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Effect of fertilizer composition and different varieties on yield, methane and nitrous oxide emission from rice field in East Java Indonesia

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Introduction: Rice, as a staple food in several Asian countries, contributes to approximately 10% of greenhouse gas (GHG) emissions during its cultivation. Furthermore, nitrogen fertilization increases the accumulation of GHG emissions. This study aims to investigate GHG emissions, including methane (CH_4) and nitrous Oxide (N_2O) resulting from the common fertilizer variations used by farmers in Indonesia for two rice varieties, Way Apo Buru and Inpari 32, and their relationship to rice yield.

Methods: The research was conducted from August to November 2022 in an open field located in Jember, Indonesia. Two rice varieties, Inpari 32 and Way Apo Buru, were employed in this study. Fertilization variations included Urea (46%-N), ZA (21%-N 24%-S), SP-36 (36%-P & 5%-S), KCl (250:100:50:50 kg ha^{-1}) (P1); NPK (16%-N:16%-P:16%-K), Urea (46%-N), ZA (21%-N & 24%-S) (225:175:100 kg ha^{-1}) (P2); NPK (12%-N:12%-P:17%-K), Urea (46%-N), ZA (21%-N & 24%-S) (175:150:100 kg ha^{-1}) (P3); and NPKS (P1) + chicken manure fertilizer 5 tonnes ha^{-1} (P4).

Results: In this research, Inpari 32 rice achieved greater yields while also exhibiting higher global warming potential. Applying NPKS fertilizer in combination with 5 tonnes ha^{-1} of manure fertilizer (referred to as P4) resulted in a substantial increase in rice yield compared to alternative fertilizer formulations.

Discussions: The various inorganic fertilizers had a relatively similar influence on growth, production yield, and greenhouse gas emissions (CH_4 and N_2O). However, the fertilizer NPKS and 5 tonnes manure fertilizer resulted in the lowest CH_4 emissions and global warming potential values.

KEYWORDS

rice, fertilizer, yield, methane, nitrous oxide

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1 Introduction

Many countries have pledged to participate in reducing greenhouse gas (GHG) emissions, such as methane (CH_4) and nitrous oxide (N_2O). Therefore, it is imperative to assess the magnitude of agricultural GHG emissions and identify mitigation opportunities (Hu et al., 2023). GHG emissions from agroecosystems are a significant contributor to global warming (Hou P. et al., 2023). The practice of rice cultivation contributes to CH_4 and N_2O emissions. Rice cultivation is accountable for more than 10% of global agricultural GHG emissions and approximately 1.3% to 1.8% of anthropogenic GHG emissions (Maraseni et al., 2018).

Nitrogen fertilization has been one of the strategies employed to enhance crop production worldwide in recent times. However, improper nitrogen fertilization practices can result in significant greenhouse gas (GHG) emissions, contributing to climate change and global warming (Guo et al., 2022). Chemical fertilizers exert a pronounced impact on soil N_2O emissions, supplying an excess of mineral N that ultimately leads to N_2O production (Shaaban et al., 2022). N_2O gas is generated by ammonia-oxidizing bacteria and archaea through nitrification and denitrification processes within the soil. CH_4 gas emanates from the soil under anaerobic conditions, exhibiting three distinct emission pathways into the atmosphere: diffusion through water layers, ebullition (bubbling), and transportation through the aerenchyma of rice plants (Santoro et al., 2011; Yuan et al., 2017).

Different fertilizer categories can induce variations in GHG fluxes and emissions, as well as variances in rice biomass throughout the growing season. GHG fluxes and CH_4 emissions significantly increase in land areas treated with organic fertilizers compared to those without fertilizers or with chemical fertilizers. CH_4 production is higher during the reproductive phase compared to other growth stages. Efforts to adapt to and mitigate the impacts of climate change are necessary for combating the consequences of climate change. This can be achieved through the implementation of technological innovations aimed at enhancing crop productivity and reducing greenhouse gas (GHG) (Wihardjaka and Harsanti, 2021). It is important to recognize that mitigation strategies for GHG emissions in rice cultivation, such as efficient nitrogen fertilizer management (Islam et al., 2022), and the selection of rice varieties with high productivity and low GHG emissions, are crucial for improving crop yields and mitigating climate change.

The influence of rice varieties on methane emissions is primarily associated with the rice plants growth performance, including factors such as the number of tillers, above and below-ground biomass, root exudates, and aerenchyma (Win et al., 2021). The objective of this research is to examine the greenhouse gas emissions (specifically CH_4 and N_2O) arising from the typical fertilizer practices employed by Indonesian farmers. These practices adhere to the guidelines prescribed by the Agricultural Research and Development Agency of the Ministry of Agriculture for paddy fields situated in specific locations. The investigation will focus on two rice varieties, Way Apo Buru and Inpari 32, and their connection to rice crop yield.

In Indonesia, the application of NPK fertilization in rice cultivation is recommended by the Indonesian Ministry of Agriculture (Ministry of Agriculture, 2021). In Jember Regency, East Java, Indonesia, there are eight variations of NPK fertilization recommendations, categorized into single and compound fertilizer variations. The compositions for single fertilizers include: 1) Urea, ZA, SP-36, KCl (200:100:50:50 kg ha^{-1}); 2) Urea, ZA, SP-36, KCl (250:100:50:50 kg ha^{-1}); and 3) Urea, ZA, SP-36, KCl (250:100:50:100 kg ha^{-1}). Meanwhile, the compound fertilizer compositions involve 1) NPK 15-15-15, Urea, ZA (175:100:100 kg ha^{-1}); 2) NPK 15-15-15, Urea, ZA (175:150:100 kg ha^{-1}); 3) NPK 15-15-15, Urea, ZA (350:100:100 kg ha^{-1}); 4) NPK 15-10-12, Urea, ZA (225:125:100 kg ha^{-1}); and 5) NPK 15-10-12, Urea, ZA (350:150:100 kg ha^{-1}). This research aims to assess rice yield and greenhouse gas emissions across different fertilization variations using two distinct rice varieties.

