Methane and nitrous oxide emission from *Kharif* rice field as influenced by nutrients and moisture regimes in new alluvial agroclimatic region of West Bengal

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Crop management practices have a significant impact on greenhouse gas (GHG) emission rates, where methane (CH_4) and nitrous oxide (N_2O) emissions from rice paddy fields are in trade-off association. A field study for two consecutive years (2013 and 2014) was conducted to continuously measure CH_4 and N_2O emissions from rice paddies under various agricultural management schedules like water regimes (irrigated and rainfed), transplanting dates and nutritional amendments (synthetic fertilizer with N as ammonium sulphate, P and K according to recommended dose, and vermicompost). Rainfed situation incurred a drop in CH_4 fluxes triggering substantial N_2O emission. Ammonium sulphate application tended to reduce CH_4 emissions, but significantly increased N_2O emissions. Enhanced CH_4 fluxes were measured during panicle initiation to flowering stage while, maximum N_2O emissions were recorded during flowering to milking stage of rice crop. Significant interrelationship between the gases was evaluated. In addition, seasonal average of CH_4 and N_2O emissions was also correlated with rice production. In conclusion, GHG concentration may control to some extent optimizing rice productivity through implementing and improving crop- and location-specific management practices.

Keywords: Agroclimatic region, methane, nitrous oxide, rice field.

INCREASING population and demand for food are placing unprecedented pressure on agriculture and natural resources[1,2]. Agriculture is estimated to account for 10–12% of anthropogenic emissions of greenhouse gases (GHGs) worldwide, including 60% of global nitrous oxide (N_2O) emissions and 50% of methane (CH_4) emissions[3]. Rice paddies are considered one of the most important sources of atmospheric CH_4, but they also emit N_2O and the intensity of emissions is related to the nitrogen (N) fertilizer application rate[4,5]. The increasing demand for rice in the future has raised tremendous concerns about increasing GHG emissions[6,7]. Rice paddies could contribute to more than 80% of CH_4 and N_2O emissions driven by microbial activities. The application of N fertilizer is one of the primary methods for enhancing rice production. Field measurements have reported that N fertilization significantly stimulated CH_4 and N_2O emissions[4], but some studies found reduction in CH_4 emissions with N fertilizer application[8]. Based on these existing data, it is difficult to determine an optimal rate of N fertilization for high productivity while reducing GHG emissions. Thus information regarding factors influencing rice yield and tendency to reduce GHG emissions is urgently needed to aid cropping technique innovation. Furthermore, it is important to explore the relationship between CH_4 and N_2O emitted from rice fields. Thus the present study is aimed (i) to assess the actual relation between CH_4 and N_2O emitted from rice and (ii) to scale rice productivity under varied CH_4 and N_2O emission potentiality.

Materials and methods

The study was conducted in new alluvial agroclimatic zone (22°17′N, 88°20′E) of Kalyani, West Bengal, India. This zone is humid tropical to subtropical and soil type is characterized as Entisols with sandy loam texture. *Kharif* season (June–October) of 2013 and 2014 was chosen for experiments with rice (*Oryza sativa* L.) variety Satabdi (IET-1444).

Figure 1 presents the average weekly air temperature and total rainfall recorded during the experimental period. The average temperature in both crop-growing seasons was nearly similar and ranged from 25.9°C to 32.5°C. However, distinct differences in rainfall distribution were noted. Total rainfall of 995.9 mm was recorded during crop-growing period of 2014, whereas the 2013 season received 791.1 mm rainfall.

Rice seedlings (25 days old) were transplanted on two dates at 15 days interval (27 June and 12 July) during both crop-growing years (plot size: 4 m × 3 m; spacing:

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20 cm × 15 cm; row-to-row and plant-to-plant). Two different types of nutrients were applied as 100% synthetic fertilizer (N : P : K :: 80 : 40 : 40; N as ammonium sulphate (250 kg/ha), P as single super phosphate and K as muriate of potash), and 100% organic amendment (N as vermicompost; 500 kg/ha). Also, 50% of total dose of ammonium sulphate was applied at the time of transplanting with full dose of single super phosphate and muriate of potash. Remaining 50% ammonium sulphate was applied at 21 days after transplanting (DAT) as topdressing. Two types of moisture regimes were considered – irrigated and rainfed. Under irrigated condition continuous 5 cm standing water was maintained up to last part of the reproductive phase of rice. Each treatment was replicated thrice in a randomized block design.

