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The impact of different fertiliser management options and cultivars on nitrogen use efficiency and yield for rice cropping in the Indo-Gangetic Plain: Two seasons of methane, nitrous oxide and ammonia emissions

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ABSTRACT

This study presents detailed crop and gas flux data from two years of rice production at the experimental farm of the ICAR-Indian Agricultural Research Institute, New Delhi, India. In comparing 4 nitrogen (N) fertiliser regimes across 4 rice cultivars (CRD 310, IR-64, MTU 1010, P-44), we have added to growing evidence of the environmental costs of rice production in the region. The study shows that rice cultivar can impact yields of both grain, and total biomass produced in given circumstances, with the CRD 310 cultivar showing consistently high nitrogen use efficiency (NUE) for total biomass compared with other tested varieties, but not necessarily with the highest grain yield, which was P-44 in this experiment. While NUE of the rice did vary depending on experimental treatments (ranging from 41% to 73%), 73%), this did not translate directly into the reduction of emissions of ammonia (NH_3) and nitrous oxide (N_2O). Emissions were relatively similar across the different rice cultivars regardless of NUE. Conversely, agronomic practices that reduced total N losses were associated with higher yield. In terms of fertiliser application, the outstanding impact was of the very high methane (CH_4) emissions as a result of incorporating farmyard manure (FYM) into rice paddies, which dominated the overall effect on global warming potential. While the use of nitrification and urease inhibiting substances decreased N_2O emissions overall, NH_3 emissions were relatively unaffected (or slightly higher). Overall, the greatest reduction in greenhouse gas (GHG) emissions came from reducing irrigation water added to the fields, resulting in higher N_2O, but significantly less CH_4 emissions, reducing net GHG emission compared with continuous flooding. Overall, genetic differences generated more variation in yield and NUE than agronomic management (excluding controls), whereas agronomy generated larger differences than genetics concerning gaseous losses. This study suggests that a mixed approach needs to be applied when attempting to reduce pollution and global warming potential from rice production and potential pollution swapping and synergies need to be considered. Finding the right balance of rice cultivar, irrigation technique and fertiliser type could significantly reduce emissions, while getting it wrong can result in considerably poorer yields and higher pollution.

1. Introduction

Rice (*Oryza sativa L.*) farming is one of the largest wide scale agricultural activities on Earth, with an estimated global production of approximately 517 million tonnes of rice harvested in the year 2021 (FAO, 2022), accounting for approximately one fifth of all calories consumed by the human population at a global scale (Elert, 2014). Asia contributes about 87% to global rice production, with China and India together accounting for 49% (Bandumula, 2017). An estimated 13.5% of all land cover in India is used to grow rice, the vast majority of which is

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transplanted into flooded or continuously irrigated paddies to increase productivity (Gupta et al., 2016a). While unquestionable that rice production in Asia is both highly productive and necessary to sustain the dietary needs of the human population, aspects of this wide scale and intensive agricultural activity can have severe consequences for the natural environment (Bhatia et al., 2010).

Rice paddies contribute largely to emissions of the powerful greenhouse gases (GHG) methane (CH_4) and nitrous oxide (N_2O) (Akiyama et al., 2005; Bhatia et al., 2012a; Gupta et al., 2016b; Cowan et al., 2021). Methane is of particular importance when considering the environmental footprint of rice paddies, which are estimated to emit 24–40 Tg CH_4 yr^{-1}, accounting for approximately 8% of global anthropogenic emissions of CH_4 (Jackson et al., 2020). As intensively managed rice paddies regularly receive large quantities of nitrogen (N) rich mineral and organic fertilisers, other forms of N loss are of importance as well. Ammonia (NH_3) emissions are also associated with fertilisers applied to rice paddies (Wang et al., 2018), which is directly harmful to health as an air pollutant (e.g., Pozzer et al., 2017) and can result in increased particulate matter (PM) in cities when it comes in contact with high concentrations of nitrogen oxides (NO_x), sulphate (SO_4) and chloride (HCl and Cl^-) (Wyer et al., 2022). These compounds are typically emitted from traffic and burning of biomass and solid waste (Saraswati et al., 2019; Wang et al., 2015; Pawar et al., 2023). The resulting formation of $PM_{2.5}$ and PM_{10} aerosols can result in serious impacts on human health such as cardiovascular and respiratory problems (Giannakis et al., 2019). Deposition of N compound can also damage biodiversity in sensitive environments (Payne et al., 2017) and losses of N from food systems largely end up in natural aquatic bodies due to leaching and run-off, which results in mass eutrophication and significant damage to aquatic biodiversity and water quality (Malone and Newton, 2020).

Nitrogen losses (and resultant N pollution in its various forms) from rice paddies are closely tied to N use efficiency of the crops (NUE). Higher NUE will in general result in less pollution in the environment as more of the applied N is consumed by and stored in the crops. Various aspects affect the NUE of rice crops, including environmental conditions such as temperature, soil moisture and oxygen availability (Alhaj Hamoud et al., 2019; Hameed et al., 2019), the availability of reactive N and other required nutrients (Ding et al., 2018; Iqbal et al., 2019; Móring et al., 2021; Mboyerwa et al., 2022), as well as the rice cultivar (Gewaily et al., 2018; Tang et al., 2019). A high NUE is not only valuable as a means to reduce pollution, it also reduces the amount of fertiliser needed and improves profit for farmers.

For mitigating emissions of GHGs, some success has been achieved by changing the management practices of rice farming. Altering the irrigation practice (Cowan et al., 2021), fertiliser application methods (Bhatia et al., 2012b; Yao et al., 2017; Malyan et al., 2019; Kirti et al., 2020; Malyan et al., 2021a,2021b), altered management of straw (Pathak et al., 2006; Allen et al., 2019), planting /seeding techniques (Bhatia et al., 2013; Jain et al., 2016), biochar amendments (Liu et al., 2015; Han et al., 2016), and use of microbial cultures (Malyan et al., 2021a,2021b; Rani et al., 2021) have been able to significantly reduce the GHG emissions associated with rice paddy cultivation. However, mitigation efforts are often difficult, due to 'pollution swapping', in which emission of one pollutant is reduced at the cost of another (Dragosits et al., 2008; Weller et al., 2014). This points to the need to develop strategies that maximise the synergies in reducing different pollution forms (Sutton et al., 2022). Rice cultivar is also an important factor affecting the CH_4 emission and global warming potential (GWP, Wang et al., 2021a, 2021b; Win et al., 2021), but more data are needed to better understand the performance of different cultivars and the mechanisms underlying such differences.

One method of reducing N_2O and NH_3 emissions is to incorporate chemical inhibitors such as urease or nitrification inhibitors with urea fertiliser (Lam et al., 2016: Zaman et al., 2009). These inhibitors typically work by reducing the rate of urea hydrolysis (block activity of the soil and plant enzyme urease) and further nitrification in soils (suppressing the action of the enzyme ammonium-mono-oxigenase in the soil bacteria Nitrosomonas), thus allowing increased N uptake by crops, and may also affect CH_4 emissions (Sahrawat, 2004; Datta and Adhya, 2014). Although naturally occurring inhibitors widely used in India, such as neem oil, have shown to potentially reduce N_2O emissions in rice paddies (e.g. Majumdar et al., 2000, Malla et al., 2005, Gupta et al., 2016b), the impacts of these inhibitors on NH_3 emissions is still not well quantified. It has been estimated that up to 40–50% of nitrogen applied to rice paddies can be lost in the form of NH_3 volatilisation (e.g. Fillery and De Datta, 1986; Wang et al., 2021a, 2021b). However, the commonly used chamber method for measuring NH_3 flux is associated with high uncertainties due to the "sticky" properties of NH_3 gas (Smith et al., 2007; Cole et al., 2007), differences in turbulence and therefore possible bias of underestimating NH_3 emissions while potentially underestimating NH_3 recapture by overlying plant canopies (Fowler et al., 2001; Sutton et al., 2009; Ni et al., 2015; Scotto di Perta et al., 2020).