2 Materials and methods

2.1 Study area and experimental design

The research was conducted from August to November 2022 in an open field located near Jl. Kutai, Kranjingan Village, Sumbersari Subdistrict, Jember (8°1202.1"S 113°4340.9"E). Based on data from the Central Statistics Agency, Indonesian (2023), the study site in the Jember region had average humidity and temperature conditions of 80.02% and 27.06°C, respectively, in the year 2022. The duration of sunlight in the Jember region in August, September, October, and November 2022 was 9%, 9%, 20%, 16%, and 26%, respectively. The study site, situated in Sumbersari Subdistrict, Jember Regency, had monthly rainfall in 2022 of 0 mm (August), 5.9 mm (September), 22 mm (October), and 23.2 mm (November) (Central Statistic Agency, 2023).

The research design employed a randomized complete block design with three replications, and the experimental plot size was 2.4 m^2 (2 x 1.2 m) for each plot. A 0.5-meter-wide buffer separated each experimental plot. Soil preparation was conducted before planting by plowing to a depth of 25 cm and providing water to achieve mud and ponding conditions. There were 60 planting holes per experimental plot, spaced 20 x 20 cm apart, with 2 rice seedlings planted in each hole. This study utilized two rice varieties, Inpari 32 (harvest age between 120 days after sowing) and Way Apo Buru (harvest age between 115-125 days after sowing). Fertilization variations consisted of Urea 250 kg ha^{-1}, ZA 100 kg ha^{-1}, SP-36 50 kg ha^{-1}, KCl 50 kg ha^{-1} (P1); NPK (16:16:16) 225 kg ha^{-1}, Urea 175 kg ha^{-1}, ZA 100 kg ha^{-1} (P2); NPK (12:12:17) 175 kg ha^{-1}, Urea 150 kg ha^-1, ZA 100 kg ha^{-1} (P3); and NPKS (P1) + chicken manure fertilizer 5 tonnes ha^{-1} (P4). Fertilization was performed periodically with the compositions listed in Table 1.

2.2 Growth and yield sample collection

The growth data observed included plant height, the number of tillers, and leaf chlorophyll content (60 days after sowing) using the SPAD-502 meter. The recorded parameters for grain yield included grain numbers, empty grain (gram), dry grain (gram), and overall

TABLE 1 Composition and dosage of fertilizers used.

Treatment	Fertilizer (kg/ha)	Time (Day After Sowing)			
		0	10	21	41
P1	Urea (46% N)	–	84	83	83
	ZA (21% N & 24% S)	–	34	33	33
	SP-36 (36% P & 5% S)	–	17	16	16
	KCl (60% K2O)	–	17	16	16
P2	NPK (16% N:16% P:16% K)	–	75	75	75
	Urea (46% N)	–	59	58	58
	ZA (21% N & 24% S)	–	34	33	33
P3	NPK (12% N:12% P:17% K)	–	59	58	58
	Urea (46% N)	–	50	50	50
	ZA (21% N & 24% S)	–	34	33	33
P4	Urea (46% N)	–	84	83	83
	ZA (21% N & 24% S)	–	34	33	33
	SP-36 (36% P & 5% S)	–	17	16	16
	KCl (60% K2O)	–	17	16	16
	Manure	5000	–	–	–

yield. Harvesting was conducted at 125 days after sowing. Data collection was performed through sampling, where four plants per experimental plot were selected for measurement. The data of yield is calculated by converting the dry weight calculation using the following equation:

$$\text{yield}\ (t\ \ ha^{-1}) = \frac{\text{dry grain (gram)} \times \text{land area of trial (0.0086 ha)}}{\text{plant spacing (20}\ m^2)}$$

2.3 Greenhouse gas sample collection

Observations and measurements of CH_4 and N_2O emissions were conducted three times during a single growing season. Greenhouse gas sampling was performed using the close chamber technique, adopted from the International Atomic Energy Agency (1993). CH_4 gas samples were collected using a chamber measuring 50 cm × 50 cm × 103 cm, while N_2O gas samples were obtained from a chamber measuring 40 cm × 20 cm × 20 cm. The time intervals between gas sampling were 5, 10, 15, and 20 minutes for both CH_4 and N_2O. Gas samples from the chambers were collected using 10 ml capacity syringes. Subsequently, the greenhouse gas samples in the syringes were immediately transported to the greenhouse gas laboratory for emission measurements.

