1 to 6 times higher than that in Boro rice. Similarly, yield-scaled NH_3 emissions in T. Aman rice ranged from 0.47 kg t^{-1} in control to 4.43 kg t^{-1} in chemical fertilizer-treated plots (Table 4). Discounting the control treatment, the highest yield-scaled NH_3 emission was recorded in chemical fertilizer, and the lowest value was in biochar with or without compost. Yield-scaled NH_3 emissions in T. Aman rice were 1.0 to 2.7 times higher than that in Boro rice, and 0.5 to 1.0 times that of T. Aman rice (Table 4).

3.4. Effects on crop yields and system productivity

Organic and inorganic fertilizers influenced the grain yield of Boro, T. Aus, and T. Aman rice ($p < 0.05$, Table 5), and system productivity of Boro – T. Aus – T. Aman rice cropping pattern ($p < 0.01$, Table 5). All the treatments were similar to each other in term of crop yield except T_1. Treatments under RD or IPNS had no statistical variation for crop yield and system production. In Boro and T. Aman rice, grain yields were the highest for application of compost and likely the system productivity was the highest for compost application and the lowest for rice husk ash, excluding the control treatment.

3.5. Effects on soil properties

Organic and inorganic fertilizers had a significant impact on soil organic carbon (SOC) during rice cultivation ($p < 0.05$, Table 6). Soil organic carbon increased by 6–14% over the control in plots treated with different amendments (Table 6). Biochar and RMA significantly increased soil total nitrogen (TN) content compared to the other treatments including control except in T. Aus season (Table 6). Likewise, organic and inorganic fertilizers significantly influenced soil C:N ratio only in Boro season but not in T. Aus and T. Aman seasons ($p < 0.05$, Table 6). The highest soil pH was measured in biochar-treated plots, which was similar to other treatments except for compost with biochar and control. Likewise, NH_4^+ concentrations in soil were significantly influenced by different organic and inorganic fertilizers ($p < 0.001$, Table 6). The highest NH_4^+ concentrations were found in plots treated with only chemical fertilizer and were lowest in control.

The relationship between the NH_3 fluxes and soil pH was positive and significant in all rice seasons (Figure 2). NH_3 fluxes had a strong correlation with soil pH in Boro rice ($R^2 = 0.79$; $p < 0.01$). Likewise, NH_3 fluxes had a moderate correlation with soil pH in T. Aus rice ($R^2 = 0.36$; $p < 0.05$) and in T. Aman rice ($R^2 = 0.50$; $p < 0.05$) (Figure 2). Like soil pH, the relationship between NH_3 fluxes and soil NH_4^+ content was also positive and significant in all rice seasons (Figure 2). Ammonia fluxes had a strong correlation with soil NH_4^+ content in Boro rice ($R^2 = 0.68$; $p < 0.01$), T. Aus rice ($R^2 = 0.86$; $p < 0.001$), and T. Aman rice ($R^2 = 0.91$; $p < 0.001$) (Figure 2).

TABLE 4 Effects of organic and inorganic fertilizers on emission factor and yield-scaled ammonia emissions in rice crops.

Treatment	Emission factor (%)			Yield scaled ammonia emission (kg t^{-1})		
	Boro rice	Aus rice	Aman rice	Boro rice	Aus rice	Aman rice
Control				0.17 ± 0.01b	1.04 ± 0.04d	0.47 ± 0.03e
Chemical fertilizer	15.8 ± 0.40a	29.2 ± 0.38a	27.9 ± 0.33a	2.88 ± 0.17a	5.83 ± 0.24a	4.43 ± 0.09a
Biochar	13.3 ± 0.21c	20.8 ± 0.37e	22.0 ± 0.30b	2.61 ± 0.24a	2.65 ± 0.18c	2.67 ± 0.11cd
Rice husk ash	14.8 ± 0.27ab	26.4 ± 0.41c	27.5 ± 0.53a	2.77 ± 0.12a	5.47 ± 0.19ab	3.51 ± 0.11b
Compost	13.6 ± 0.39bc	27.4 ± 0.78b	26.6 ± 0.87a	2.42 ± 0.04a	4.54 ± 0.37b	3.02 ± 0.08c
Compost + Biochar	12.0 ± 0.11d	24.3 ± 0.42d	23.7 ± 0.55b	2.34 ± 0.09a	3.28 ± 0.28c	2.36 ± 0.13d
CV (%)	4.43	2.67	3.47	10.94	14.14	9.38
Level of significance	*	*	**	***	***	***