While CH_4 emissions have been widely studied in rice paddies across Asia, there is still a lack of understanding regarding emissions of N_2O and NH_3, especially from studies where pollution mitigation efforts have been carried out (Móring et al., 2021). In this study, we aim to add to this knowledge by quantifying emissions of CH_4, N_2O and NH_3 over two years, growing four rice cultivars with the application of four fertiliser types during this period; i) prilled urea, ii) neem coated urea, iii) neem coated urea with a coating of Limus® urease inhibitor (Limus® is a novel multi-patented urease inhibitor with two active ingredients (N-(n-butyl) thiophosphoric triamide (NBPT) and N-(n-propyl)-thiophosphoric triamide (NPPT)); patented by BASF) and iv) a 50:50 farmyard manure and neem coated urea along with bio fertiliser mix. The study aims to establish the environmental costs and benefits of each of these management practices, as well as the impact that each has on the overall nitrogen use efficiency (NUE) of a rice crop in conditions typical to the Indo-Gangetic plain (IGP) region.

2. Methods

2.1. Experimental site and soil

A field experiment was conducted growing rice in kharif (rainy season) during 2017 and 2018 in a silty clay loam (Typic Ustochrept) soil at the experimental farm of the Indian Agricultural Research Institute (IARI), New Delhi, India. The site is located in the Indo-Gangetic alluvial tract at 28°40′ N and 77°12′ E, at an altitude of 228 m above mean sea level having subtropical and semi-arid climate. From July to September, approximately 80% of the annual rainfall (750 mm) typically occurs. The soils are classified as well drained, with the groundwater table at approximately 6.6 m and 10 m below surface during the rainy and dry seasons, respectively. The mean maximum and minimum temperatures during the rice growth period from July to October are 35 °C and 18 °C, respectively. The alluvial soil of the experimental site had a bulk density of 1.38 g cm^{-3}, pH (1:2 soil:water) of 8.01, organic carbon of 4.2 g kg^{-1} and total N of 0.24 g kg^{-1}. Rainfall and temperature data were collected from the meteorological laboratory on IARI campus, located 300 m from the experimental site, using a shielded thermometer placed at 1.5 m to measure air temperature, and the tipping bucket method for rainfall measurements (Fig. 1).

2.2. Crop management and treatments

Rice was grown in the July to October growing seasons in both 2017 and 2018 under intermittent flooding regime where irrigation was applied when fine cracks developed on the soil surface. Split plot designs were implemented in both 2017 and 2018 to apply a cultivar of fertilisers to four varieties of rice, with each plot measuring 6 by 7 m. The four rice varieties used in the experiment were Pusa (P)– 44, IR-64,

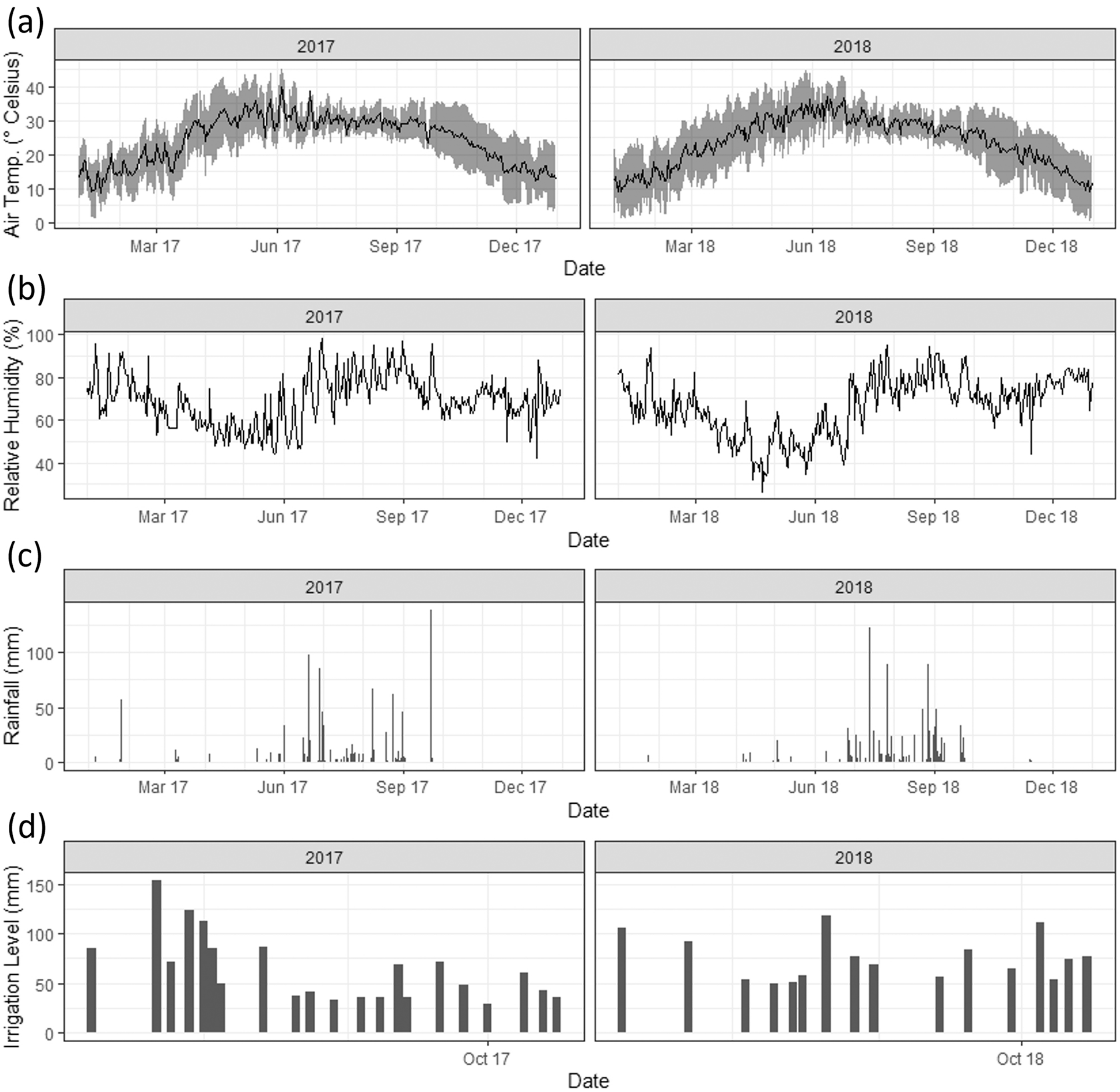

Fig. 1. (a) Air temperature, (b) relative humidity, (c) rainfall and (d) level of irrigation water standing above soil surface (for intermittent flooded rice treatment) at the Indian Agricultural Research Institute field site through January 2017 to December 2018. Minimum and maximum air temperature is shown in shaded area. Irrigation water depth was only measured during the crop growth period after irrigation.

Table 1
Field management and fertiliser application in the two growing seasons.