Greenhouse gas emissions (CH_4 and N_2O) were manually measured using gas chromatography to determine the gas concentrations within the syringes. The concentration of CH_4 gas was measured using a GC Shimadzu 8A with a Flame Ionisation Detector (FID), while the concentration of N_2O gas was measured using a GC Shimadzu 14A with Electron Capture Detector (ECD) and Thermal Conductivity Detector (TCD). Subsequently, the emissions of these gases were calculated using the formula:

$$E = \frac{dc}{dt} \times \frac{Vch}{Ach} \times \frac{mW}{mV} \times \frac{273.2}{(273.2 + T)}$$

This formula is used to calculate the emissions of CH_4 or N_2O gases, where E represents the emission of CH_4 or N_2O (mg m-2 day-1), dc/dt is the difference in CH_4 or N_2O concentration over time (ppm min-1), Vch is the volume of the chamber (m3), Ach is the chamber area (m2), mW is the molecular weight of CH_4 or N_2O (grams), mV is the molecular volume of CH_4 or N_2O (a constant value of 22.41), and T is the average temperature during gas sampling (degrees Celsius).

2.4 Data analyses

Analysis of variance (ANOVA) was employed to assess the influence of rice varieties and fertilizer variations on growth, yield, cumulative greenhouse gas emissions, global warming potential (GWP), and yield-scaled GWP. *Post hoc* Duncan tests ($p < 0.05$) were conducted if the ANOVA results were significant. CH_4 and N_2O fluxes were presented using descriptive statistical analysis to identify trends in gas emissions at three different observation times. Additionally, correlation and linear regression analyses were conducted to determine the relationship between greenhouse gas emissions and grain number, empty grain, dry grain, and yield.

3 Results

3.1 Paddy growth

Different fertilization treatments have shown a significant influence on plant height, tiller count, and rice plant chlorophyll content (Table 2). The application of NPKS fertilizer (P1) + 5 tonnes ha^{-1} of manure tends to produce the best plant height and tiller count compared to other treatments. Furthermore, NPKS fertilizer (P1) + 5 tonnes ha^{-1} of manure exhibits the highest chlorophyll content in the Way Apo variety, although it is not significantly different from the NPK 225 kg ha^{-1} Urea 175 kg ha^{-1}, ZA 100 kg ha^{-1} fertilization treatment. Both NPKS fertilizer (P1) + 5 tonnes ha^{-1} of chicken manure and NPK 225 kg ha^{-1} Urea 175 kg ha^{-1}, ZA 100 kg ha^{-1} fertilization treatments also demonstrate no significant variation in yield between the Inpari 32 and Way Apo rice varieties.

3.2 CH_4 and N_2O emission

Variations in fertilization applied to rice plants result in relatively similar trends in CH_4 and N_2O fluxes across each treatment level (Figure 1). CH_4 emission fluxes exhibit high values during the early stages of rice plant growth, followed by a decline as the rice plants enter the reproductive phase and reach physiological maturity. CH_4 and N_2O fluxes in both rice varieties also follow the same pattern (Figure 2), with decreasing emission levels followed by aging of the rice plants. This occurs because rice cultivation in Indonesia typically involves a substantial amount of water during the vegetative phase, followed by reduced water requirements as the rice plants enter the generative phase leading up to harvest. Under certain conditions, rice fields are drained before harvest.

3.3 Yield, global warming potential (GWP), and GWP-scaled

Fertilization variations applied to two rice varieties resulted in different production outcomes (Table 3). The application of NPK fertilizer at 175 kg ha^{-1} Urea 150 kg ha^{-1}, and 100 kg ha^{-1} ZA in both rice varieties yielded the lowest grain numbers and dry grain numbers while producing the highest empty grain numbers. On the other hand, the application of NPKS fertilizer (P1) + 5 tonnes ha^{-1} of manure fertilizer in both rice varieties resulted in the lowest empty grain numbers compared to other fertilization variations. The use of manure and NPK fertilizers can enhance soil pH, vegetative growth variables (plant height and tiller count), grain yield, and yield components (number of filled grains per panicle and 1000-grain weight). Grain yield can increase by up to 24.19% with the application of 20 tons ha^{-1} of manure fertilizer and 100% of the inorganic fertilizer dose compared to no organic fertilizer application (Herliana et al., 2019).

Fertilization variations in both Inpari 32 and Way Apo rice varieties also yielded similar results in terms of yield, with NPKS fertilizer (P1) + 5 tonnes ha^{-1} of manure fertilizer in both varieties producing the highest yield compared to other fertilizer variations (Table 4). The NPK fertilizer at 175 kg ha^{-1} Urea 150 kg ha^{-1}, and 100 kg ha^{-1} ZA variations also resulted in the lowest yield. The lowest Global Warming Potential (GWP) in both rice varieties was achieved with the NPKS fertilizer (P1) + 5 tonnes ha^{-1} of manure fertilizer.

3.4 Relationship between CH_4, N_2O emission and paddy yield

The results of the correlation analysis indicate a negative correlation between CH_4 emissions and grain numbers, dry grain yield, and overall yield (Table 5). On the other hand, N_2O emissions show a positive correlation with paddy yield. However, the correlation analysis results between CH_4 uptake and N_2O emissions concerning paddy yield reveal an insignificant influence.

The regression analysis results reveal that cumulative CH_4 emissions have a negative impact on rice yield potential. High CH_4 emissions exhibit a decreasing trend in terms of rice grain formation parameters. In contrast, cumulative N_2O emissions show an increasing trend in grain number and empty grain. The increase

TABLE 2 Paddy growth on differences in varieties and fertilizer composition.