*$p < 0.05$, **$p < 0.01$, ***$p < 0.001$, respectively. Columns (Mean ± SE) with different letters vary significantly.

TABLE 5 Effects of organic and inorganic fertilizers on the grain yield of crops and system productivity in the Boro - T. Aus - T. Aman cropping pattern.

Treatment	Grain yield (t ha^{-1})			System productivity (t ha^{-1})
	Boro rice	Aus rice	Aman rice	
Control	4.12 ± 0.25b	2.81 ± 0.14b	3.49 ± 0.15b	10.4 ± 0.20b
Chemical fertilizer	6.89 ± 0.31a	3.91 ± 0.27a	6.04 ± 0.14a	16.8 ± 0.31a
Biochar	6.55 ± 0.71a	4.13 ± 0.22a	5.92 ± 0.18a	16.6 ± 0.68a
Rice husk ash	6.70 ± 0.37a	3.75 ± 0.14a	6.09 ± 0.23a	16.6 ± 0.59a
Compost	7.06 ± 0.29a	3.83 ± 0.33a	6.32 ± 0.05a	17.2 ± 0.45a
Compost + Biochar	6.45 ± 0.21a	4.21 ± 0.33a	6.26 ± 0.29a	16.9 ± 0.51a
CV (%)	12.1	13.7	7.8	5.8
Level of significance	*	*	*	**

*$p < 0.05$, **$p < 0.01$, respectively. Columns (Mean ± SE) with different letters vary significantly.

4. Discussion

In accord with our hypothesis, the co-application of biochar, RMA and compost together with N fertilizer, while suppling the same amount of N as N fertilizer alone, decreased NH_3 volatilization loss by 16–28% without changing the soil N status. In the following discussion, we first examine the dynamics of NH_3 fluxes, the NH_3 emission factors for treatments and the IPNS treatment co-benefits for soil properties and crop yield.

4.1. Peak of NH_3 fluxes

The NH_3 flux peak was within 2–3 days after urea application indicating that NH_3 volatilization was a rapid progress that was almost completed within 1 week after each split fertilizer application. The NH_3 volatilization flux patterns were consistent among treatments, suggesting that they were primarily driven by the urea applied. The NH_3 emission patterns were consistent with previous studies in the same (Uddin et al., 2021) and dissimilar geographical areas (Fan et al., 2006) as our experiment. The NH_3 flux from urea hydrolysis usually peaks at 3–7 days after application (Rochette et al., 2009) which is in line with our results but not to Drury et al. (2017) who stated that the peak emissions can take up to 9–15 days if rain occurs after N application. That fluxes were highest from T_2 may be attributed to the highest rate of urea applied which rapidly converted into NH_4^+ through the ammonification process, which was the first step of ammonia volatilization (Frimpong et al., 2016; Uddin et al., 2021). As NH_3 is in a dynamic equilibrium with NH_4^+ and H^+, urea treatment elevates soil pH through urease hydrolysis (Sommer et al., 2004). Following the peak on day 2–4 after urea application, the NH_3 fluxes rapidly declined. While organic amendments did not alter the timing of the peak of NH_3 fluxes, they decreased the magnitude of the peak which could be attributed to the lower rate of chemical N-fertilizer based on the IPNS approach. The decrease in soil NH_4^+ content and a drop in pH with the organic amendments helps explain the decrease in NH_3 volatilization (Adviento-Borbe et al., 2010). Other processes leading to a decrease in NH_3 volatilization could

TABLE 6 Effects of organic and inorganic fertilizer on soil properties after urea application in Boro, T. Aus and T. Aman rice.