Activity	Date	Type and amount of mineral fertiliser applied (kg N ha^{-1})
2017		
Rice transplanted	20/07/2017	FYM (BF)
Fertiliser	10/07/2017	FYM (50)
Fertiliser	08/08/2017	NCU (25 + LCC), FYM (12.5)
Fertiliser	30/08/2017	NCU (25 + LCC), FYM (12.5)
Fertiliser	15/09/2017	NCU (25 + LCC), FYM (12.5)
Fertiliser	26/09/2017	NCU (25), FYM (12.5)
Harvest	25/10/2017–03/11/2017	
2018		
Rice transplanted	16/07/2018	FYM (BF)
Fertiliser	07/07/2018	FYM (50)
Fertiliser	30/07/2018	NCU, PRI, LIM (all 40); FYM (20)
Fertiliser	27/08/2018	NCU, PRI, LIM (all 30); FYM (15)
Fertiliser	18/09/2018	NCU, PRI, LIM (all 30); FYM (15)
Harvest	24/10/2018–02/11/2018	

MTU 1010, and CRD 310. Rice was raised in a nearby nursery and 30 days old seedlings were transplanted into the puddled fields on 20th July 2017 and on 15th July in 2018 at a spacing of 20 × 15 cm. Irrigation water was applied throughout the rice growing period via the check-basin method. Each irrigation event increased the depth of the water in the plots by approximately 0.5–2 cm, varying each time (Fig. 1d). Overall, 21 irrigations were given in 2017 and 16 irrigations were given in 2018. Two weeks prior to harvest, all irrigation was stopped and the fields dried.

The fertiliser treatments varied between 2017 and 2018 (Table 1). In 2017, the three treatments applied to each of the four rice varieties were:

a) control (**CON**) (which received no nitrogen),
b) neem coated urea (**NCU**) applied at 100 kg N ha^{-1} in four splits of 25 kg N ha^{-1} using leaf colour chart (LCC) informed application, and
c) integrated treatment of farmyard manure+NCU+Biofertiliser (**FYM**) applied at 100 kg N ha^{-1} (50% of N in the form of farmyard manure applied ten days prior to rice transplanting and 50% through NCU in four splits of 12.5 kg N ha on same days as in NCU treatment+Biofertiliser). Total N content of manure was 0.53% and 0.55% for 2017 and 2018, respectively.

For biofertiliser application, the roots of the rice seedlings were dipped for two hours before they were transplanted in the biofertiliser culture comprising of mix of cyanobacterial strains—*Anabaena torulosa, Nostoccarneum, Nostocpiscinale* and *Anabaena doliolum* which have a symbiotic association with *Azolla*. For LCC based NCU application (neem coated urea was applied 15 days after transplanting and subsequently all application were based on LCC readings of level 4 on a IRRI certified Leaf Colour Chart as per Cowan et al. (2021). A basal dose of 26 kg P ha^{-1}, 50 kg K ha^{-1} and 10 kg Zn ha^{-1} was applied to all the treatments.

In 2018, five treatments were used in the experimental setup in each of the four rice varieties:

a) control (**CON**) plots (which received no nitrogen);
b) neem coated urea (**NCU**) applied at 100 kg N ha^{-1} in three splits of 40 kg N ha^{-1} at 15 days after transplanting (DAT), then 30 kg N ha^{-1} at 42 and 63 DAT based on LCC,
c) farmyard manure+NCU+ Biofertiliser (**FYM**) applied at 100 kg N ha^{-1} (50% of N in the form of farmyard manure applied a week prior to rice transplanting +50% through NCU in three splits on same days as NCU),
d) Prilled urea (**PRI**) applied at 100 kg N ha^{-1} each in three splits as in NCU treatment, and
e) Limus® coated over neem coated urea (**LIM**) applied at 100 kg N ha^{-1} each in three splits as in NCU treatment.

The neem oil present on NCU is expected to have a benefit by acting as a nitrification inhibitor. Conversely, Limus® acts as a urease inhibitor (e.g. Matczuk and Siczek, 2021). By coating NCU with Limus® in treatment e) a dual benefit of urease and nitrification inhibition is expected.

2.3. Plant sampling and estimation of yield

Rice plant samples were collected at harvest to estimate the above-ground biomass of different rice varieties. Rice yields were determined from one square metre of area in each plot in triplicate. The grains were separated from the straw, dried and weighed. Grain moisture was determined immediately after weighing (20–22%) and sub-samples were dried in an oven at 65 °C for 48 h. The dried grain and biomass samples were ground and used to estimate the total N content using the Kjeldahl method (Blume et al., 1982). Plant nitrogen content was calculated separately for (i) grain and (ii) straw. Crop nitrogen use efficiency (NUE) was reported as the additional effect of fertiliser application on yield and aboveground biomass over the control plots. In this way, NUE was calculated after subtracting the equivalent nitrogen content of the control plots for the harvested grain (NUE_{grain}) and the total harvested biomass ($NUE_{total\ biomass}$) i.e:

$$NUE_{\mathrm{total\ biomass}} = \frac{\mathit{Total\ N\ content\ of\ treated\ crop(Grain\ and\ stem)} - \mathit{Total\ N\ content\ of\ control\ crop(Grain\ and\ stem)}}{\mathit{Total\ N\ fetiliser\ applied}} \quad (1)$$

2.4. Collection and analysis of greenhouse gas samples and fluxes

Collection of greenhouse gas samples was carried out using the static chamber technique using chambers enclosing soil surface and overlying rice canopy (e.g. Bhatia et al., 2005). Transparent chambers of 50 cm × 30 cm x 100 cm (length x width x height) were made of 6 mm thick acrylic sheets. An aluminium soil base frame (channel) of 15 cm height and 5 cm internal diameter was placed in the field for each chamber. The channels were inserted at 10 cm depth in the soil and stayed in situ for the duration of the experiment. They were filled with water to make the system airtight. The chambers were placed over the rice plants on the sampling days. A small rotary fan and a glass thermometer were also attached to each chamber. Gas samples were drawn through a silicone septum on top of the chamber with a 50 ml syringe attached to a hypodermic needle (24 gauge) at 0, 30, and 60 min for both CH_4 and N_2O. Syringes were made airtight with a 3-way stopcock. Headspace volume inside the chambers was recorded to calculate concentrations of N_2O and CH_4. Concentrations of CH_4 in the gas samples was analysed using a gas chromatograph (GC) fitted with a flame ionisation detector (FID)(GC 8 A Series, Shimadzu) and N_2O samples were analysed using a GC with electron capture detector (ECD)(Hewlett Packard 5890 Series II) as per Pathak et al., (2002, 2003). Gas standards of 2 and 5 ppm for CH_4 and 500 and 1000ppb for N_2O were used as calibration standards.

Fluxes of N_2O and CH_4 were calculated as:

$$F = \frac{dC}{dt} \cdot \frac{\rho V}{A} \quad (2)$$

where F is the gas flux from the soil (nmol m^{-2} s^{-1}), dC/dt is the rate of change in the concentration in time in nmol mol^{-1} s^{-1} estimated by linear regression, ρ is the density of air in mol m^{-3}, V is the volume of the chamber in m^3 and A is the ground area enclosed by the chamber in m^2.