Varieties	Fertilizer	Plant height		Tiller numbers		Chlorophyll
		35 DAS	65 DAS	35 DAS	65 DAS	
Inpari 32	P1	54.5 ± 0.58b	92.3 ± 0.51ab	17.9 ± 0.3b	24.3 ± 0.36b	40.4 ± 0.41a
	P2	55.8 ± 0.68ab	93.5 ± 1.01ab	19.2 ± 0.55ab	25.8 ± 0.51a	41.1 ± 0.61a
	P3	53.7 ± 0.67b	91.4 ± 0.58b	15.7 ± 0.44c	22.2 ± 0.44c	40.4 ± 0.29a
	P4	57.1 ± 0.71a	94.3 ± 0.9a	19.8 ± 0.46a	26.9 ± 0.42a	41.5 ± 0.22a
Way Apo	P1	58.3 ± 0.33bc	91.8 ± 0.85ab	16.4 ± 0.55a	23 ± 0.52a	38.3 ± 0.52b
	P2	58.8 ± 0.3ab	93.3 ± 0.73ab	17.3 ± 0.74a	23.8 ± 0.65a	41.3 ± 0.8a
	P3	56.7 ± 0.58c	90.8 ± 0.87b	16.2 ± 0.44a	22.7 ± 0.44a	38 ± 0.29b
	P4	60.5 ± 0.8a	94.4 ± 0.98a	17.5 ± 0.43a	24 ± 0.43a	41.2 ± 0.47a

Data represent mean ± SEM. Value followed by the same letter indicates no significant difference based on Duncans test ($p<0.05$). P1: Urea 250 kg ha^{-1}, ZA 100 kg ha^{-1}, SP- 36 50 kg ha^{-1}, KCl 50 kg ha^{-1}, P2: NPK 225 kg ha^{-1} Urea 175 kg ha^{-1}, ZA 100 kg ha^{-1}, P3: NPK 175 kg ha^{-1} Urea 150 kg ha^{-1}, ZA 100 kg ha^{-1}, P4: NPKS (P1) + manure fertilizer 5 tonnes ha^{-1}.

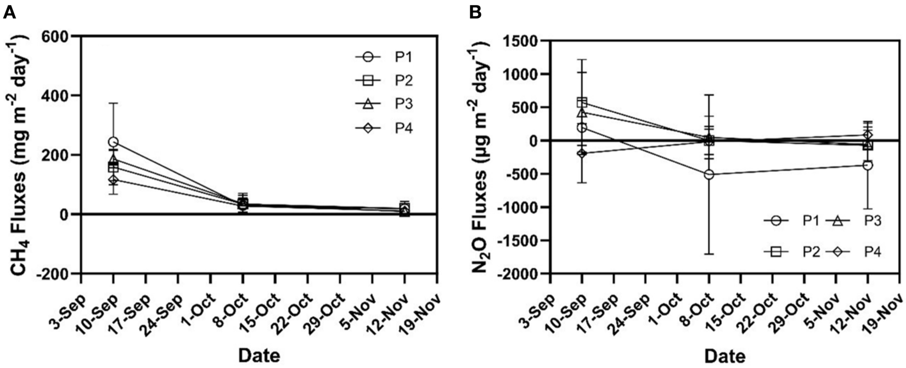

FIGURE 1
Measured of CH_4 **(A)** and N_2O **(B)** emission fluxes from paddy plants in differences composition of fertilizers during one growing season. P1: Urea 250 kg ha^{-1}, ZA 100 kg ha^{-1}, SP- 36 50 kg ha^{-1}, KCl 50 kg ha^{-1}, P2: NPK 225 kg ha^{-1} Urea 175 kg ha^{-1}, ZA 100 kg ha^{-1}, P3: NPK 175 kg ha^{-1} Urea 150 kg ha^{-1}, 100 kg ha^{-1} ZA, P4: Urea 250 kg ha^{-1}, ZA 100 kg ha^{-1}, SP- 36 50 kg ha^{-1}, KCl 50 kg ha^{-1}, and manure fertilizer 5 tonnes ha^{-1}.

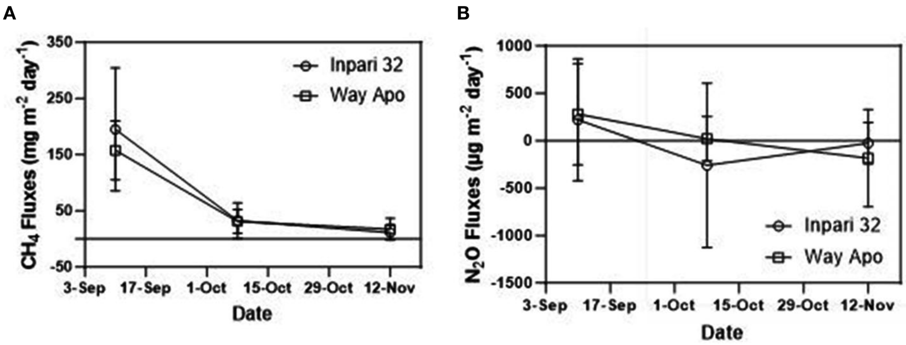

FIGURE 2
Measured of CH_4 **(A)** and N_2O **(B)** emission fluxes from paddy plants in differences varieties of paddy during one growing season. In this study, it is revealed that the trends in CH_4 and N_2O fluxes are more fluctuating in single-fertilizer variation treatments compared to single-rice variety treatments. This suggests that the fertilizer variations used in the study have less influence on CH_4 and N_2O emission rates in rice cultivation. Treatments P1, P2, and P3 each contain inorganic NPKS fertilizer at different doses that are not excessively high. On the other hand, treatment P4 is a variation of NPKS fertilizer (P1) combined with manure content. Although statistically, the differences in rice varieties and fertilizer variations used in the study do not show significant differences (Figure 3), the addition of manure content in treatment P4 and differences in rice varieties reveal factors that play a crucial role in global warming potential emissions.

in N_2O emissions is also linearly followed by an increase in dry grain yield and overall yield. However, the regression analysis results for greenhouse gas emissions in this study demonstrate a coefficient of determination (R2) that is not significant concerning rice grain yield. The relationship between CH_4 uptake and N_2O emissions with paddy yield is more clearly depicted in Figure 3. Longer-term observations are needed to better elucidate the relationship between CH_4 and N_2O emissions and rice production.