Sampling of CH_4 and N_2O emitted from rice soil was measured using closed chamber technology. A portable sensor-based nitrous oxide analyser (Technovation Series 2005, Serial No. 12045) was fitted to the chamber to measure N_2O emission rate from rice soil. For measuring CH_4 fluxes from rice fields, gas samples were collected through 20 ml syringe fitted with three-way stopcock prior to analysis and then measured by gas chromatography (gas chromatograph with flame ionization detector; model: Perkin Elmer, Clarus 480). Air temperature within the chamber was recorded using a thermometer fitted to the chamber. There was an internal fan for homogenizing the chamber atmosphere before sampling. Measurements were done during 10 am to 5 pm. Emissions of N_2O and CH_4 were continuously observed for each treatment during important phenological phases of rice crop, i.e. tillering to panicle initiations, panicle initiations to flowering, flowering to milking and milking to dough stage.

Methane flux rate was calculated according to the following equation

$$F = \frac{K \times 273 \times V \times 60}{(273+T) \times A} \times \frac{\mathrm{d}c}{\mathrm{d}t} \times 24,$$

where F is the flux rate (mg/m^2/day), K the conversion factor of methane (0.714), V the chamber volume (3.66 m^3), T the chamber temperature (°C), A the area of chamber (1.22 m^2) and dc/dt is the changes in concentration with time.

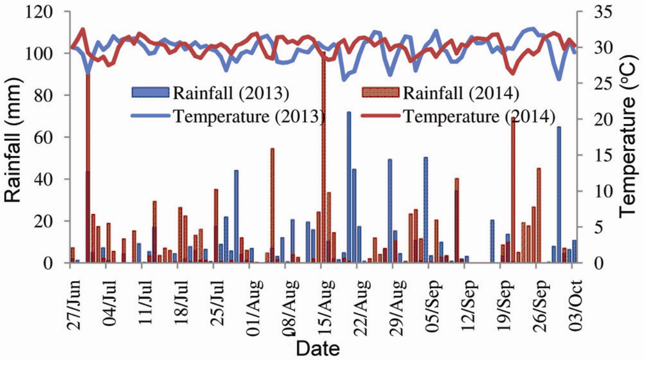

Figure 1. Weekly average air temperature and total rainfall during rice-growing seasons of 2013 and 2014.

Nitrous oxide flux rate was calculated according to the following equation

$$F = \frac{PVMU}{ART} \times \frac{\mathrm{d}c}{\mathrm{d}t} \times 1000,$$

where F is the flux rate (mg/m^2/day), P the pressure of the chamber, V the chamber volume (3.66 m^3), M the molecular weight of nitrogen, U the unit conversion factor (0.00144 min/(μl d)), A the area of the chamber (1.22 m^2); R the gas constant (0.082), T the chamber temperature (K) and dc/dt is the changes in concentration with time.

Rice yields were determined after harvesting. The grains were separated from straw, sun-dried and weighed.

Analysis of variance at 5% significance level was done to find the critical differences between the recorded parameters during the aforesaid phenological phases.

Results and discussion

Seasonal CH_4 and N_2O emissions during rice growing period

During 2014, maximum seasonal average of CH_4 flux was recorded for vermicompost fertilized irrigated rice crop transplanted on 12 July (78.46 mg/m^2/day) followed by 27 June transplanted rice under the same treatment (34.00 mg/m^2/day). CH_4 flux during rice growing period of 2013 was measured as 37.79 and 30.56 mg/m^2/day respectively, for vermicompost amended irrigated rice transplanted on 27 July and 12 June.

Seasonal average of CH_4 flux was considerably lower for rainfed rice transplanted on 12 July under vermicompost and ammonium sulphate fertilizer (–6.78 and 3.52 mg/m^2/day respectively) during 2014. During 2013, ammonium sulphate amended irrigated rice emitted lower CH_4 – 1.04 and 3.80 mg/m^2/day under 12 July and 27 June transplanting dates respectively. Minimum seasonal average of CH_4 emission during 2013 was noticed under rainfed condition (ranging between 4.55 and 13.51 mg/m^2/day) (Figure 2).