2.5. *Estimation of ammonia volatilisation losses*

Transparent static chambers measuring 305 × 152×300 mm (length x width x height) were placed on soil base frames inserted in between the rows of rice plants in the plots for 24 h (two replicates per treatment, separate bases than used for the GHG measurements but with the same principle). The volatilised ammonia gas inside the chamber was bubbled through 0.01 N boric acid ($B(OH)_3$) solution containing mixed indicator (methyl red and bromocresol green) using a vacuum pump with a flow rate of 3 l min^{-1} for 3.5 min. The volatilised ammoniacal N was determined by the titration of boric acid solution with 0.001 N sulphuric acid (H_2SO_4) as per Bremner (2016). The calculation of ammonia flux was done using Eq. (3), where N is NH_3-N in mg, Svol is the volume of 0.001 N H_2SO_4 in ml (multiplied by 2 to convert to Mol) and 28.014 is the molar weight of 2 nitrogen atoms as two moles of ammonium combine with one mole of sulphate in solution.

$$N = (Svol \times 2 \times 28.014) \div A \quad (3)$$

2.6. *Temporal data interpolation*

In the absence of an effective model by which to interpolate between measurement dates, we used a locally weighted smoothing (LOESS) function to estimate cumulative emissions of N_2O and CH_4. This was implemented by the geom_smooth function in the R package "ggplot2" with a span of 0.25. The advantage of this method is that it was able to estimate an uncertainty to the fitted model which linear interpolation cannot. Due to the sticky properties of NH_3, canopy interactions and differences in turbulence the chamber method is limited in terms of calculating fluxes (e.g. as NH_3 gas will also attach to the chamber walls during measurements; some emitted NH_3 may be recaptured by overlaying canopy), thus potentially underestimating or overestimating fluxes to some degree. However, the 24-hour long concentration measurements provided by the method does allow for a relative comparison of NH_3 emissions expected from the different treatments in this experiment and remains a valid tool to carry out these comparisons under the circumstances of working in rice paddies with limited access to power if the above concerns are considered. Sophisticated gap-filling was not required for NH_3 fluxes as measurements lasted 24 h, with the exception of the 5th to 6th day after fertilisation in 2018, for which the measurement lasted 48 h due to logistical constraints. Here, the flux is averaged over these dates. Cumulative fluxes for NH_3 were only calculated up to day 6 after fertilisation as no colour change was detected afterwards, indicating no or very low fluxes.

2.7. *Uncertainty analysis*

All uncertainties are reported as 95% confidence intervals (C.I.s) in this study. For means of data following a normal distribution, this was calculated by taking the sample standard deviation and dividing by the square root of the sample size and multiplying by 1.96. For the LOESS fit function, the standard error of the fit is provided by the geom_smooth R package which was then multiplied by 1.96. Cumulative errors were calculated by use of gaussian error propagation (least squares method), combining all 95% errors sequentially.

3. Results

3.1. *Crop yield and NUE*

In the 2017 trials, total aboveground biomass harvests (dried shoot and grain) ranged from 9.2 to 14.9 t ha^{-1} (Table S1). The mean total aboveground biomass for the different fertiliser treatments were 9.9 ± 0.8, 14.3 ± 0.6 and 13.9 ± 0.6 t ha^{-1} for the CON, FYM and NCU treatments, respectively (Table 2). The total harvested aboveground biomass was significantly higher for the FYM treatment over NCU (t-test $p < 0.01$). Grain harvest followed a similar pattern, with 3.4 ± 0.3, 5.5 ± 0.4 and 5.3 ± 0.5 t ha^{-1} for CON, FYM and NCU, respectively. While average dried grain yields were higher for the FYM treatments than NCU, this difference was not statistically significant (t-test $p = 0.14$). Total N content of the harvests varied from 63 to 145 kg N ha^{-1} (see Table S1). After subtracting N content of the control plots, the total $NUE_{total\ biomass}$ of FYM and NCU treatments are estimated to be 64.9

Table 2

Mean yields for the total plant biomass harvested (stalk, leaves and grain) and grain only are presented, grouped by fertiliser type and crop cultivar. The nitrogen use efficiency ($NUE_{total\ biomass}$) is presented as a percentage of the nitrogen applied to the crop mass, minus that of the control plot crops. Confidence intervals (95%) are included (Individual plot data including details on cultivar and fertiliser management are presented in Table S1).

Year	Treatment/ Varieties	Total Aboveground Biomass Yield		Grain Yield		$NUE_{total\ biomass}$		NUE_{grain}	
		t ha^{-1}		t ha^{-1}		%		%	
2017	CON	9.9	±0.8	3.4	±0.3				
	FYM	14.3	±0.6	5.5	±0.4	64.9	±9.8	35.1	±8.1
	NCU	13.9	±0.6	5.3	±0.5	58.9	±6.2	33.6	±6.1
	MTU 1010	13.2	±2.3	4.7	±1.6	60.9	±5.7	43.9	±5.3
	CRD 310	13.2	±3.0	4.4	±0.8	72.9	±9.5	33.4	±5.0
	IR-64	12.4	±3.2	5.0	±1.4	59.6	±10.6	28.0	±2.6
	P-44	12.0	±2.5	4.8	±1.6	54.4	±2.2	32.2	±6.9
2018	CON	11.2	±1.2	3.3	±0.2				
	FYM	15.3	±1.7	5.0	±0.4	53.0	±6.9	32.6	±4.3
	NCU	15.2	±1.7	5.3	±0.3	51.3	±9.1	34.2	±6.9
	PRI	14.8	±1.5	4.9	±0.3	42.8	±6.2	27.8	±5.2
	LIM	15.9	±1.5	5.6	±0.4	60.8	±9.1	37.8	±6.0
	MTU 1010	15.4	±1.7	4.8	±0.7	53.7	±9.3	30.2	±4.9
	CRD 310	15.7	±1.8	4.7	±0.8	59.5	±8.4	38.5	±5.4
	IR-64	12.3	±1.4	4.6	±0.8	41.0	±5.4	27.0	±2.9
	P-44	14.5	±1.8	5.3	±0.9	53.7	±6.5	36.8	±4.6

Notes: Treatment values represent averages for all rice varieties, while values for rice varieties represent averages of all treatments, including control (CON).

± 9.8 and 58.9 ± 6.2%, respectively. The NUE_{grain} of the FYM and NCU treatments are estimated to be 35.1 ± 8.1 and 33.6 ± 6.1%, respectively.

In the 2018 trials, dried biomass harvests (shoot and grain) ranged from 9.7 to 17.3 t ha^{-1} (Table S1). The mean dried biomass harvests were 11.2 ± 1.2, 15.3 ± 1.7,15.9 ± 1.5 15.2 ± 1.7 and 14.8 ± 1.5 t ha^{-1} for CON, FYM, LIM, NCU and PRI treatments, respectively. Grain harvest was 3.3 ± 0.2, 5.0 ± 0.4, 5.6 ± 0.4, 5.3 ± 0.3 and 4.9 ± 0.3 t ha^{-1} for CON, FYM, LIM, NCU and PRI treatments, respectively. Variation in plot yields was relatively large compared to treatment effect, with no clear differences between the treatment types with the exception of the control plots. The value of $NUE_{total\ biomass}$ was highest for the LIM treatment (60.8 ± 9.1%) and lowest for the PRI treatment (42.8 ± 6.2%). This was true also for grain NUE_{grain}, which was 37.8 ± 6.0 and 27.8 ± 5.2% for LIM and PRI treatments, respectively.

Comparison of control plot yields in 2017 and 2018 show that 2018 had the larger total harvest (excluding N application). Control plot total biomass yields were substantially higher (though not statistically significant) in 2018 than in 2017 (t-test $p = 0.06$), with mean total yields of 11.2 ± 1.2 t ha^{-1} and 9.9 ± 0.8, respectively.