4 Discussion

The decrease in CH_4 flux during the generative phase is attributed to the reduced activity of methane-producing bacteria under dry drainage conditions (aerobic conditions), which inhibits CH_4 production and enhances CH_4 oxidation (Conrad, 2007). CH_4 flux gradually increases from the early planting stage to the early generative phase (promordia) and then slightly decreases before increasing again after harvest (Setyanto et al., 2016). Greenhouse gas emissions in rice cultivation tend to decrease around 50-90 days after planting (DAP). This reduction is due to a decrease in the number of tillers and a decrease in the photosynthetic rate, leading to reduced assimilation for methane production (Ardiarini et al., 2020). Methane flux decreases after the flowering stage because the photosynthetic rate decreases after seed development, and the availability of assimilates for methane formation decreases (Wihardjaka and Sarwoto, 2015). Previous research has also shown similar results, with the highest methane fluxes observed during the vegetative and early reproductive phases (about 25 days after showing), followed by a decline during the flowering and maturity phases (Chandrasekaran et al., 2022).

Methane and nitrous oxide emissions from the application of chemical and manure fertilizers can vary depending on environmental factors (such as climate and soil conditions), crop-related factors (crop type), and management factors (types of chemical and organic fertilizers), as well as the rate and timing of application (Win et al., 2021). The use of chemical and organic fertilizers contributes to 23-31% of global anthropogenic N_2O

TABLE 3 Paddy grain yield on differences varieties and fertilizer composition.

Varieties	Fertilizer	Grain Numbers	Empty Grain (gram)	Dry Grain (gram)
Inpari 32	P1	117 ± 7.87a	19 ± 0.14ab	36 ± 1.23b
	P2	130 ± 4.55a	13 ± 1.21b	41 ± 1.96b
	P3	115 ± 5.44a	26 ± 0.42a	35 ± 1.52b
	P4	132 ± 5.38a	15 ± 4.22b	54 ± 3.84a
Way Apo	P1	106 ± 8.12a	16 ± 2.82ab	32 ± 0.89b
	P2	114 ± 9.85a	11 ± 0.87b	33 ± 1.4b
	P3	98 ± 4.28a	22 ± 2.52a	31 ± 1.06b
	P4	120 ± 7.11a	14 ± 2.1b	40 ± 0.32a

Data represent mean ± SEM. Value followed by the same letter indicates no significant difference based on Duncans test ($p<0.05$). P1: Urea 250 kg ha^{-1}, ZA 100 kg ha^{-1}, SP- 36 50 kg ha^{-1}, KCl 50 kg ha^{-1}, P2: NPK 225 kg ha^{-1} Urea 175 kg ha^{-1}, ZA 100 kg ha^{-1}, P3: NPK 175 kg ha^{-1} Urea 150 kg ha^{-1}, 100 kg ha^{-1} ZA, P4: NPKS (P1) + manure fertilizer 5 tonnes ha^{-1}.

TABLE 4 Paddy yield, GWP, and Yield-Scaled on differences varieties and fertilizer composition.

Varieties	Fertilizer	Yield (t ha^{-1})	GWP (kg CO_2 ha^{-1})[a]	Yield-scaled GWP (kg CO_2-eq t^{-1} grain)[b]
Inpari 32	P1	7.9 ± 0.27 b	1551.1 ± 347.12 a	199.5 ± 46.34 a
	P2	8.8 ± 0.42 b	984.1 ± 487.05 a	117.8 ± 63.56 a
	P3	7.6 ± 0.33 b	1917.7 ± 682.19 a	243 ± 136.1 a
	P4	11.6 ± 0.83 a	929 ± 325.27 a	77 ± 21.49 a
Way Apo	P1	7 ± 0.19 b	1088.2 ± 298.81 a	156.4 ± 43.07 a
	P2	7.2 ± 0.3 b	1352.6 ± 145.96 a	188.1 ± 13.08 a
	P3	6.6 ± 0.23 b	1153.8 ± 79.68 a	173.6 ± 7.24 a
	P4	8.6 ± 0.07 a	730.8 ± 93.14 a	84.9 ± 11.49 a

Data represent mean ± SEM. Value followed by the same letter indicates no significant difference based on Duncans test ($p<0.05$). P1: Urea 250 kg ha^{-1}, ZA 100 kg ha^{-1}, SP- 36 50 kg ha^{-1}, KCl 50 kg ha^{-1}, P2: NPK 225 kg ha^{-1} Urea 175 kg ha^{-1}, ZA 100 kg ha^{-1}, P3: NPK 175 kg ha^{-1} Urea 150 kg ha^{-1}, 100 kg ha^{-1} ZA, P4: NPKS (P1) + manure fertilizer 5 tonnes ha^{-1}. [a]GWP = (CH_4 × 25) + (N_2O × 298). [b]Yield-scaled GWP (kg CO2-eq t−1 grain) = GWP/rice yield.

emissions, with most of these emissions occurring from the soil after fertilizer application. Fertilizer application (organic or inorganic) stimulates CH_4 production by enhancing rice plant growth, thereby providing a carbon source for methane-producing bacteria. Under flooded conditions, rice plant growth increases CH_4 emissions by supplying a carbon source and supporting CH_4 transport to the atmosphere (Cai et al., 2007). Organic fertilizers supply inorganic N in the form of NH_4^+ and NO_3^-, which can increase N_2O production. Organic fertilizers provide labile C compounds, which can enhance denitrifying bacterial activity and trigger N_2O emissions (Lazcano et al., 2021).

