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Nutrient management may reduce global warming potential of rice cultivation in subtropical India

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ABSTRACT

Agricultural practices contribute to greenhouse gas (GHG) emissions; therefore, it is essential to modify the production technologies. We analyzed decadal variation in CO_2 and CH_4 over a major rice cultivating area in subtropical India using GOSAT satellite data, which shows a sturdy increase. Furthermore, we carried out long-term field experiments with different nutrients management in the research farm to validate CERES–Rice (Crop Environment Resource Synthesis) and DNDC (De-nitrification and Decomposition model) models. The variations in Global warming potential per kg rice grain production over 90 years (2005–2095) are also projected. This study used a simulation technique to predict the rice yield using CERES–Rice and GWP using the DNDC model for three varied nutrient management treatments: chemical fertilizer (CF) at full (100%) recommended level (CF100), organic fertilizer using vermicompost at full recommendation (VC100), and integration of organic and chemical fertilizer (VC50 + CF50). The CF100 treatment showed the highest rate of increase in GWP as 0.014 and 0.021 kg CO_2eq kg-grain season^{-1} in RCP 4.5 and 8.5 scenarios, respectively. Integrating organic fertilizers with chemical fertilizers may give a nearly similar yield in later decades of the century in both RCP 4.5 and 8.5 climate scenarios with substantial reductions (77% in RCP 4.5 and 66% in RCP 8.5) in the rate of change in GWP as compared to sole chemical fertilizer application. This study recommends integrated nutrient management using organic fertilizers as a feasible way to limit the GHG emission from rice fields and minimize global warming in future climate scenarios.

1. Introduction

One of the primary reasons for global warming is expanding human intervention in natural ecosystems. For instance, land-use-related CO_2 emissions are responsible for about 14% of annual anthropogenic CO_2 (Le Quéré et al., 2020), out of which 10% is directly linked to agriculture (Mbow et al., 2014). India is primarily an agricultural economy and also the second-largest producer of rice (Mamun et al., 2021). However, at the same time, India is also the fourth largest CO_2 emitter and the third largest emitter of GHGs globally, having agri-intensive (July–December) and agri-nonintensive (January–June) periods as significant contributors (IEA, 2021; Singh et al., 2022). Still, few studies in India analyze the effect of agricultural management on atmospheric emissions and climate change along with mitigation measures through management practices (Singh et al., 2021; Kuttippurath et al., 2020). Therefore, the question is whether we can reduce the environmental footprints of rice production by adopting better and far-sighted management decisions.

Rice has a production status of 100 million tons in India, contributing to 41% of the country's total food production (Rajwade et al., 2015). However, rice production is also accounted for the highest share of total GHG emissions, especially in the eastern India (Tripathi et al., 2021). In particular, the West Bengal state in eastern India, the largest rice producer, lacks specific climate-smart solutions to deal with food security and climate change (Bag, 2011).

A complex systemic correlation exists between yield improvement measures and GHG emissions in rice cultivation (Sapkota et al., 2018).

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For instance, conventional nutrient management efforts to improve rice grain involve chemical fertilizers that add considerably to global warming through enhanced emission of N_2O (Dong et al., 2011; van der Ploeg et al., 2001). Dong et al. (2021) reported that slow-release fertilizer addition significantly decreased CH_4 emissions by 33.4% during the rice-growing season. Liu et al. (2019) reported that reducing doses of nitrogen fertilizers can substantially alter the GHG emissions from rice fields. On the other hand, the alternative option of organic nutrient management practices (e.g., farmyard manure, vermicompost, aerobic compost, and biochar) has shown a significant decrease in the emission of N_2O. Still, major apprehension while following such interventions is the reduction of rice grain yield (Abbhishek et al., 2021). Henceforth, Panchasara et al. (2021) reviewed the current state of GHG emissions trends from rice fields and recommended scrutinizing mitigation measures to maintain productivity.