	Treatment	SOC (%)	STN (%)	Soil C:N ratio	Soil pH	Soil NH_4^+ content (mg N kg^{-1})	Soil NO_3^- content (mg N kg^{-1})	Soil mineral N content (mg N kg^{-1})
Boro	Control	1.71 ± 0.05b	0.11 ± 0.01b	16.0 ± 0.27bc	6.55 ± 0.01c	14.3 ± 0.94c	3.7 ± 1.85b	18.0 ± 2.24c
	Chemical fertilizer	1.82 ± 0.05ab	0.10 ± 0.01b	18.7 ± 0.81a	7.56 ± 0.10ab	30.2 ± 1.28a	3.8 ± 1.56ab	34.0 ± 1.28a
	Biochar	1.98 ± 0.02a	0.13 ± 0.01a	15.1 ± 0.35c	7.78 ± 0.13a	20.1 ± 0.96b	4.8 ± 0.96ab	24.9 ± 1.91bc
	Rice husk ash	1.92 ± 0.04ab	0.13 ± 0.01a	15.2 ± 0.30c	7.55 ± 0.02ab	24.9 ± 1.10b	6.7 ± 0.96ab	31.6 ± 1.83ab
	Compost	1.95 ± 0.09ab	0.11 ± 0.01b	18.3 ± 0.97ab	7.64 ± 0.06ab	24.9 ± 1.10b	10.5 ± 1.83a	35.4 ± 1.83a
	Compost + Biochar	1.93 ± 0.06ab	0.10 ± 0.01b	18.8 ± 0.65a	7.36 ± 0.09b	23.0 ± 0.41b	6.7 ± 0.96ab	29.7 ± 1.29ab
	CV (%)	5.67	5.74	6.37	2.20	9.29	45.91	7.53
	Level of significance	*	*	*	**	* * *	*	**
Aus	Control	1.58 ± 0.03b	0.15 ± 0.01	10.26 ± 0.39	6.48 ± 0.06b	16.9 ± 0.45d	2.05 ± 0.68	18.9 ± 0.68d
	Chemical fertilizer	1.75 ± 0.04a	0.15 ± 0.01	11.57 ± 0.42	7.01 ± 0.17a	40.3 ± 0.68a	2.73 ± 0.00	43.0 ± 0.68a
	Biochar	1.67 ± 0.03ab	0.16 ± 0.01	10.42 ± 0.37	7.14 ± 0.06a	26.2 ± 0.68c	3.41 ± 1.72	29.6 ± 1.37c
	Rice husk ash	1.71 ± 0.04ab	0.15 ± 0.01	11.27 ± 0.22	7.11 ± 0.06a	35.5 ± 0.00b	1.37 ± 0.79	36.9 ± 0.79b
	Compost	1.78 ± 0.03a	0.17 ± 0.01	10.25 ± 0.38	6.52 ± 0.03b	34.2 ± 0.79b	2.73 ± 1.12	36.9 ± 1.37b
	Compost + Biochar	1.69 ± 0.02ab	0.16 ± 0.01	10.33 ± 0.37	6.64 ± 0.07b	36.2 ± 0.68b	2.05 ± 0.68	38.3 ± 0.01b
	CV (%)	4.12	6.45	7.11	2.16	3.81	76.94	5.23
	Level of significance	*	ns	ns	**	**	ns	**
Aman	Control	1.44 ± 0.03b	0.15 ± 0.02b	9.55 ± 0.34	6.56 ± 0.03c	19.4 ± 0.58e	2.05 ± 0.68b	21.5 ± 0.59d
	Chemical fertilizer	1.51 ± 0.02ab	0.17 ± 0.01ab	8.90 ± 0.24	7.24 ± 0.02b	55.1 ± 1.87a	2.73 ± 1.12b	57.8 ± 2.36ab
	Biochar	1.59 ± 0.05ab	0.18 ± 0.02a	8.82 ± 0.48	7.41 ± 0.04ab	46.4 ± 1.58cd	3.41 ± 0.68b	49.9 ± 2.05bc
	Rice mill ash	1.57 ± 0.03ab	0.18 ± 0.02a	8.96 ± 0.25	7.60 ± 0.07a	53.0 ± 0.94ab	9.56 ± 1.76a	62.6 ± 1.58a
	Compost	1.54 ± 0.08ab	0.18 ± 0.02a	8.78 ± 0.21	7.49 ± 0.13ab	49.2 ± 1.12bc	8.88 ± 0.68a	58.1 ± 0.68a
	Compost + Biochar	1.67 ± 0.03a	0.18 ± 0.01a	9.01 ± 0.15	7.42 ± 0.09ab	42.6 ± 0.68d	6.15 ± 1.31ab	48.7 ± 1.76c
	CV (%)	5.40	5.99	6.28	1.90	5.71	4.17	3.05
	Level of significance	*	**	ns	**	**	**	**