Continuous flooding promotes the anaerobic soil environment with lower redox potential leading to increase CH_4 emission density[9–11]. Application of vermicompost provided substrates for methanogenesis as organic carbon compounds resulted in maximum CH_4 production. *In situ* studies have shown that organic matter incorporation markedly increased CH_4 emission[12,13]. However, rainfed situation triggered aerobic condition in rice soil which is not suitable for specific CH_4 production and oxidation. It is reported that water regime plays an important role in methanogenesis by intensifying bacterial chemical reduction in the soil[14].

The pattern of seasonal variations in average N_2O fluxes from rice paddy was different compared to that of CH_4 fluxes. During both the years, N_2O emissions potentiality showed a peculiar trend under irrigated situation (range: –5.15 to 8.41 and –6.02 to14.21 mg/m^2/day during 2013 and 2014 respectively). In rainfed rice environment transplanted on 27 June under ammonium sulphate and vermicompost maximum N_2O was emitted during 2014 (34.24 and 11.96 mg/m^2/day respectively). However, under the same treatment N_2O fluxes were lower (2.73 and 8.78 mg/m^2/day respectively) during 2013. On the other hand, considerable N_2O fluxes were measured under rainfed rice transplanted on 12 July with ammonium sulphate and vermicompost during 2013 (16.23 and 15.20 mg/m^2/day) and 2014 (11.21 and 12.43 mg/m^2/day) (Figure 2).

Results reflect that rainfall distribution pattern (Figure 1) during both the years strongly influences N_2O emissions. Rice transplanted on 12 July received maximum rainfall, i.e. 805 mm, whereas rice transplanted on 27 June received 650 mm of rainfall (Figure 1). Rice–soil environment is subjected to an alternate dry–wet cycle due to intermittent rainfall and water management practice under rainfed condition. Alternate aerobic–anaerobic cycling considerably increases N_2O emission by influencing the nitrifier and denitrifier communities. Dependency of N_2O emission on water regime is consistent with previous studies[15].

In the present study, some negative CH_4 and N_2O fluxes were measured influenced by microbial uptake of CH_4 and N_2O under changed soil moisture content, temperature, pH, oxygen and available nitrogen. Change in chamber temperature is also responsible for negative flux of N_2O as the respective flux density is the measurement of emission density at different time intervals. A negative value indicates low N_2O emission, where gradient of slope is less. These views are supported by other researchers as well[16,17].

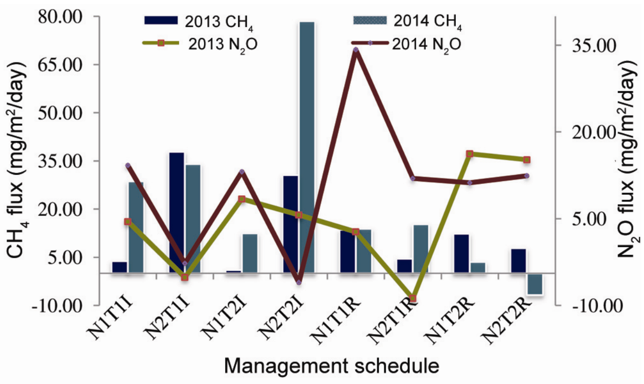

Figure 2. Seasonal variation in average CH_4 and N_2O flux from rice under various management schedules during 2013 and 2014.

CH_4 and N_2O emission potentiality under different management schedules

Table 1 represents the influence of treatment combinations on CH_4 and N_2O fluxes from rice during various growth phases.

Effect of nutrient: Emission of CH_4 during rice growing period amended with ammonium sulphate ranged from –1.08 to 20.72 mg/m^2/day. Under vermicompost fertilization, intensification of CH_4 emission was observed which ranged from 12.39 to 36.54 mg/m^2/day during tillering to dough stage. Maximum CH_4 emission density was noticed under vermicompost during tillering to panicle initiation (36.54 mg/m^2/day) (Table 1). Decomposition of organic matter in rice paddies would offer the predominant source of methanogenic substrates, and thus promote CH_4 production, particularly in the early stage of rice development[4,18]. Lower CH_4 flux in case of ammonium sulphate application could possibly be due to the inhibition of CH_4 oxidation by constraining the availability of O_2. Previous studies also documented reduced CH_4 emission from rice fields with sulphate-containing fertilizers, as a result of competition between sulphate-reducing bacteria and methanogens for hydrogen and acetate substrates[19,20].