Three GHGs (i.e., CH_4, CO_2, N_2O) out of six major GHGs constitute prominent fluxes from rice fields. Studies reported that soil organic carbon status, nutrient management, and soil water status are key factors controlling the fluxes of these gases (Win et al., 2020). However, managing soil nutrients as a part of climate-adaptive technologies in rice cultivation might be a mitigation option for prominent GHGs in rice cultivation (Bhattacharyya et al., 2012).

A sizeable portion of studies in the past have relied on future climate scenarios for impact studies of long-term nutrient management on crop yield. Furthermore, low radiative forcings like RCP 1.9 and 2.6 represent very strong and strong declining emission scenarios, respectively which are less likely to happen now (O'Neill et al., 2014). Therefore, studies recommend medium and high warming scenarios through radiative forcing of 4.5 W/m^2 and 8.5 W/m^2, respectively (Riahi et al., 2017; Myhre et al., 2013; He et al., 2018; Hwang et al., 2019).

In this study, we have analyzed the decadal variations in CH_4 and CO_2 using GOSAT (Greenhouse Gases Observing Satellite) data for the largest rice-producing region (i.e., West Bengal) lying in subtropical India. In the study region, paddy is cultivated around the year in all three agricultural seasons (i.e., rainy/*kharif*: June–October; post-rainy/*rabi*: October–February; summer/*zaid*: March–May); therefore, it suits the aim of the study evaluating the alternative nutrient management practices in paddy for lower GHG emissions without significant loss of yield compared to traditional practices. We have selected a few representative nutrient management practices as conventional and alternative strategies based on experiences from long-term field experiments. This study analyzes the effect of natural organic fertilizers (e.g., Vermicompost as VC-100), chemical fertilizers (100% recommended NPK as CF-100), and their combination (NPK:50% of recommended dose with 50% vermicompost based on N equivalence) on grain production and GHG fluxes, by using crop and soil biogeochemistry models. The broader aim of our simulation exercise is to recommend a suitable alternative nutrient management practice for lower GWP footprints in rice farming for future climate scenarios in sub-tropical India. It would equally tackle the problem of climate change and food security for 16–18% of the global population. The specific objective of this study was to assess the GHG flux and rice grain yield for the future climate scenarios, defined by the RCPs 4.5 and 8.5 of IPCC, using DNDC and CERES-Rice models, respectively. Furthermore, we calculated the yield-scaled GWP (i.e., GWP kilogram-$grain^{-1}$) for different nutrient management practices. The outcome of this study might have policy implications for successfully implementing the commitments made by India at the UNFCCC-COP summit (2021) (GoI, 2021).

2. Data and methods

We analyzed long-term GOSAT data for atmospheric CO_2 and CH_4 over the study area. GOSAT is a sun-synchronous polar orbit satellite placed at about 666 km. It is a dedicated satellite to measure CO_2 and CH_4 present in the atmosphere of Earth using TANSO–FTS (Thermal and Near Infrared Sensor for Carbon Observation–Fourier Transform Spectrometer) (Kuze et al., 2009). It was launched in Japan in January 2009. Japan Aerospace Exploration Agency (JAXA) developed the satellite in collaboration with the Ministry of Environment (MOE), and the National Institute for Environmental Studies (NIES) of Japan. GOSAT overpasses at 13:00 (local time) every three days, and the diameter of the footprint in nadir is approximately 10 km. GOSAT is also equipped with the second sensor TANSO–CAI (Cloud and Aerosol Imager), which is used to reject cloudy scenes during the retrieval process (Morino et al., 2019). In general, the measurement of GOSAT follows other approaches to GHG monitoring that include ground-based stations, balloons, ships, tall towers, and balloon measurements (Inoue et al., 2013; Zhang et al., 2021). NIES complete physics SWIR L3 version 02.81 dataset of GOSAT CH_4, CO_2 over India from 2009 to 2020 is used in this study. The SWIR L3 products are the estimated results of column-averaged gas concentrations for one month on a global 2.5 by 2.5–degree grid, based on the column abundances (XCO2 and XCH4) of the SWIR L2 products by the spatial statistical method, i.e., Kriging as in Watanabe et al. (2015). The retrieved CO_2 and CH_4 data have been validated using observation at selected TCCON (Total Column Carbon Observation Network) sites and showed small biases of about −0.33 ppm and −1.9 ppb, respectively, for CO_2 and CH_4 (Morino et al., 2019). However, we did not analyze N_2O concentrations using satellites to avoid the biases and variations due to the resolutions of different sensors. Nevertheless, the measurement of N_2O and CH_4 was performed in field experiments to calibrate and validate the crop models and calculate the GWP of rice production.