*$p < 0.05$, **$p < 0.01$, ***$p < 0.001$, respectively; ns, not significant. Columns (Mean ± SE) with different letters vary significantly.

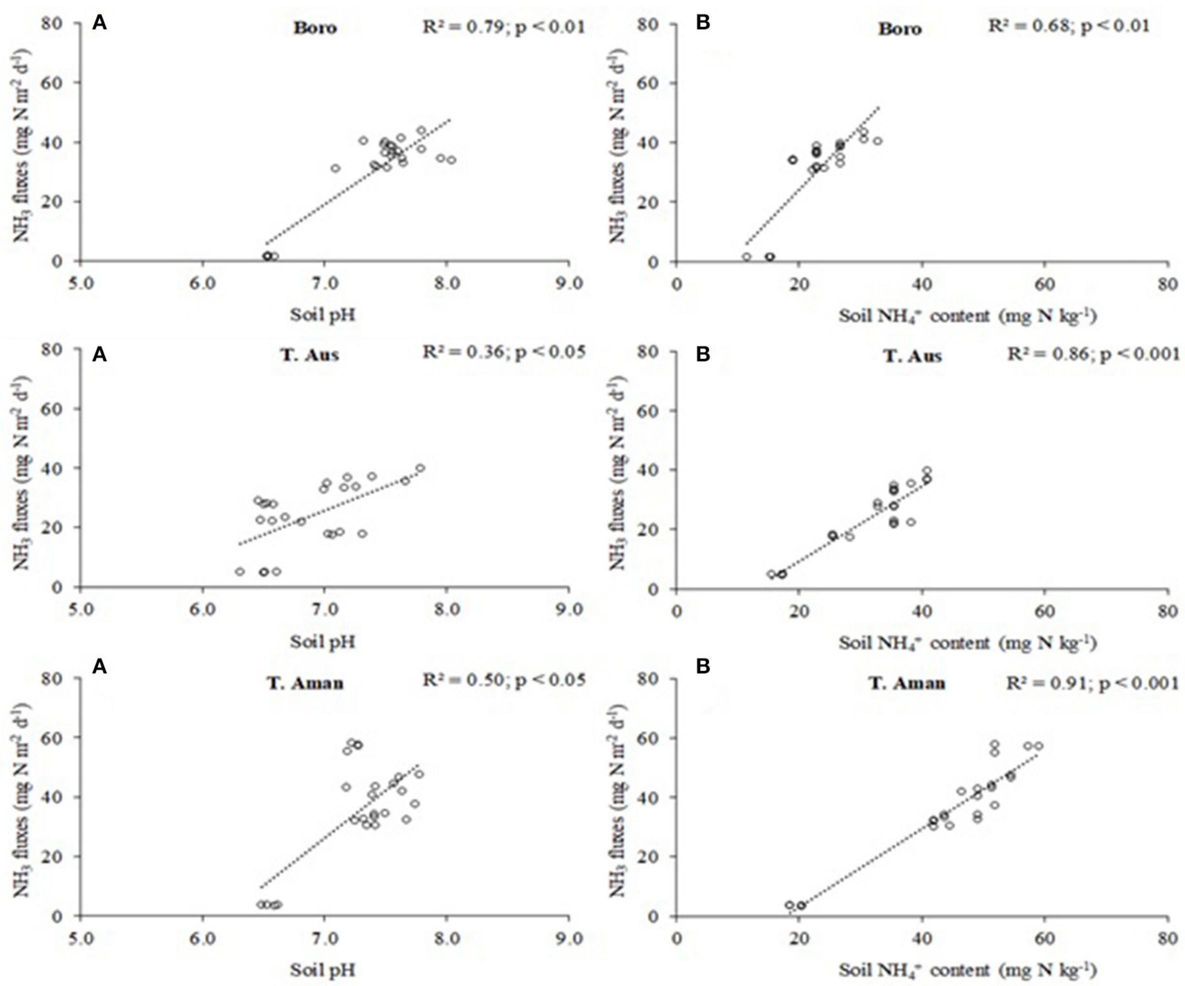

FIGURE 2
Relationship between NH_3 fluxes and soil pH **(A)** or soil NH_4^+ content **(B)** in the rice crops; $n = 24$.

be the infiltration of mineral N into the crop rooting zone, and increased nitrification over time (Adviento-Borbe et al., 2010). When the NH_3 fluxes for Boro, Aus and Aman seasons were examined in relation to the soil chemical properties, the closest positive correlation was with soil pH followed by soil NH_4^+ as found in previous studies (Sommer et al., 2004; Rochette et al., 2013).

4.2. Ammonia fluxes, emission factor, and rice yields

While NH_3 volatilization is a major N loss from paddy fields, the rate of N loss is dependent on the fertilization type, time of application, environmental conditions and N application rate (Wang et al., 2016). Pan et al. (2016) stated that about 30% of the applied urea was lost through NH_3 fluxes which were consistent with our result that the N loss *via* volatilization ranged from 16% in Boro to 28% in T. Aman rice season. When N supplied in the urea fertilizer was adjusted based on the N content in the organic amendments, NH_3 fluxes were reduced. In this study biochar alone and with compost reduced the NH_3 loss during three rice growing seasons. The NH_3 fluxes of N fertilizer was higher for Aman rice than for Aus and Boro rice which is most likely due to the seasonal variations in temperature being the lowest in Boro season (15–25°C) and the highest in T. Aman season (25–35°C) while in T. Aus the temperature was moderate (20–30°C). High temperature in standing water in rice fields induces rapid urea hydrolysis and higher ammonia volatilization (Sun et al., 2017). While the Aus season in the Indo-Gangetic plain has high rainfall and moderate temperature, the urea application rate in this season was lower than the other two seasons due to lower yield potential, which may lower volatilization.

Biochar was very effective in reducing NH_3 emissions by reducing chemical N input but may also control the N releases. Our results also showed consistency with Sun et al. (2017) and Asada et al. (2002), where their meta-analysis suggested that NH_3 fluxes were reduced with the application of biochar pyrolyzed at ∼400°C. Ammonia adsorbed onto the biochar surface directly reduces the substrate concentration of NH_3 for the volatilization process (Clough et al., 2013). However, the liming effect of alkaline biochar may increase NH_3 fluxes (Sun et al., 2017; Sha et al., 2019). The pH increase in soil amended with biochar in the present study was not high enough to enhance NH_3 fluxes (Kelly et al., 2015). Among the amended plots biochar required the lowest rate of urea fertilizer to equalize total N input with recommended chemical fertilizer dose, which may explain the lower NH_3 fluxes than in compost amended plots. Co-application of biochar with compost has the potential to reduce NH_3 emissions due to high surface area to adsorb NH_4, high internal porosity to trap NH_4^+ ions but this will depend on N mineralization rate and their inherent N content which varies among biochar and compost products.