Yet there are striking differences in N_2O emission intensity between rice phenophases under both nutrient treatments. Maximum N_2O emission was recorded during panicle initiation to milking stage of rice under ammonium sulphate application (17.98–15.57 mg/m^2/day). The rise in emission rate from active tillering onwards may be related with topdressing (just before panicle initiation). Also, canopy development at these growth phases might alter soil environment, thus affecting microbial activity. Nitrogen fertilizer stimulates the denitrifying bacteria, which are more capable of outcompeting methanogens for growth substrates. As a result, N fertilizer could indirectly suppress methanogenic activity. Besides, N_2O will be generated as intermediates which are toxic to methanogens[21]. Minimum N_2O emission was associated with vermicompost application during milking to dough stage. Higher C : N ratio in soil probably reduces N_2O emission[22]. Significant variations in CH_4 and N_2O fluxes were noticed during tillering to panicle initiation stage. No significant variation in CH_4 emission rates was observed in the other rice growth stages.

Effect of transplanting dates: In case of different dates of transplanting, peak methane emissions were recorded during 12 July (32.80 mg/m^2/day) followed by 27 June (24.63 mg/m^2/day) at active tillering to panicle initiation stage and panicle initiation to flowering stage. During panicle initiation to dough stage there was a decreasing trend of CH_4 emission density under 12 July transplanting date. However, in case of 27 June transplanted crop, rise

Table 1. CH_4 and N_2O emission (mg/m^2/day) potentiality of rice paddy influenced by individual and combined experimental factors

	Tillering to panicle initiation		Panicle initiation to flowering		Flowering to milking		Milking to dough	
Experimental factors	CH_4	N_2O	CH_4	N_2O	CH_4	N_2O	CH_4	N_2O
N1 (ammonium sulphate)	14.02	8.79	20.72	17.98	–1.08	15.57	10.88	9.99
N2 (vermicompost)	36.54	3.11	24.82	11.58	27.08	7.66	12.39	–7.78
SEm (±)	2.86	1.37	2.70	0.67	8.13	1.00	2.67	1.09
CD (at 5%)	8.46	4.06	NS	1.99	24.06	2.95	NS	3.22
T1 (transplanting 27 June)	17.76	6.12	24.63	14.58	12.63	7.35	20.67	–2.18
T2 (transplanting 12 July)	32.80	5.53	20.91	16.15	13.38	15.11	2.61	3.69
SEm (±)	2.86	1.37	2.70	0.67	8.13	1.00	2.67	1.09
CD (at 5%)	8.46	NS	NS	1.99	NS	2.95	7.92	3.22
I (irrigated)	39.10	0.61	28.00	7.50	23.41	6.85	22.86	4.33
R (rainfed)	11.46	11.29	17.54	22.06	2.60	16.38	0.42	–2.12
SEm (±)	2.86	1.37	2.70	0.67	8.13	1.00	2.67	1.09
CD (at 5%)	8.46	4.06	8.00	1.99	NS	2.95	7.92	3.22
Y1 2013	18.80	6.17	15.54	15.71	9.17	8.36	12.18	–8.99
Y2 2014	31.76	5.73	30.00	13.85	16.83	14.86	11.09	11.20
SEm (±)	2.86	1.37	2.70	0.67	8.13	1.00	2.67	1.09
CD (at 5%)	8.46	NS	8.00	NS	NS	2.95	NS	3.22
N × T SEm (±)	4.04	1.94	3.82	0.95	11.50	1.41	3.78	1.54
CD (at 5%)	NS	NS	NS	2.81	NS	4.17	11.19	NS
N × MR SEm (±)	4.04	1.94	3.82	0.95	11.50	1.41	3.78	1.54
CD (at 5%)	11.97	5.75	11.32	2.81	34.03	NS	11.19	4.56
N × Y SEm (±)	4.04	1.94	3.82	0.95	11.50	1.41	3.78	1.54
CD (at 5%)	NS	5.75	NS	2.81	NS	NS	NS	4.56
T × MR SEm (±)	4.04	1.94	3.82	0.95	11.50	1.41	3.78	1.54
CD (at 5%)	11.97	NS	NS	2.81	NS	4.17	11.19	4.56
T × Y SEm (±)	4.04	1.98	3.82	0.95	11.50	1.41	3.78	1.54
CD (at 5%)	11.97	NS	11.32	2.81	NS	4.17	NS	4.56
Y × MR SEm (±)	4.04	1.94	3.82	0.95	11.50	1.41	3.78	1.54
CD (at 5%)	11.97	NS	NS	2.81	34.03	4.17	NS	4.56
N × Y × T × MR SEm (±)	8.09	2.74	7.65	1.34	22.99	1.99	7.56	2.18
CD (at 5%)	23.93	8.13	22.64	3.98	68.05	5.89	NS	6.44