We collected the field data from a long-term field experiment; conducted during the *Kharif* season (2009–2017). The experiment comprises nine different inorganic and organic nutrient management treatments to examine yield, above-ground crop-biomass, crop growth, phenological attributes, soil nutrient dynamics and GHG emissions during the growing season. Based on the performance and yield of the rice crop after 5 years of continuous rice-chickpea sequence, we selected three different nutrient management practices for simulation. It includes the three best-performing treatments for grain yield (viz. sole-chemical (CF100), sole-organic basal (VC100), and integrated nutrient management practices (CF50 + VC50)) (Table: S1). However, we also simulated a zero/no fertilization control for capturing the native plant rhizosphere emissions. Absolute control treatment (based on native soil fertility) captures the intervention effect of management practices while silencing the background noise of GHG flux coming from the interaction of crop and environment.

The experimental site (Kharagpur) lies in the acid lateritic soil belt (pH 5.4), which receives an annual average rainfall of 1600 mm with the peak downpour in the wet season (June–October). We are reporting NDVI (2009–17) as a proxy for biophysical indicators during the agri-intensive period (July–December), covering two cropping seasons *kharif* and *rabi* and agri-non-intensive period (January–June) covering only *zaid* season crops (Shelestov et al., 2017). We have used Moderate Resolution Imaging Spectrodiometer (MODIS) derived NDVI data (MOD13C2 version6) for the analysis. The analyses show that the study area has average NDVI values ranging from 0.5- to 0.8, while the study location (black dot) has an NDVI of 0.7. Similarly, the agri-non-intensive period shows NDVI ranging from 0.4- to 0.8, while the study region has an NDVI of 0.6. The average maximum temperature at the experimental site varied from 30^0 to 39^0C and the minimum from 21^0 to 30^0C. The soil texture of the experimental site is sandy-loam.

At the experimental location, rice was grown in the *kharif* season in a randomized complete block experimental design since 2013. The cropping history during the experimental period is brief (Table S2) and explained in detail in our other paper (Kumar et al., 2018). The management and intercultural activities followed during the long-term experiment were used as input parameters in the respective models **(Table S3).**

The nutrient management treatments, including organic, chemical, and combinations, were tested for a nutrient dose recommendation of 100 kg-N ha^{-1}, 50 kg-P_2O_5 ha^{-1}, and 60 kg-K_2O ha^{-1} for an upland direct-seeded rice crop. We applied chemical fertilizer (CF) treatment with urea as recommended N source (CF 100), single super phosphate as P_2O_5 source, and Muriate of potash as K_2O source. In contrast, organic fertilizer treatments were applied with Vermicompost (Total-N 1.5%) (VC) to meet the recommended dose of N (VC 100). In the selected treatments, control received no fertilization; CF 100 received sole mineral fertilizer in three equal splits; VC 100 received sole vermicompost in two equal splits (i.e., half before seeding and a half at the panicle initiation stage). Integrated N management treatment; VC50 + CF50 received half of the nitrogen requirement through the vermicompost application as a basal dose. The remaining half was through the top dressing of chemical fertilizers in splits at critical crop stages.