3.2. *Impact of crop cultivar*

On average, MTU 1010 and CRD 310 varieties had the largest total harvest in both 2017 and 2018, averaging 13.2 ± 2.3 t ha^{-1} in 2017 and 15.4 ± 1.7 and 15.7 ± 1.8 t ha^{-1} in 2018, respectively (means and confidence intervals of all treatments; see Table 2). The P-44 cultivar had the lowest total harvest in 2017, averaging 12.0 ± 2.5 and the IR-64 cultivar was lowest in 2018 with a mean of 12.3 ± 1.4 t ha^{-1} (see Table S1 for harvest details). However, grain only yield was highest in the IR-64 plots in 2017 (5.0 ± 1.4 t ha^{-1}) and the P-44 cultivar showed highest yields in the 2018 trials (5.3 ± 0.9 t ha^{-1}). In terms of NUE, the CRD 310 cultivar performed better than the other cultivars in 2017 for $NUE_{total\ biomass}$ (72.9%), but the highest NUE_{grain} was observed in the MTU 1010 plots (43.9%), as a result of the varying N content of the stem and grain between cultivars. In 2018, the $NUE_{total\ biomass}$ of the cultivars was more comparable, ranging from 41.0% to 59.5% across the cultivars. In 2018, the CRD 310 cultivar also had both the highest total $NUE_{total\ biomass}$ (59.5%) and highest NUE_{grain} (38.5%). The average $NUE_{total\ biomass}$ for all fertilised varieties was 55.3%, and the average NUE_{grain} for all cultivars was 33.5%.

For control plots only, MTU 1010 and CRD 310 cultivars had the highest total biomass harvest for both 2017 and 2018. However, grain yields are slightly higher in 2017 than in 2018 for the control plots, at 3.4 ± 0.3 and 3.3 ± 0.2 t ha^{-1}, respectively, although not significantly (t-test $p = 0.34$). The highest grain yield in 2017 was in the CRD 310 plots (3.65 t ha^{-1}), and in 2018 was in the P-44 plots (3.62 t ha^{-1}).

3.3. *Greenhouse gas fluxes*

Individual flux measurements of CH_4 in 2017 ranged from 0.2 to 54.8 nmol m^{-2} s^{-2} (Fig. S1). Variability was high between the measurements in all plots, and no significant differences were found between rice cultivars for CH_4 emissions. Rice cultivars are therefore grouped to focus on comparing treatment effects). All treatment plots observed a similar pattern of emissions, rising from lows in July, and maintaining relatively high emission throughout the growing period when irrigation water was applied. Emissions of CH_4 were highest from the FYM plots, with mean emissions of 30 ± 1.6 nmol m^{-2} s^{-2}, compared to the CON and NCU plots with mean emissions of 15.3 ± 0.9 and 19.6 ± 1.2 nmol m^{-2} s^{-2}, respectively. Emissions of CH_4 in 2018 were lower in comparison, and less variable in nature than those measured in 2017 (Fig. S1). Flux measurements of CH_4 in 2018 ranged from 0.14 to 32.1 nmol m^{-2} s^{-2}. Fluxes of CH_4 in 2018 were again highest from the FYM plots, with mean emissions of 10.8 ± 0.9 nmol m^{-2} s^{-2}, compared to the CON, NCU, PRI and LIM plots with mean emissions of 6.0 ± 0.6, 8.1 ± 0.7, 6.1 ± 0.6 and 6.6 ± 0.6 nmol m^{-2} s^{-2}, respectively.

Individual flux measurements of N_2O in 2017 ranged from 0.06 to 1.4 nmol m^{-2} s^{-2} (Fig. S2). Measurements from both fertiliser treatment plots were significantly higher than those from the control plot with mean fluxes of 0.13 ± 0.003, 0.25 ± 0.01 and 0.32 ± 0.02 nmol m^{-2} s^{-2} for CON, FYM and NCU treatments, respectively. Peaks of N_2O fluxes in the NCU plots coincided with the fertiliser applications during the growing period, with immediate, but short-lived increases in emissions. Emissions of N_2O in 2018 were relatively higher than those observed in 2017 with fluxes ranging from 0.05 to 2.4 nmol m^{-2} s^{-2}. As in 2017, emissions from the control plots remained relatively low while large peaks in N_2O emissions were observed immediately after fertiliser application in the other experimental plots. All plots that received N application showed peaks of N_2O emissions after application.

Cumulative emissions of CH_4 were highest in the FYM plots in both 2017 and 2018 (Table 3, Fig. 2), representing an increase of 101% and 85%, respectively, compared to the control plots over the growing period. While CH_4 emissions from the NCU plots were higher than control in 2017, this was not the case in the 2018 trials. All N application treatments resulted in an increase in N_2O emissions when compared to control plots. In 2017, FYM emissions of N_2O were slightly but significantly lower than that of NCU. FYM treatment also emitted the least N_2O of the treatments used in 2018 (Table 3). The treatment with the highest associated N_2O emissions was that of PRI application; however, these emissions were only observed in 2018, for which emissions of all treatments were considerably higher than those observed in 2017, including the control plot. Global warming potential (GWP) values from the IPCC 2022, Sixth Assessment Report (AR6) ($CH_4 = 34$, $N_2O = 298$) are applied to the cumulative fluxes. The total GWP of the different

Table 3
Cumulative GHG emissions (CH_4 and N_2O), expressed as CO_2 equivalent using global warming potential (GWP) values provided from the IPCC 2022, Sixth Assessment Report (AR6) ($CH_4 = 34$, $N_2O = 298$). Yield scale emissions calculated using yield data as presented in Table 2. Confidence intervals (95%) are included (Individual plot data are presented in Figs. S1 and S2).

Fertiliser Event	CH_4 Flux kg ha^{-1}		N_2O Flux kg N ha^{-1}		GWP kg CO_{2eq} ha^{-1}		Share of GWP CH_4/N_2O (%)	Yield Scaled kg CO_{2eq} per kg grain
2017								
CON	22.5	±0.4	0.34	±0.00	926	±13	83/17	0.27
FYM	45.2	±0.6	0.61	±0.01	1825	±21	84/16	0.33
NCU	28.5	±0.5	0.71	±0.02	1300	±18	74/26	0.25
2018								
CON	7.2	±0.2	0.38	±0.01	421	±8	58/42	0.13
FYM	13.3	±0.3	1.31	±0.03	1063	±17	42/58	0.21
NCU	7.1	±0.2	1.40	±0.04	900	±21	27/73	0.17
PRI	8.0	±0.3	1.60	±0.04	1020	±21	27/73	0.21
LIM	9.8	±0.3	1.35	±0.04	965	±22	34/66	0.17