Y1, 1st year (2013); Y2, 2nd year (2014); N, Nutritional treatments; T, Transplanting dates; MR, Moisture regime; CD, Critical differences.

in CH_4 flux was observed at milking to dough stage. This fluctuation in emission of CH_4 was augmented with rice growth pattern. Both the transplanting dates influenced the emission density in different ways as they passed through various climatic conditions. Influence of temperature on CH_4 production rates has been well documented. It is established that increasing ambient temperature between 25°C and 35°C increases CH_4 production[23]. The decrease in CH_4 emission during panicle initiation onwards was probably due to comparatively lower temperature and continuous rainfall during this period (Figure 1). Earlier findings[24] documented that seasonal variation in CH_4 fluxes from rice paddy is related to variation in CH_4 production dependent on temperature and rainfall[24]. Maximum N_2O emission was noticed during panicle initiation to flowering stage under both transplanting dates (14.58 and 16.15 mg/m^2/day for 27 June and 12 July respectively). Milking to dough stage showed minimum N_2O emission (–2.18 and 3.69 mg/m^2/day for transplanting dates 27 June and 12 July respectively).

Maximum variation among mean CH_4 emissions due to transplanting dates was observed during active vegetative stage. N_2O emission responded to significant variation during maturity.

Effect of moisture regime: Soil moisture regime incurred a pronounced variation in CH_4 and N_2O emissions during rice growing period. Maximum methane emission density was observed during active vegetative period (39.10 mg/m^2/day) under irrigation. Methanogenesis might have favoured the strict anaerobic condition during active vegetative phase of rice crop. Water regime regulates the soil redox potential (Eh) and soil temperature which could create favourable conditions for methanogens during the period of increasing microbial population[25–27]. Rates of CH_4 fluxes from irrigated rice started to decline after panicle emergence up to dough stage (from 28.00 to 22.86 mg/m^2/day) (Table 1). During reproductive to maturity stages of rice crop higher root secretion and high metabolic activity with changing redox potential did not favour methane emission. Thus reduced emission occurred at flowering to dough stage. The soil in a moderately wet state instead of alternating between flooding and drying would potentially decrease both CH_4 emissions[22].

Table 2. Relationship between emission density of CH_4 and N_2O from rice paddy under different management schedules at important phenological phases during 2013 and 2014 cropping season

	Coefficient of determination (R^2)							
	Tillering to panicle initiation		Panicle initiation to flowering		Flowering to milking		Milking to dough	
Factors	2013	2014	2013	2014	2013	2014	2013	2014
N1	0.75 ($y = 0.07x + 4.23$)	0.21 ($y = -0.08x + 14.01$)	0.77 ($y = -0.41x + 14.68$)	0.68 ($y = -0.27x + 34.21$)	0.82 ($y = 0.77x + 17.37$)	0.35 ($y = 0.41x + 15.72$)	0.51 ($y = -0.90x + 12.76$)	0.54 ($y = 0.80x + 9.88$)
N2	0.77 ($y = -0.86x + 27.57$)	0.78 ($y = -0.38x + 13.09$)	0.14 ($y = -0.81x + 37.2$)	0.98 ($y = 1.43x - 42.03$)	0.01 ($y = 0.05x + 0.49$)	0.37 ($y = -0.08x + 16.22$)	0.78 ($y = 0.60x - 27.62$)	0.37 ($y = 0.05x + 3.87$)
I	0.945 ($y = -0.46x + 9.22$)	0.77 ($y = -0.37x + 16.52$)	0 ($y = 0.02x + 10.95$)	0.35 ($y = 0.53x - 15.11$)	0.31 ($y = -0.09x + 2.68$)	0.16 ($y = -0.05x + 13.46$)	0.86 ($y = -0.40x + 10.69$)	0.26 ($y = 0.06x + 4.72$)
R	0.75 ($y = 1.37 - 5.4$)	0.30 ($y = -0.91x + 21.21$)	0.45 ($y = 2.76x - 8.77$)	0.05 ($y = -0.18x + 28.52$)	0.08 ($y = 0.47x - 2.74$)	0.01 $y = (0.03x + 18.28)$	0.14 ($y = 0.49x - 22.37$)	0.68 ($y = 0.73x + 18.42$)
T1	0.18 ($y = -0.46x + 13.45$)	0.68 ($y = -0.66x + 17.57$)	0.35 ($y = -0.80x + 21.77$)	0.03 ($y = 0.16x + 10.05$)	0.02 ($y = -0.11x - 0.45$)	0.67 ($y = -1.17x + 34.33$)	0.48 ($y = 0.62x - 32.67$)	0.10 ($y = 0.23x + 13.18$)
T2	0.82 ($y = -0.53x + 13.89$)	0.84 ($y = -0.39x + 20.90$)	0.01 ($y = 0.11x + 18.25$)	0.25 ($y = -0.80x + 31.27$)	0.39 ($y = 0.56x + 14.36$)	0.24 ($y = -0.05x + 12.81$)	0.07 ($y = -0.22x + 5.04$)	0.19 ($y = -0.02x + 3.77$)