The medium duration (approx. 125 days) rice cultivar was selected as a test crop in the model to match the field experiment (e.g., Naveen in this case). We provided the models with the details of soil parameters (Table S4), as explained in detail by Kumar (2017). In addition, we provided the irrigation details to be used in the model simulation as per the schedule followed in the field experiment to maintain the soil saturation during the entire growing period of rice.

2.1. Crop models

The crop growth and soil biogeochemistry models have helped temporal analysis of GHG emissions and grain yield. These models can well capture the fundamental soil-crop-atmosphere dynamics and further assess the variability in fluxes of GHG in future climate scenarios. The DNDC, being a generic numerical model, simulates carbon and nitrogen dynamics in the agro-ecosystem at each time step. The model simulates soil biogeochemistry through interacting modules for plant growth, soil climate, nitrification, denitrification, decomposition, and fermentation (Li et al., 1997). Input parameters as required in simulation include soil parameters, meteorological parameters, and details of management practices. The model simulates GHG's flux values on the interaction between the various constituent sub-models and their boundary conditions. The CERES-Rice, available on the platform of DSSAT (Decision Support System for Agro-Technology Transfer), is a mechanistic model used for rice growth and yield simulations, with meteorology, soil, and crop management data as inputs. However, both models need to be well-calibrated and validated for specific cultivars to get reliable predictions in policy decisions.

2.2. Calibration and validation of models

The DNDC model was calibrated by adjusting the crop parameters of upland rice (Table S5) grown in nitrogen non-limiting conditions until we obtained close matches between observed and simulated CH_4 and N_2O emissions in 2016–2017. we adjusted the crop phenological and physiological parameters following measurements during the crop's growing season. The CERES-Rice model was calibrated by adjusting the crop genotypic coefficients (Table S6) for the rice cultivar 'Naveen'. The experimental data on phenology, biomass, and yield components collected from 2013- to 2016 were used to calibrate the models.

The experimental results were used to validate the models for above-ground biomass, CH_4 flux, and N_2O flux from the selected nutrient treatments. PBIAS was used to estimate the average tendency of simulated data. Earlier studies have reported that PBIAS values must be <25% for a good model performance (Abbaspour et al., 2015; Mendoza et al., 2020). It was calculated as

$$PBIAS = 100 \times \frac{\sum_{i=1}^{n} (Q_{obs} - Q_{sim})_i}{\sum_{i=1}^{n} Q_{obs,i}}$$

Where Q_{obs} is observed, and Q_{sim} is simulated flux values. Positive values indicate underestimation, whereas negative values indicate an overestimation by the model (Mendoza et al., 2021). The GHG emission values from different selected treatments of field experiment and DNDC model results were compared, which agree well with the normalized RMSE value of 8.2% and 13.4% for N_2O and CH_4, respectively, across the treatments and all replications ($N = 48$). Additionally, PBIAS values ranged from 7.4 to 21% for CH_4 and 1.6–15.3% for N_2O in the nutrient management treatments (Table 1). The CERES-rice was also validated using the experimental data for crop biomass collected during the growing season. The normalized RMSE value of about 7.95% for CF-100 treatment, including all replications ($N = 15$), while PBIAS ranging from 4.8 to 20% for different days after transplantation indicated a good model performance (Table 2).

2.3. Gas sampling, flux, and GWP calculation

The flux of CH_4 and N_2O used for validation of the DNDC model was measured at 10 days intervals during the growing seasons of 2016–2017 from the treatment plots using the static chamber-Gas Chromatograph (GC) method (Zou et al., 2005). The static chamber was made up of Polyvinyl Chloride plates with a standard size of 65 × 42 × 75 cm. We placed the chamber box on a base iron channel previously fixed in plots before seeding. We filled the channel with water to keep the whole setup airtight. The gas samples were drawn off in gas sampling bags at 0, 30, 60 min intervals from the chamber. We monitored the air temperature inside the chamber during the collection process of gases. The samples were analyzed for CH_4 and N_2O using a GC system (Model: GC2010, Shimadzu corp.). The flux of GHG was determined using the following equation adapted from Sampanpanish, 2012.