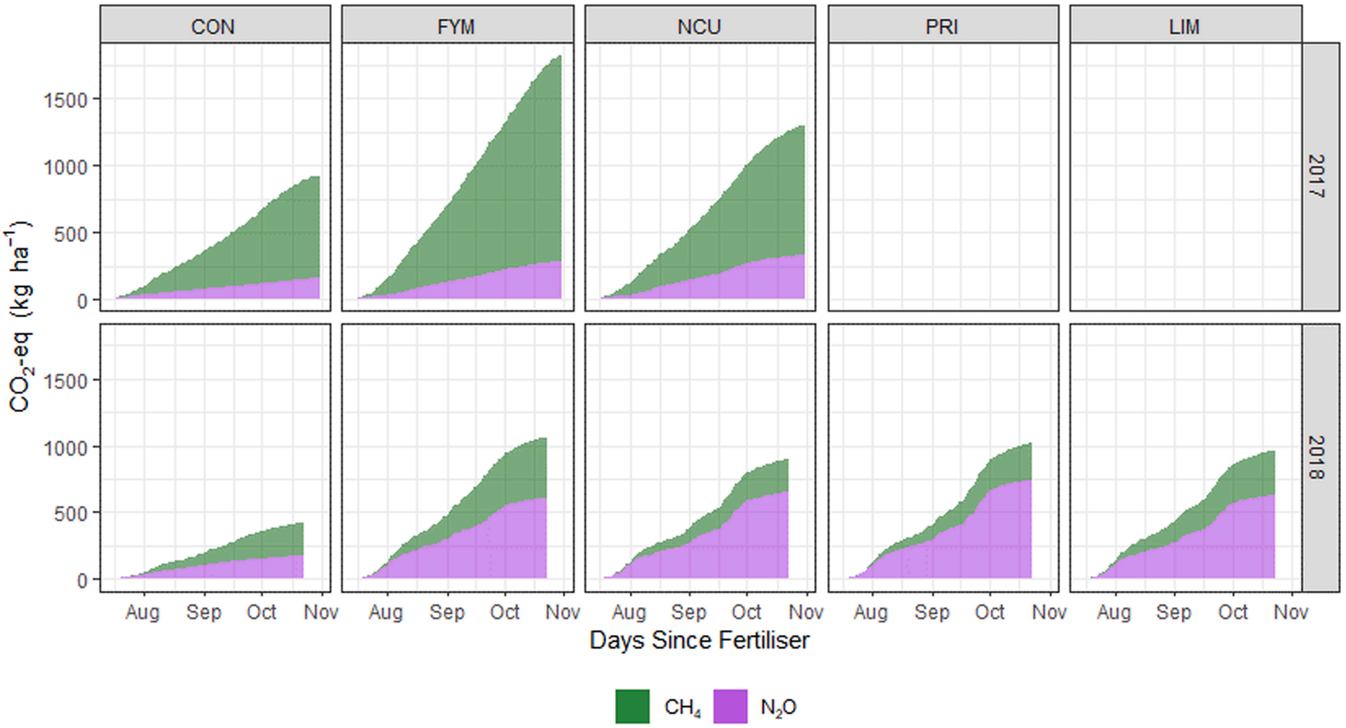

Fig. 2. Cumulative greenhouse gas emissions (CH_4 and N_2O) from treatment plots, temporally interpolated from measurement data using a LOESS function. Global Warming Potential (GWP) expressed as CO_2 equivalent using values for a 100 year time horizon provided from the IPCC 2022, Sixth Assessment Report (AR6) (CH_4 = 34, N_2O = 298).

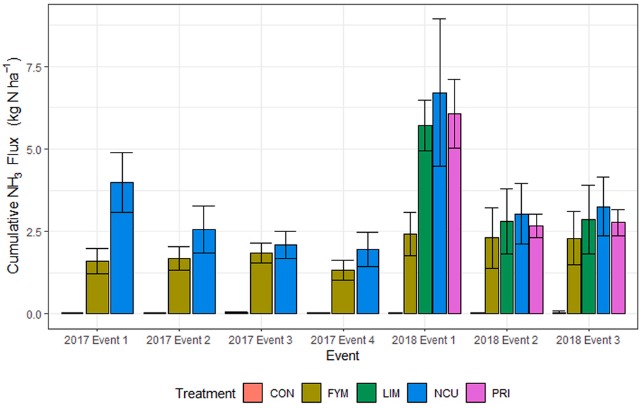

Fig. 3. Cumulative emissions of NH_3 are presented for each individual fertiliser application event across 2017 and 2018. Each event consists of 7 days of cumulative emissions (see Fig. S3). Confidence intervals (95%) are included as error bars (chamber replicates = 8 for each treatment).

treatments varied by treatment and by year. In 2017, the GWP was dominated by high CH_4 emissions, while in 2018, higher N_2O emissions dominate emissions from the fertilised plots (Fig. 2). In both years, the FYM treatment had the highest associated GWP, and highest emissions in terms of yield scaled kg CO_{2eq} kg grain^{-1}. In both cases, this is due to the large CH_4 emissions associated with FYM, which represented the majority of the GWP of the treatment.

Emission factors (EFs) of N_2O in the plots in 2017 were 0.27% and 0.37% for FYM and NCU treatments, respectively. Emission factors of N_2O in 2018 were 0.93%, 1.02%, 1.22% and 0.97% for FYM, NCU, PRI and LIM treatments, respectively.

Table 4
Cumulative emissions of ammonia (NH_3) expressed as NH_3-N and emission factors (EFs) reported for different N application treatments which all received a total of 100 kg N each year over multiple events (4 events in 2017 and 3 events in 2018). Confidence intervals (95%) are included.

Year	Fertiliser	NH_3 Emission		NH_3 EF	
		kg N ha^{-1}		%	
2017	CON	0.10	±0.03		
	FYM	6.5	±0.7	6.4	±0.7
	NCU	10.6	±1.3	10.5	±1.3
2018	CON	0.11	±0.04		
	FYM	7.0	±1.4	6.9	±1.4
	LIM	11.4	±1.6	11.3	±1.6
	NCU	13.0	±2.6	12.9	±2.6
	PRI	11.5	±1.2	11.4	±1.2

3.4. *Ammonia fluxes*

Ammonia emissions from control plots remained close to zero for the majority of the measurement period in both years, with a mean flux of 1.5 ± 0.2 nmol m^{-2} s^{-1}. Emissions for all treatments followed a similar pattern in the days immediately after N application, peaking after approximately 2 days and returning to pre-application magnitude after 7 days (Fig. S3). While mineral fertiliser applications were broadly similar in terms of emission behaviour, emissions from the FYM plots were considerably lower in both 2017 and 2018 than the other N application treatments (Fig. 3). It should be noted that the FYM treatment contained 50% nitrogen as FYM and 50% as NCU, and a low ammoniacal nitrogen content in the FYM itself indicates that most N was there present in organic N forms not liable to NH_3 emission. Emissions of NH_3 were considerably higher in the 2018 trials than the 2017 trials for the treatments applied (FYM and NCU). Despite high uncertainties in cumulative emissions, the emissions follow consistent trends. For each fertilisation event, cumulative NH_3 emissions were always highest from the NCU plots on average, with PRI and LIM following as 2nd and 3rd highest emitters, respectively (Fig. 3, Table 4). Cumulative emissions from control plots were similar in both 2017 and 2018 at 0.10 ± 0.03 and 0.11 ± 0.04 kg N ha^{-1}, respectively (Table 4). Emission factors for NH_3 varied from 6.4% to 12.9% of applied nitrogen, with NCU plots having the highest emission factor in both years (Table 4).

4. Discussion

4.1. Crop yields

Crop yields in 2018 were considerably higher than in 2017, and both years were within the range typically expected of the field site (Cowan et al., 2021; Bhatia et al., 2012b). Experimental work carried out in 2016 saw mean annual grain yields in control plots of 3.1–3.3 kg ha^{-1}, which compares well with the 3.3 and 3.4 kg ha^{-1} yields in control plots for 2017 and 2018, respectively (Cowan et al., 2021). Due to the consistency of control plot yields during this period, we can infer that observed differences in yields in the fertilised plots between the years are likely to be influenced more by agronomic management and crop cultivar than by environmental factors. In terms of grain and straw yields, differences were observed between the treatment types and rice cultivars, though uncertainty in measurements (relative uncertainty of 10–25% in yield estimates) may explain some of this variation (Table 2). While grain yield is the overall intended harvest, there is still value in considering rice stems and the total mass of the crop which will affect its total NUE, hence reduce N pollution to the environment.