N1, Ammonium sulphate; N2, Vermicompost; I, Irrigated; R, Rainfed; T1, 27 June; T2, 12 July.

On the other hand, considerably lower CH_4 fluxes were recorded under rainfed condition ranging from 0.42 to 17.54 mg/m^2/day (Table 1). Well-distributed rainfall in rainfed plots resulted in anaerobic–aerobic alteration. Under such condition presence of oxygen in soil layer reduced the production of CH_4 through inhibiting the metabolism of methanogenic bacteria.

An inverse result was obtained in case of N_2O emissions. Anaerobic–aerobic alteration under rainfed situation reduces CH_4 emission rates, but simultaneously promotes N_2O emission. Maximum N_2O emission density was noticed during panicle initiation to flowering stage (22.06 mg/m^2/day) followed by 16.38 and 11.29 mg N_2O/m^2/day during flowering to milking and tillering to panicle initiation stage respectively. Dry–wet alternation in soil stimulated N_2O generation and emission. Changes in soil moisture regime as rainfed field stimulated nitrification (through soil drying) and denitrification (through soil wetting by rainfalls), and thus influenced N_2O emission[12,28]. Our previous study also reported the same trend[29]. During maturity period negative N_2O emission occurred (–2.12 mg/m^2/day), which may be due to changes in C : N ratio which produce N_2O sink in rice soil. Continuous flooding condition establishes anaerobic environment which does not favour N_2O production and emission. N_2O emission rates ranged between 0.61 and 7.50 mg/m^2/day under irrigation throughout the rice growing period. Nitrifying bacteria do not favour anaerobic condition to produce N_2O emission, because N_2O is rapidly broken down to nitrogen (N_2)[30]. Tillering to panicle initiation stage exerted maximum variation in CH_4 and N_2O emissions under different water management regions (Table 1).

Effect of year: CH_4 and N_2O emissions from rice paddy varied distinctly during both cropping seasons. During the rice growing period of 2014, maximum CH_4 and N_2O fluxes were obtained with peak emissions of 31.76 mg CH_4/m^2/day during active vegetative stage and 14.86 mg N_2O/m^2/day during later stage of reproductive phase. The 2013 season exhibited minimum emission density of CH_4 and N_2O, ranging from 9.17 to 18.80 mg/m^2/day and –8.99 to 15.71 mg/m^2/day respectively (Table 1). This variation is probably due to changing rainfall distribution pattern and air temperature during both the years.

Interaction effect of different factors on emission potentiality: In the present study, CH_4 and N_2O emissions were less affected by the interaction of N × T, N × Y (nutritional treatment × year) and T × MR (transplanting date × moisture regime). Significant variation was noted due to N × MR (nutritional treatment × moisture regime) during each rice phenophase (except during flowering to milking for N_2O), with maximum variation in both GHGs during tillering to panicle initiation stage. Results suggest that the emission factor responsible for CH_4 and N_2O emissions tended to be dependent on water management and nutrient amendment. Furthermore, interaction of all factors (N × Y × T × MR; nutritional treatment × year × transplanting date × moisture regime) exerted significant variations between mean N_2O and CH_4 fluxes of rice paddy, especially during the vegetative period.