Additionally, previous research has shown that rice variety differences significantly affect greenhouse gas emissions. Short-duration and water-efficient rice varieties can reduce CH_4 emission fluxes under low-water irrigation conditions (Chandrasekaran et al., 2022). In this study, the Way Apo rice variety produced lower CH_4 emissions compared to Inpari 32 under the P1, P3, and P4 fertilizer variations. On the other hand, under the P2 fertilizer variation, Way Apo rice resulted in higher CH_4 emissions than Inpari 32. However, the CH_4 emissions produced from the rice variety differences were not statistically significant. The lower CH_4 emissions from the Way Apo rice variety compared to Inpari 32 can be attributed to the fact that Way Apo rice is an amphibious rice phenotype, adapted to water-scarce irrigation conditions (Supijatno et al., 2016). Additionally, rice characteristics such as plant height, tiller count, and the size of aerenchyma cavities play a role in managing methane emissions. Inpari 32 has genetic characteristics of wider root aerenchyma cavities, broader stem aerenchyma cavities, taller plants, and a higher number of tillers. The higher number of tillers can increase CH_4 production capacity because it can enhance the density and number of aerenchyma vessels (Ardiarini et al., 2020).

Cumulative CH_4 emissions in the Inpari 32 rice variety are highest in the P3 fertilizer variation. Meanwhile, cumulative CH_4 emissions in the Way Apo rice variety are highest in the P2 fertilizer variation. The P4 fertilizer variation (NPKS + manure) results in the lowest cumulative CH_4 emissions in both rice varieties (Figure 4A). Previous research has reported that the addition of single inorganic nitrogen fertilizer linearly increases CH_4 emission rates in rice cultivation (Bhattarai et al., 2021; Zhou et al., 2019; Mohanty et al., 2020; Yang et al., 2023). Although theoretically, nitrogen fertilizer plays a significant role in regulating greenhouse gas emissions. However, some recent studies have reported that single inorganic P and K fertilizers play a role in managing nitrogen conversion in the soil. Zhu et al. (2022) reported that Continuous application of inorganic P fertilizer decreases NH_4 emissions by

TABLE 5 Correlation Between Cummulative of CH_4, N_2O emission, grain number, empty grain, dry grain, and yield.

	CH_4	N_2O	Grain Number	Empty Grain	Dry Grain	Yield
CH_4	1					
N_2O	0.178	1				
Grain Number	-0.019	0.088	1			
Empty Grain	0.146	0.022	-0.185	1		
Dry Grain	-0.113	0.084	.723**	-0.290	1	
Yield	-0.114	0.085	.722**	-0.290	1.000**	1