All the treatments, except control without N fertilizer applied, had the same yield in all three rice seasons even though the urea application rates were different. Moreover, the N uptake was also the same in each treatment (data not presented). Therefore, questions arise of how biochar-treated soils provided similar N for plant uptake in comparison to a full dose of urea. A moderate substitution (<40%) of N fertilizer by manure has been reported to significantly increase N use efficiency by 14 and 25% for upland crops and rice, respectively (Xu et al., 2016; Zhang et al., 2020). In the present study, rice plants were initially paler green in biochar-treated plots suggesting that it decreased initial N mineralization rate. In addition, N from urea in biochar-treated plots may have been used more efficiently due to better synchronization of N supply and demand.

Rice husk ash had less efficiency in NH_4^+ retention in all seasons and in controlling NH_3 fluxes than biochar, but still decreased N losses relative to the urea fertilizer alone. While ashes are often alkaline, the present RMA did not alter soil pH and was effective in decreasing NH_4 content in soil except in Aman season and in decreasing NH_3 losses, except in the Boro season. As an abundant biowaste in the Indo-Gangetic Plain, RMA can be used to reduce N fertilizer input and to reduce atmospheric NH_3 emissions. However, as the ashing conditions are likely to vary with farm-produced RMA, more study is needed to determine the consistency of the effects reported here.

4.3. Integrated plant nutrition system effects on soil properties

In addition to their effects on NH_3 losses, organic amendments had significant effects on some soil properties. In the current research, sole biochar application increased soil pH compared to control treatment, however compost + biochar combination and sole compost application decreased soil pH. Poultry manure biochar may have increased soil pH through its liming effect over the sole compost and chemical fertilizers application but when the mixture of compost and biochar was applied, soil pH decreased relative to the sole biochar application. Herein, soils treated with solitary biochar had the highest pH (7.78) which is not enough to raise NH_3 loss, followed by soils treated with both biochar and compost (7.42). Slight increase in soil pH in biochar treated plots could have increased NH_3 emissions but the lower NH_4^+ contents in soils resulted in lower NH_3 emissions.

Application of biochar solely or in combination with compost at a rate of 3 t ha^{-1} has increased SOC in our study, which is in line with previous research (Liu et al., 2021). Biochar is distinguished from compost by its larger proportion of more stable organic carbon molecules (Mahmoud et al., 2018; Eissa, 2019) making it more efficient in enhancing soil physicochemical parameters (Eissa, 2019). Furthermore, Trupiano et al. (2017) also reported that the application of compost and biochar to soils, either alone or in combination, enhanced soil SOC content compared to un-amended soils, implying that biochar and/or compost is a potential source of soil carbon sequestration.

5. Conclusion

Volatilization loss of N from paddy fields in floodplain soils causes economic losses and is a major concern for air and water quality. Application of biochar alone or in combination with compost on an integrated plant nutrition system basis reduced the rate of N-fertilizer application as well as ammonia volatilization. The NH_3 emission factor ranged from 12% in compost plus biochar to 16% in chemical fertilizer-treated plots in Boro rice, from 21% in biochar to 29% in compost treated plots in Aus rice, and from 22% in biochar to 28% in chemical fertilizer-treated plots in Aman rice. Pooling the three rice growing seasons together, either biochar or biochar plus compost mixture reduced N volatilization by 36–37% while compost alone can reduce it by 23%. All the treatments had same crop yield except the control without N fertilizer. Hence, biochar with or without compost mixture has a great potential for mitigating year-round NH_3 volatilization in the triple rice cropping system along with a decrease in the rate of applied N-fertilizer in floodplain soils without losing crop yield and system productivity.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

MJ and MAH worked on research planning and paper editing. CM worked on research planning, calculation, and paper editing. RB worked on planning and paper editing. MZ contributed in research planning and methodological development. MBH worked on research planning. JF conducted field and laboratory work, data processing, analysis, and paper draft preparation. NM worked in draft preparation. MMJ worked on research planning, data interpretation and paper editing. All authors contributed to the article and approved the submitted version.

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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/fsufs.2022.1067112/full#supplementary-material

SUPPLEMENTARY DATA 1
Environmental weather data of the experimental site registered during the experimental period (January 2021 to December 2021).

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