In 2017, the FYM treatment (which had 50% substitution of urea by FYM along with biofertiliser) provided the highest grain and total biomass yields, while also having a higher total NUE than the NCU fertiliser treatment. The MTU 1010 and CRD 310 cultivars had the highest total aboveground biomass yields in 2017; however, grain yield was higher for the IR-64 and P-44 cultivars (Table 2). In 2018, the LIM treatment provided both the highest grain and total biomass yields, though differences between all the treatments were relatively small (<12%). Similar to year 2017, MTU 1010 and CRD 310 varieties had the highest total yields; however, grain yield was highest in the P-44 plots. Higher grain yields (3.4–8.8%) than NCU were observed in FYM plots in 2017 with the IR-64 being the highest grain yielding plot (5.0 ± 1.4 t ha^{-1}). Though the total N fertiliser applied in FYM and NCU plots was similar (100 kg N ha^{-1}), however, additional cyanobacteria biofertiliser applied in these plots and may have led to grain yield increase. Malyan et al. (2019) was able to get at par rice grain yield using *Azolla* and reducing urea application by 25%, which is assumed was possible as *Azolla* is able to fix atmospheric N. Though most paddy soils have a natural population of *Azolla* providing for a potential source of nitrogen fixation, the application of additional biofertiliser has been reported to increase nitrogen fixation in soil (Prasanna et al., 2014).

While comparable in the control plots, the N content of the CRD 310 grain harvest was consistently higher than the other rice cultivars after receiving fertiliser, averaging 1.53% N, compared with 1.36%, 1.34% and 1.30% N for the MTU 1010, IR-64 and P-44 cultivars, respectively (See Table S1). Overall, in terms of total yield and NUE, the CRD 310 cultivar was the best performing across the years; however, in terms of total grain yield, the P-44 had slightly higher than the others, averaging 5.68 t ha^{-1} over 2017 and 2018 in plots that received fertiliser.

The application of Limus®, a urea inhibitor coated over NCU led to higher yields in the all the rice cultivars. In 2018, the highest grain yield was in P-44 with the LIM treatment (6.20 t ha^{-1}). The yield increase with Limus® ranged from 4.5% to 8.7% over NCU, 11.3–16.1% over PRI and 9.3–14.5% over FYM treatments in the different rice cultivars. This is reflected in the NUE values for the LIM treatment, which were 35–40% higher than the comparable treatment using prilled urea (PRI), (Table 2). As the mechanism of action of Limus® is as a urease inhibitor, this suggests that Limus® achieved a significant reduction in ammonia emissions, consistent with previous studies (e.g. Li et al., 2015; Krol et al., 2020).

The NUE of the different treatments and cultivars relies on the yield of the harvested crop and is strongly dependent on the N content of the stem and grain in the crops (essentially the protein content). The grain and total NUE was the highest in LIM treatments which had co-application of a nitrification and urease inhibitor in all the rice varieties. Urease inhibitors significantly inhibit hydrolysis of urea, directly affect ammonium availability. They may also indirectly affect nitrification and NO_3^- concentration in soil, thereby, simultaneously reducing the substrate for denitrification (Meng et al., 2020; Sanz-Cobena et al., 2011). It is also possible to use co-application of double inhibitor (Urease and nitrification) which may yield a synergistic effect with the nitrification inhibitor blocking the growth of ammonia-oxidising bacteria and the urease inhibitor impeding the growth of ammonia-oxidising archaea (Lan et al., 2022), thereby improving the fertiliser recovery efficiency and mitigating N loss. Yang et al. (2020) reported a 10% increase in rice yield with co-application of urease inhibitor and *Azolla* reflected by increased panicle number, total biomass and higher NUE (Meng et al., 2020; Yang et al., 2020).

Overall, based on the variations in agronomic practice and the different rice cultivars used, that these provided comparable variation in performance expressed in terms of yield and NUE for total biomass and grain. When excluding the agronomic management, the variation between treatments in 2018 is larger for the genetic drivers of total biomass (11% coefficient of variation) than the agronomic drivers (3%). By contrast, genetics and agronomy management provided similar levels of variation for grain yield (6%, 6%, respectively), $NUE_{total\ biomass}$ (15%, 14%, respectively) and NUE_{grain} (13%, 16%). This illustrates how both genetic and agronomic management have similar potential to improve yield and NUE.

Considering both agronomy and genetics, results show that the best performing combination depends on the indicator chosen. In 2017 CRD-310 and the FYM treatment performed strongest for $NUE_{total\ biomass}$, suggesting a possible better environmental performance, whereas IR-64 and the FYM treatment had the highest grain yield (Table S1). In 2018, $NUE_{total\ biomass}$ and grain yield were for all cultivars achieved using the LIM treatment, with CRD-310 again performing the best for $NUE_{total\ biomass}$ and P-44 having the highest yield. These examples illustrate how breeding outcomes need to be based on prior agreement on indicator priorities. The consistently strong performance of the FYM treatment (2017) and LIM (2018) demonstrates the robust applicability of these treatments across rice cultivars.

4.2. Environmental impacts

In 2017, a significant environmental cost of the rice production was in the high CH_4 emissions observed, with the total GWP of emissions from the crop reaching 1825 kg CO_{2eq} ha^{-1} for the FYM plots (Table 3). In 2017 there were naturally higher emissions of CH_4 in all plots compared to 2018, including the control. This was a sustained emission, lasting throughout the measurement campaign (Fig. S1), and thus unlikely to be the direct result of infrequent weather events such as brief warm periods or rainfall events. It was shown at the site that more frequent irrigation (continuous flooding) can result in higher CH_4 fluxes in Cowan et al. (2021). As 21 irrigations were given in 2017 and only 16 irrigations were given in 2018, it could be hypothesised that the difference in CH_4 emissions between the years was due to changes in irrigation management at the site. This would also explain the difference in N_2O emissions at this site, which are also seen to rise considerably when irrigation was reduced (Cowan et al., 2021). A reduction in irrigation water may also be the reason for the increased NH_3 emissions between the years. As NH_3 volatilisation is predominantly driven by physical factors (i.e. temperature and humidity), and environmental variables were relatively similar during both growing seasons, the irrigation regime is one possible cause for the differences. Where soils are drier or water is shallower, ammonium in the water is likely to be more concentrated and thus is more likely to volatilise. Another factor is that fertiliser was applied in greater amounts in 2018 (40, 30 and 30 kg N ha^{-1}) than in 2017, where 25 kg N ha^{-1} was applied 4 times. While cumulative emissions of NH_3 in the 7 days after N application correlate strongly with applied N (linear regression $R^2 = 0.85$, $p = <0.0001$), this relationship does not appear to impact the EF of the application ($p = 0.885$), thus there is no evidence to suggest application amount alone is driving differences in emissions between the years (Fig. S4).

In terms of treatments, the first key finding is that genetics had no significant effect on the gaseous emissions (Fig. S5). This is in contrast to the yield and NUE indicators, where both genetics and agronomy contributed to variation in performance (see previous section). In the case of CH_4, N_2O and NH_3 emissions, the variation in losses can be entirely explained by the agronomic practices. This emphasises the critical role of agronomic practice for environmental performance. In principle, higher NUE should be expected to be linked to smaller N losses, but this has not been clearly shown in this study, and would require more comprehensive assessment of all N losses, including leaching and denitrification to N_2.