$$\mathrm{Fi} = \frac{\mathrm{Vstd.\Delta Yi.Mi}}{\mathrm{Vm.A.\Delta t}}$$

Where Fi is the flux for gas i, Mi is the molar mass of gas i, A is the cross-section area of the box, ΔYi is the change in the concentration of gas i during the contact time Δt, Vm is the molar volume of air at STP which is 22.4 l mol^{-1} and Vstd calculated as:

$$\mathrm{Vstd.} = (\mathrm{p} - 1760\ \mathrm{mm\ of\ Hg}) - 1(\mathrm{T} - 1273\ \mathrm{K})$$

Here, Vstd. is standard Volume, p and T being pressure and temperature inside the chamber.

The calculation of the GWP involved the integration of radiative efficiency and time-dependent decay rate over a given time horizon for the reference gas, which is considered CO_2 (IPCC, 2007). In addition, we used coefficient factors of conversion for CH_4 and N_2O to CO_2 equivalents applied in the equation (Wuebbles et al., 2017).

$$GWP(kg\,CO2eq - 1ha) = \{(CH4((kgC - 1ha)x21) + (N2O(kgN - 1ha)x310) + (CO2(kgC - 1ha))\}$$

2.4. Meteorological data for future climate scenario

We analyzed the effect of future climate on GHG emissions from rice fields under different nutrient management for the study purpose. The REMO-downscaled future scenario weather data (We downloaded representative concentration pathways (RCP) 4.5 and 8.5 of coupled MPI-ESM model from the data archive of Indian Institute of Tropical Meteorology, Pune, India, for coordinated regional climate downscaling experiment (CORDEX) in south Asia domain for the nearest grid of Kharagpur location, for example, Teichmann et al. (2013). The RCP 4.5 and 8.5 are expected to have global radiative forcing of 4.5 and 8.5 Wm^{-2}, respectively.

Non-parametric Mann-Kendall test was used to obtain S statistics and *Z*- value using following equations (Wang et al., 2020):

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} sgn(x_i - x_k)$$

Table 1
Validation of DNDC model with GHG fluxes from different nutrients management treatments.

Nutrients management	Methane flux (kg year^{-1})			Nitrous oxide flux (kg year^{-1})		
	Observed	Simulated	PBIAS (%)	Observed	Simulated	PBIAS (%)
Control	0.54	0.50	7.4	0.52	0.60	−15.3
CF 100	0.72	0.80	11	6.28	6.40	−1.9
VC 100	0.54	0.47	12.9	3.54	3.60	−1.6
VC50 + CF50	0.55	0.43	21	4.20	4.50	−7.1

Table 2
Validation of CERES-Rice with observed and simulated values for above-ground biomass of rice in Chemical fertilizer treatment.

Day	Above ground biomass (kg ha^{-1})		
	Observed	Simulated	PBIAS, %
20	175	210	−20
40	364	425	−16.75
60	698	732	−4.87
80	2400	2545	−6.0
100	6800	7200	−5.8%

$$sgn(x_i - x_k) = \begin{cases} +1, if\ (x_i - x_k)\rangle 0 \\ 0, if\ (x_i - x_k) = 0 \\ -1, if\ (x_i - x_k)\langle 0 \end{cases}$$

$$var(S) = \left\{\frac{n(n-1)(2n+5)}{18}\right\}$$

Where n is sample size, X_k and X_j are from k = 1,2, …n-1 and j = k + 1, …,n.

The test statistics Z calculated as

$$Z = \begin{cases} \left\{S - 1|\sqrt{var(S)}\right\}, if\ S > 0 \\ 0, if\ S = 0 \\ \left\{S + 1|\sqrt{var(S)}\right\}, if\ S < 0 \end{cases}$$

The trend in simulated results was calculated using Sen's slope estimate using the equation:

$$\beta(Sen's\ slope) = Median\left\{\frac{(x_i - x_k)}{j - i}\right\}, j > i$$

where ß is Sen's slope estimate, indicating an upward or downward trend in the time series.