Association between CH_4 and N_2O emissions

The present study clearly indicates a trade-off association between the CH_4 and N_2O emissions from rice paddy under different management practices during important growth phases. We obtained a linear relationship between the two GHGs over two experimental seasons of 2013 and 2014 (Table 2). There was an inverse relationship between CH_4 and N_2O emissions during tillering to panicle initiation stage. Here increased CH_4 emission was associated with readily available organic carbon from nutritional source as well as the increased CH_4 transport capacity of rice due to well-developed aerenchyma tissues[31,32]. Soil water saturation level did not favour nitrification and denitrification, thus reducing N_2O emission. During panicle emergence to flowering opposite emission trends were observed. Greater availability of nitrogen (just after top dressing) probably increased the N_2O emission as nitrogen inputs within soil determine the N_2O production rates[33]. C : N ratio with lack of optimum temperature along with well-distributed precipitation controlled CH_4 emission. The end of growing season responded positively to emissions of both gases under ammonium sulphate application. Hence, the rice plant at flowering to ripening stages offers a relatively favourable ecological niche for a methanogenic microbial community[34]. Rise in N_2O emissions may be due to the shift from anaerobic to aerobic conditions which enhances mineralization of available C and N, thereby favouring N_2O emissions[5]. The present findings in terms of trade-off relation between the two gases are in conformity with earlier findings[35–37].

Table 3. Yield of rice as influenced by different individual and combined experimental factors

Experimental factors	Yield of rice (kg/ha)	Experimental factors	Yield of rice (kg/ha)
N1	4586.41	T1	4341.8
N2	3775.08	T2	3950.93
SEm (±)	148.68	SEm (±)	148.68
CD (at 5%)	440.09	CD (at 5%)	440.10
I	4695.70	Y1 (2013)	4561.48
R	3665.78	Y2 (2014)	3800.00
SEm (±)	148.68	SEm (±)	148.68
CD (at 5%)	440.10	CD (at 5%)	440.10
N × Y × T × MR	SEm (±)	297.36	
	CD (at 5%)	880.18	

Table 4. Coefficient of determination (R^2) between seasonal average CH_4 and N_2O flux and rice productivity during 2013 and 2014 under different management factors

	CH_4 versus productivity (R^2)		N_2O versus productivity (R^2)	
Factors	2013	2014	2013	2014
N1	0.68	0.86	0.20	0.17
N2	0.13	0.15	0.95	0.18
I	0.22	0.45	0.00	0.72
R	0.00	0.87	0.65	0.57
T1	0.17	0.06	0.74	0.41
T2	0.05	0.28	0.31	0.49

Influence of GHG fluxes on rice productivity

Rice productivity was significantly affected by nutrient amendments, transplanting dates, and moisture regime (Table 3). Combination of all factors showed maximum critical difference (at 5% significance level) among mean values of rice yield. According to two years' data, the highest yield was obtained from ammonium sulphate amended rice transplanted on 27 June under irrigation.

Seasonal average of CH_4 flux showed significant inverse relationships with rice yield under ammonium sulphate application during 2013 and 2014 ($R^2 = 0.68$ and 0.86 respectively). During cropping season of 2014, significant associations were noted under rainfed rice ($R^2 = 0.87$) (Table 4). Denier van der Gon *et al.*[38] reported a negative correlation between grain yield and CH_4 emissions. This could be due to the availability of more photosynthetic C as root exudates, since it was not being used in seed production.

During 2013 seasonal average of N_2O emission exerted direct correlation (negative) with rice yield under vermicompost application ($R^2 = 0.95$) and rainfed condition ($R^2 = 0.65$ and 0.57 during 2013 and 2014 respectively) (Table 4). These associations rely on plant uptake pattern of available nitrogen and subsequent loss through microbial activity.

Conclusion

A complete perspective is provided in this study to assess vital information on the interactive nature of different GHGs and their association with rice productivity, which limits the reliability of mitigation strategies. The achieved outputs of the present study opened up the possibilities to immediately develop some specific mitigation technologies. However, sound rice production is imperative for future generations. The challenge is to develop technologies by modifying indigenous traditional knowhow that optimize rice yields and at the same time minimize GHG emissions. For location-specific recommendations long-term experiments in this line are essential for a better understanding.

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