Considering the different treatments, environmental outcomes vary in terms of the different pollutants. The incorporation of FYM into the rice paddies increased CH_4 emissions in both 2017 and 2018 as compared to the other fertiliser types. However, with the exception of the control plots, the FYM treatments appear to produce the lowest emissions of N_2O in both 2017 and 2018. The highest N_2O emissions in the experiment were observed in the PRI treatment plots, reaching 1.6 kg N_2O-N ha^{-1}, or 1.22% of the N applied. Potentially, due to the slow mineralisation and release of the N in the organic FYM materials, crops can better compete with microbial processes for available N. However, increasing organic carbon in the rice paddy appears to strongly affect methanogenesis, and CH_4 emissions remain high throughout the growing season where large quantities of FYM are applied. This is unsurprising as it is known methanogens prefer very wet, warm, carbon rich environments, so applying FYM to rice paddies in tropical conditions creates the ideal environment for CH_4 production (Bartlett and Harriss, 1993).

While the CH_4 emissions from rice paddies are well established in literature (e.g. Maraseni et al., 2018; Gupta et al., 2021), there is less known about N_2O emissions. In 2017, N_2O emissions were typical of urea application observed elsewhere in the world, with EFs below 0.5% of applied N (e.g. Cowan et al., 2020). In 2018, EFs were higher ranging from 0.93% to 1.22% of applied N, which is closer, to the generic 1% value used in Tier 1 reporting of fertiliser application by the IPCC (IPCC, 2014). EFs of N_2O at the site in 2016 ranged between 0.55% and 0.7% (Cowan et al., 2021), somewhere in between what was observed for the 2017 and 2018 experiments, suggesting emissions were typical for the soil.

This study provides further evidence that reducing irrigation to prevent CH_4 emissions as a GHG mitigation strategy can result in significantly higher N_2O emissions. However, overall, even while N_2O emissions did increase in 2018, the overall CO_{2eq} emissions were still considerably lower in 2018 than in 2017, where CH_4 dominated the annual GWP. In terms of CO_{2eq} of grain produced, the FYM treatments emit significantly more than the mineral fertiliser treatments, but this does not take into account the carbon footprint of energy used in production and transportation of the mineral fertilisers (FYM was only 50% urea N). Assuming a range of approximately 1.6–3 kg CO_{2eq} per kg N in the production of urea (Hoxha and Christensen, 2018), we could make a realistic assumption that up to 150 kg CO_{2eq} extra should be attributed to the mineral fertiliser GWP for production, though livestock is not without additional GWP of its own and the full LCA of organic and mineral fertilisers in the region is beyond the scope of this study.

The NCU and LIM treatments both contain the nitrification inhibiting neem oil coating (in case of LIM Limus® coated over neem coated urea). In theory, nitrification inhibitors should reduce N_2O emission in comparison to untreated urea (PRI) as they slow down the microbial activity that produces N_2O fluxes and allow plants to better compete for the N in the soil. This does appear to be the case in the 2018 plots in which the highest N_2O emissions were from the PRI plots, and the coated urea plots also recorded higher yields and NUEs than the untreated urea. It has been observed in the past that nitrification inhibitors can lead to increased NH_3 emissions (Lam et al., 2016). As nitrification is inhibited, it can lead to higher concentrations of ammonium in soils, which can lead to an increase in NH_3 emissions. However, the urease inhibitor in the LIM treatment should counter this by slowing the breakdown of the urea molecules. The results in this experiment suggest that the neem coating is consistently increasing NH_3 emissions in comparison to PRI treatments and the LIM urease inhibitor seems to slightly reduce this effect. While the NH_3 emissions from the LIM treatment are still higher than those of the untreated PRI plots, they are lower than the NCU treatments where no urease inhibitor is present. The rather modest reductions in NH_3 emissions from the LIM treatment contrast with much larger reductions of 60–70% found in other trials. This indicates the need for further investigation of the compatibility of Limus® and NCU and the dependence on various coating protocols. In principle the higher NUE and yield obtained with the LIM treatment (Table 2) for 2018 compared with other treatments, might appear contradictory to the limited reduction in NH_3 emissions seen here, especially given that the NCU and LIM treatments showed similar N_2O emissions. Again, this indicates the need for further assessment of such combinations of different inhibitor types.

While the impact of crop cultivar on GHG and NH_3 emissions was not significant (Fig. S5), the major trade off in the environmental cost of the fertilisers observed in this study is that the treatment with the highest GHG cost (FYM) also has the lowest NH_3 emissions associated with it. However, this may be misleading, as the FYM was applied before NH_3 measurements took place and the total NH_3 emissions from the plots may vary outside the measurement periods. The limitations of NH_3 flux measurements are well known, and the warm humid climate of rice paddies in India is increasing the difficulty of applying effective long-term NH_3 measurements at field sites (including fallow periods and low emission periods between N application where N deposition can be expected). While we would encourage more long-term micrometeorological measurements of NH_3 in the future in this region, this work would not be without major logistical and economic constraints and would not work on small experimental plots as used here.

There was saving in environmental costs due to the adding of neem oil and Limus® to urea for both GHG and NH_3 mitigation, however, the statistical uncertainties were large as compared to the differences between treatments (Tables 3, 4). In terms of GHG reduction, while reducing irrigation frequency appears to have increased N_2O emissions, the overall GWP of the rice is reduced due to smaller CH_4 emissions. It seems irrigation of rice paddies is more influential than fertiliser management or rice cultivar. The irrigation effect may also apply to NH_3 emissions, but it is uncertain what is predominantly driving differences observed in the fluxes in this study. The magnitude of individual emission events was directly correlated to the amount of N applied, but this did not seem to adjust the overall EF as a response. Further research and methodology development in this area would improve understanding of emission drivers.

5. Conclusions

This study shows that rice cultivar can impact yields of both grain, and total biomass produced in given circumstances, with the CRD 310 cultivar showing consistently high NUE compared to other varieties, but not necessarily with the highest grain yield which was in Pusa-44 in this experiment. While we have shown distinct differences in rice cultivar performance, more evidence is required to test for consistency in yields, especially in varying climates and under different management regimes to maximise both environmental and economic outcomes. Here we have shown that addition of a cultivar of N fertilisers can significantly alter airborne N pollution in the form of NH_3 and the potent GHG N_2O, but in reducing these emissions with the use of FYM application, subsequent CH_4 emissions increased substantially. Understanding pollution swapping and synergies is essential in any attempts to improve environmental credentials of agricultural activities, especially where yield and cost may be significantly impacted. Decreasing irrigation application (and saving water) resulted in a large decrease in CH_4, but increased N pollution in the form of N_2O and NH_3 as a result. The use of fertilisers with nitrification (i.e. neem oil) reduced N_2O emissions, but resulted in a minor increase in NH_3 emissions. The co-application of nitrification and urease inhibitor reduced N_2O without affecting NH_3 emission. However, the addition of these chemicals resulted in an increase in crop and grain yields and nitrogen use efficiency which could offset any additional costs in fertiliser production. We recommend that research continues to explore the costs and benefits of rice cultivation management options in terms of both economic and environmental factors, which may provide a strong evidence base to encouraging more sustainable farming through education and policy in the future.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.agee.2023.108593.

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