3. Results

3.1. Historical concentrations of CO_2 and CH_4

We analyzed the atmospheric methane and carbon dioxide concentration from 2009 to 2020 using GOSAT satellite measurements (Fig. 1). We observed the significant increasing trends of about 7–9 ppb in annual CH_4 concentration over one of the major rice-producing regions of subtropical India (i.e., the West Bengal region of India) between 2009 and 2020. The CH_4 concentration increased from 1799 ppb in 2009 to 1886 ppb in 2020 over the experimental site (i.e., Kharagpur) lying in the study region (i.e., West Bengal). The annual CH_4 concentration over Kharagpur shows a significant increasing trend (8.64 ppb/year; $p < 0.05$) from 2009 to 2020. In addition, the CO_2 concentration over Kharagpur was 384 ppm in 2009, which increased to 412 ppm in 2020. We observed the increasing trends of about 2.46 ppm/year in the annual CO_2 concentration of Kharagpur during the last decade.

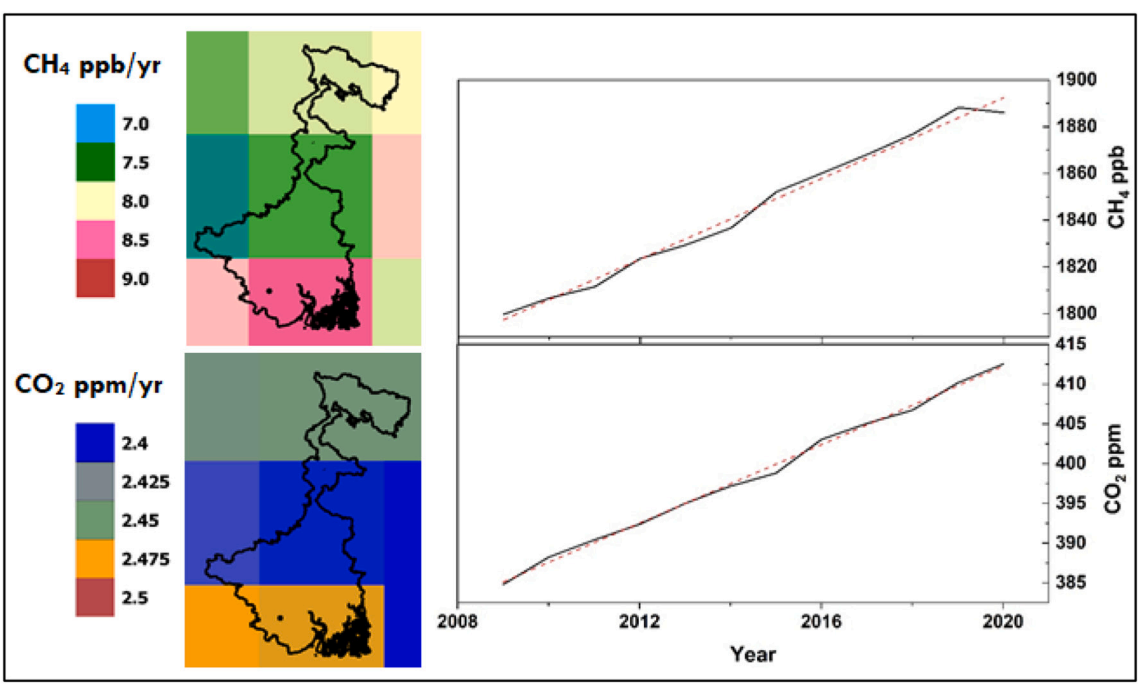

Fig. 1. Trends in atmospheric CO2 and CH4 concentrations over West Bengal (left panels) and Kharagpur (right panels) as estimated from GOSAT satellite measurements from 2009 to −2020.