**: significant (p-value<0.001), N = 24.

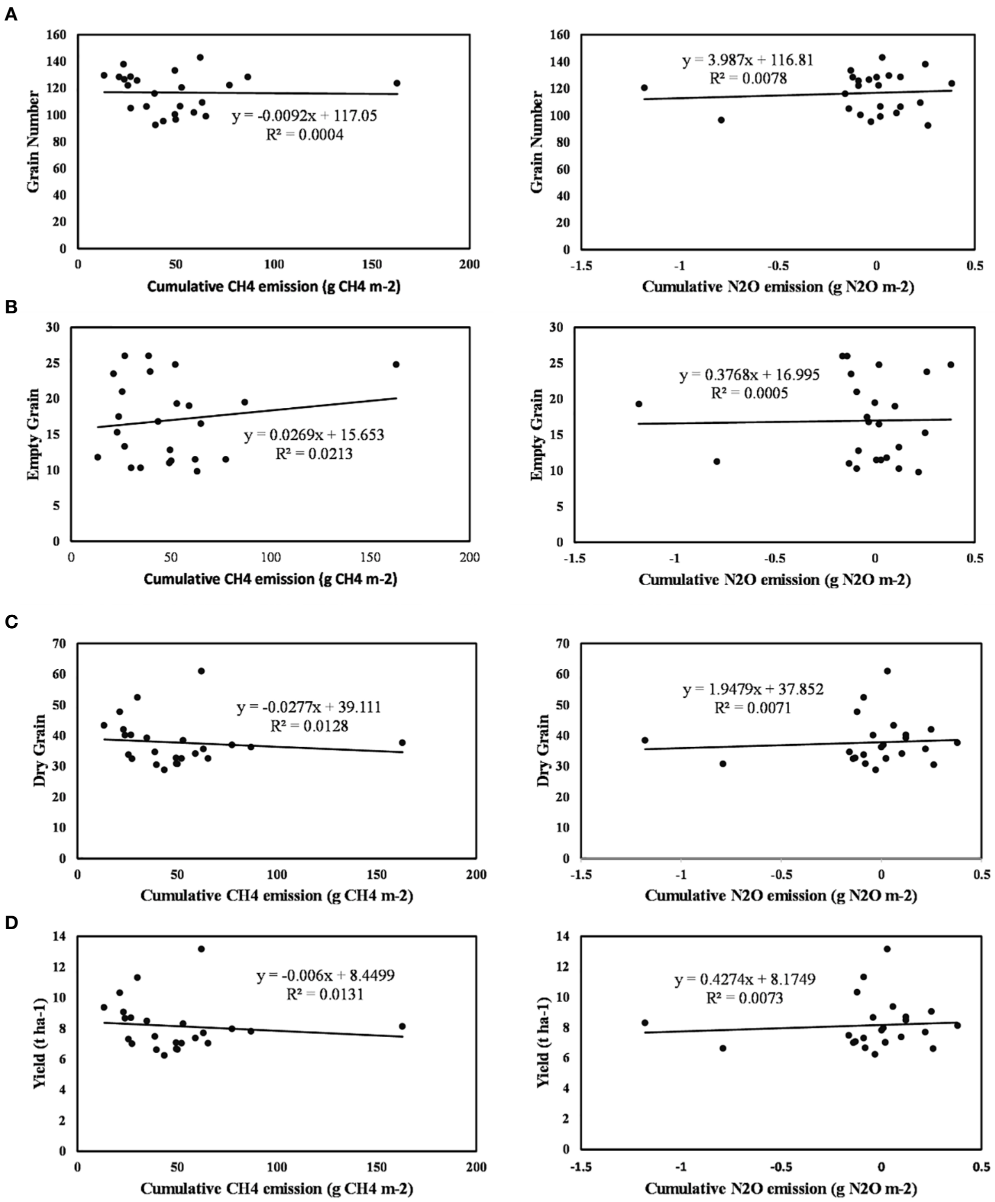

FIGURE 3
Regresion between cummulative of CH_4 uptake and N_2O emission with **(A)** grain number, **(B)** empty grain, **(C)** dry grain, and **(D)** yield. N = 24.

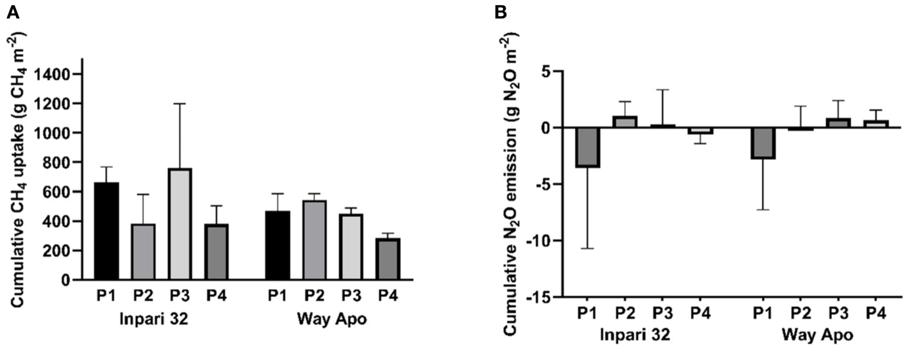

FIGURE 4
Cummulative of CH_4 **(A)** and N_2O emission **(B)** from paddy plants on differences in varieties and composition of fertilizers during one growing season. P1: Urea 250 kg ha^{-1}, ZA 100 kg ha^{-1}, SP- 36 50 kg ha^{-1}, KCl 50 kg ha^{-1}, P2: NPK 225 kg ha^{-1} Urea 175 kg ha^{-1}, ZA 100 kg ha^{-1}, P3: NPK 175 kg ha^{-1} Urea 150 kg ha^{-1}, 100 kg ha^{-1} ZA, P4: NPKS (P1) + manure fertilizer 5 tonnes ha^{-1}.

stimulating CH_4 oxidation without affecting CH_4 production. Datta et al. (2013) also reported that Combination of inorganic NPK fertilizer in rice plants in India resulted in lower CH_4 emissions compared to single nitrogen fertilizer application, and these results were similar to treatments without nitrogen fertilizer.

The research results indicate that fertilizer variations do not have a statistically significant influence on cumulative nitrous oxide (N_2O) emissions (Figure 4B). Nitrous oxide (N_2O) emissions are produced through the processes of nitrification and denitrification in the soil (Ji et al., 2018; Chen et al., 2020). This process starts when there is available inorganic nitrogen, such as nitrate (NO_3^-) and ammonia (NH_4+), in the soil, which is used as an alternative energy source when oxygen (O_2) in the soil is limited by denitrifying bacteria. Nitrate is converted into various forms of nitrogen gas (N_2), including N_2O, during the denitrification process. Subsequently, N_2O is released into the atmosphere as part of greenhouse gas emissions (Chen et al., 2020). Soil properties such as moisture, temperature, pH, soil type, chemical composition, and nitrification-denitrification bacterial activity play a crucial role in N_2O fluxes (Xiong et al., 2007; Morimoto et al., 2011; Behnke et al., 2018). However, nitrogen availability in the soil is a limiting factor affecting N_2O emission rates, especially in flooded soil conditions (Gu et al., 2013; Zhang et al., 2018). In this study, the fertilizer variations used cannot explain the best fertilizer composition to suppress N_2O emissions in rice cultivation.