3.2. GHG flux simulation

The simulation results using the DNDC model indicated higher flux values for all GHGs in RCP 8.5 than in RCP 4.5 in chemical fertilizer treatment (CF 100) compared to the control treatment (Fig. 2). The CH_4 and CO_2 emissions were higher in VC100, but N_2O emission was more prominent in CF100 than in rest nutrients management treatments. The organic treatment (VC100) and integrated treatment (CF50 + VC50) showed comparable results for N_2O emissions in both scenarios.

Flux trend analysis indicated an increasing trend ($p < 0.05$) of N_2O flux in future years for all nutrient management treatments (Table 3). A robust, increasing trend in GHG flux (kg year^{-1}) was observed in the conventional nutrient management practice of CF100 compared to two alternatives of sole organic (VC100) and integrated nutrient management (CF50 + VC50) in both climates forcing 4.5 and 8.5 scenarios, as indicated by z-values. These results can be corroborated with the highest emission of N_2O as simulated in CF100 treatment, i.e., 0.056 kg-N year^{-1} and 0.61 kg-N year^{-1} in RCP 4.5 and RCP 8.5 scenarios, respectively (Fig. 2). CF100 treatment was followed by an integrated fertilizer-based treatment (CF50 + VC50) in N_2O flux through the soil. However, the lowest N_2O flux among the nutrients management was simulated in organic treatment (VC100), with an increasing trend ($p < 0.001$) of 0.003 kg-N year^{1} for the RCP 4.5 scenario, but similar results (0.005 kg-N year^{-1}) with CF50 + VC50 treatment was observed in RCP 8.5 scenario. In contrast, CH_4 and CO_2 fluxes were highest for the organic treatment (VC-100), showing a significant ($p < 0.001$) positive trend in both cases, which was followed by the CF50 + VC50 and CF100 treatments. Sen's slope estimates that the increase in flux per year (kg-C year^{-1}) for CH_4 and CO_2 was higher in the RCP 8.5 than in the RCP 4.5 scenario.

3.3. Simulated global warming potential and grain yield of rice

GWP calculated based on conversion factors indicates that chemical fertilizers (CF100) and organic fertilizer (VC100) showed higher potential in enhanced radiative forcing of 8.5 scenarios compared to 4.5 scenarios. However, integrated nutrient management treatment showed comparable results in both scenarios, similar to the control treatment (Fig. 2).

The trend analysis for GWP suggests that all the treatments add significantly ($p < 0.001$) to the existing radiative forcing in both RCP scenarios. However, the maximum rate of addition to global warming is through CF100 treatment, followed by integrated nutrient management (CF50 + VC50) and organic fertilizer (VC100) treatment (Table 4). The CF100 treatment adds more rapidly to global warming at the rate of 36.42 kg CO_2 eq ha^{-1}season^{-1} in RCP 4.5 and 42.56 kg CO_2 eq ha^{-1}season^{-1} in RCP 8.5 scenario. Although organic nutrient management (VC100) also showed a significant positive trend for global warming with the rate of 6.26 and 10.64 kg CO_2eq ha^{-1}season^{-1} in RCP 4.5 and RCP 8.5 scenarios, respectively, this was the lowest among the various nutrient management treatments. Furthermore, the GWP showed similar trends (z ranging from 6.5 to 6.8 and 9–10 in RCP 4.5 and 8.5, respectively) for sole organic (VC100) and integrated nutrient management practice (CF50 + VC50) as indicated by z-values of Mann-Kendall's test. We conducted a temporal average (15 years) analysis to see beyond the inter-annual variability among the treatments and revealed that chemical fertilizer increases global warming throughout the period. Still, organic fertilizer treatment (VC100) and integrated nutrient management treatment (CF50 + VC50) are comparatively stable in both scenarios (Fig. 3a and b). The comparative analysis of the intervention effect of organic fertilizer treatment (VC100) and integrated nutrient management treatment (CF50 + VC50) over the conventional practice of chemical fertilizer application (CF-100) while adjusting the background emission through zero/no-fertilization is presented in Fig. S2. Our analyses showed that the comparative reduction in GWP due to alternative interventions compared to conventional practice ranged from 10- to −70% in the RCP 4.5 scenario. However, in RCP 8.5, the comparative reduction due to interventions was from 50- to −75% compared to conventional practice. Furthermore, in the RCP 4.5 scenario highest reduction of 70% in GWP compared to conventional practice (CF-100) was observed in only organic fertilizer treatment (VC-100), whereas in RCP 8.5, both organic fertilizer treatment (VC100) and integrated nutrient management treatment (CF50 + VC50) were comparable.