In summary, the fertilizer variations used in this study cannot elucidate their relationship with greenhouse gas emission rates in rice cultivation. This is because short-term manure fertilizer additions have not significantly altered carbon and nitrogen stocks in the soil and have resulted in fluctuating CH_4 and N_2O emissions (Anggria et al., 2012; Cheng et al., 2016). Many studies have reported that nitrogen stocks are more influenced by inorganic nitrogen inputs than by manure fertilizer. However, some research has indicated that long-term manure application enhances organic carbon and nitrogen stocks in the soil (Chu et al., 2007; Ren et al., 2014; Abrar et al., 2023). It is important to emphasize that high doses of manure fertilizer do not necessarily lead to high greenhouse gas emissions (Cheng et al., 2016).

Manure fertilizer can improve the physical, chemical, and biological properties of the soil, such as enhancing soil quality and structure, as well as stimulating soil enzyme activity (Hou Q. et al., 2023). The application of manure fertilizer significantly increased crop yields by approximately 7.6% compared to mineral fertilizers (Du et al., 2020). The combination of chemical and/or organic compost fertilizers has a significant impact on rice yield and yield components. The mixed application of chemical and organic fertilizers enhances plant growth and yield components (Sung et al., 2023).

The research results indicate that the addition of manure fertilizer results in lower Global Warming Potential (GWP) values and yield-scaled GWP compared to the use of inorganic NPKS fertilizers. Manure fertilizer contains slowly decomposing organic matter, which can increase the soils organic carbon content and extend the carbon cycle (Ren et al., 2014; Kacprzak et al., 2023). This condition can reduce greenhouse gas emissions, especially N_2O emissions, which typically occur in anaerobic conditions (Sun et al., 2019; Mayer et al., 2022). Additionally, manure fertilizer can enhance soil sustainability by improving water and nutrient retention, which can increase crop productivity and reduce the need for inorganic fertilizers. In contrast, the use of inorganic fertilizers, especially in excessive doses, can lead to more acidic and unsustainable soil conditions, which can increase greenhouse gas emissions, particularly N_2O (nitrous oxide), which has a high global warming potential (Jahangir et al., 2022).

The high yield-scaled GWP associated with the use of inorganic fertilizers compared to the addition of organic fertilizers is due to the imbalance between the amount of fertilizer used and crop production. Excessive nitrogen fertilizer doses compared to plant requirements can increase N_2O emissions because inorganic fertilizers contain nitrogen that is more readily degraded into N_2O (Bhuiyan et al., 2021; Jahangir et al., 2022). Additionally, plants grown with high nitrogen rates can experience nutrient stress and inefficient growth, which, in turn, can reduce crop yield (Wang et al., 2020; Guo et al., 2022). Therefore, imbalances in the use of inorganic fertilizers (especially nitrogen) can result in high yield-scaled GWP, where greenhouse gas emissions relative to crop yields tend to be higher.

More photosynthate translocation is allocated toward grain formation, thereby enhancing grain productivity and reducing the efficiency of greenhouse gas emissions into the atmosphere. In varieties with low yields, more photosynthate is allocated to other vegetative parts to enrich soil carbon status and increase plant biomass productivity, resulting in higher greenhouse gas production and emissions (Gorh and Baruah, 2019). Conversely, CH4 emissions, soil pH, soil organic carbon, plant height, and the number of filled grains exhibit negative correlations with grain yield (Haque et al., 2021).

The emission of greenhouse gases, the availability of soil carbon, nutrient mineralization, soil fertility, and plant growth are components that should be interrelated. SOC and total nitrogen rates exhibit a linear quantitative relationship (Cheng et al., 2016). Greenhouse gas emissions, particularly N_2O emissions, are among the causes of nitrogen loss in the soil (Smeaton et al., 2011; Ashraf et al., 2020). High SOC accumulation has been reported to mitigate nitrogen loss by suppressing N_2O flux (Lee et al., 2020). In flooded lands, N_2O flux exhibits a linear relationship with CH_4 emission rate. Therefore, a high greenhouse gas emission rate indicates high soil carbon and nitrogen loss, resulting in reduced soil fertility and inadequate plant nutrient supply.

5 Conclusion

In comparison to the Way Apo Buru rice variety, Inpari 32 rice variety exhibited higher yields but also demonstrated a higher global warming potential. The application of NPKS fertilizer (Urea 250 kg ha^{-1}, Ammonium sulfate (ZA) 100 kg ha^{-1}, Superphosphate (SP-36) 50 kg ha^{-1}, and Potassium chloride (KCl) 50 kg ha^{-1}), along with 5 tonnes ha^{-1} of manure fertilizer (referred to as P4), significantly increased rice seed production compared to other fertilizer compositions. Furthermore, the P4 fertilizer composition resulted in lower CH_4 emissions and global warming potential than other compositions. Greenhouse gas emissions are indicative of nitrogen and carbon losses in the soil. Therefore, this study revealed that higher CH_4 emissions are associated with lower rice seed production. N_2O emissions showed a positive correlation with rice production but were not statistically significant. Thus, a more intensive observation of N_2O flux is required to provide a more accurate explanation of the relationship between greenhouse gas emissions and rice seed production.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material. Further inquiries can be directed to the corresponding author.

Author contributions

S: Conceptualization, Data curation, Funding acquisition, Investigation, Methodology, Project administration, Supervision, Validation, Writing – original draft, Writing – review & editing. DF: Project administration, Software, Validation, Visualization, Writing – review & editing. MS: Methodology, Project administration, Resources, Validation, Visualization, Writing – original draft, Writing – review & editing.

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Conflict of interest

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

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