Simulated grain yields for future years using the CERES-Rice model (Fig. S3) were used to estimate the GWP per unit of grain production. Different nutrient management practices influence the grain yield significantly. Therefore, the yield scaled GWP was used for deciding the appropriate sustainable nutrient management practice. All nutrient management treatments indicated a higher intensity of GWP in RCP 8.5 scenarios than in 4.5 scenarios. However, integrated nutrient management treatment (CF50 + VC50) showed comparable predictions in both scenarios, similar to control. Nevertheless, in the late future years (after 2060), each treatment showed distinct variation in emission patterns with respective climate forcing in both scenarios. Trend analysis indicated a significant increasing trend ($p < 0.001$) per year for every treatment in both scenarios (Table 4). The highest rate of increase in GWP simulated were 0.014 and 0.021 kg CO_2eq kg-grain^{-1}season^{-1} in CF100 treatment and lowest rate of increase were 0.004 and 0.006 kg CO_2eq kg-grain^{-1}season^{-1} in VC100 in RCP 4.5 and 8.5 scenarios, respectively. Temporal average (15 years) indicated that chemical fertilizer (CF 100) having the highest emission with higher grain production is followed by control with the lowest resilience to climate change resulting in less grain production but significant emissions. The GWP intensity for grain production seems comparatively stable through the years for organic (VC 100) and integrated nutrient management treatment (CF50 + VC50) in both scenarios (Fig. 4).

4. Discussion

Our analysis of the historical concentration of CH_4 and CO_2 indicated a rising concentration in the last decade. The primary reason for this increase might be the emissions from agricultural fields apart from other anthropogenic sources. Paddy fields undergo methanogenesis and release methane during the growing season through ebullition (Singh et al., 2018). However, at the harvest of paddy, the receding soil moisture might promote the methanotrophs causing the oxidation of CH_4 to CO_2. Furthermore, methanotrophs are also known to utilize CO_2 and convert it into methanol, which might depend on the substrate concentration (Sahoo et al., 2021). The study area is predominantly a rice cultivating region in subtropical India due to its climate and topography; it constitutes a significant hotspot for GHG emissions. Therefore, we need to comparatively evaluate the nutrient management techniques used in rice farming to mitigate/adapt to climate change.

Previous studies on the projection of emissions from rice-based cropping systems have indicated that nutrient management practices have a significant role in developing mitigation strategies for GHG emissions (Linquist et al., 2018). Nutrient management in rice is an important area that needs scientific attention to develop more powerful GHG mitigation strategies.

4.1. Effects of different nutrient management on GHG emission

Our analyses indicated that under both RCP (4.5 Wm^{-2} and 8.5 Wm^{-2}) scenarios, the GHG emissions showed an increasing tendency owing to the increase in the rate of soil reaction for denitrification and decomposition with increasing temperature (Odorico, 2006). The maximum N_2O emission was observed in the chemical fertilizer-based treatment and is consistent with previous findings that showed positive correlations between N_2O emissions and fertilizer application (Mei et al., 2011). The chemical fertilizers such as urea can add more NH_4-N and NO_3-N to the soil and a strong positive correlation exists between

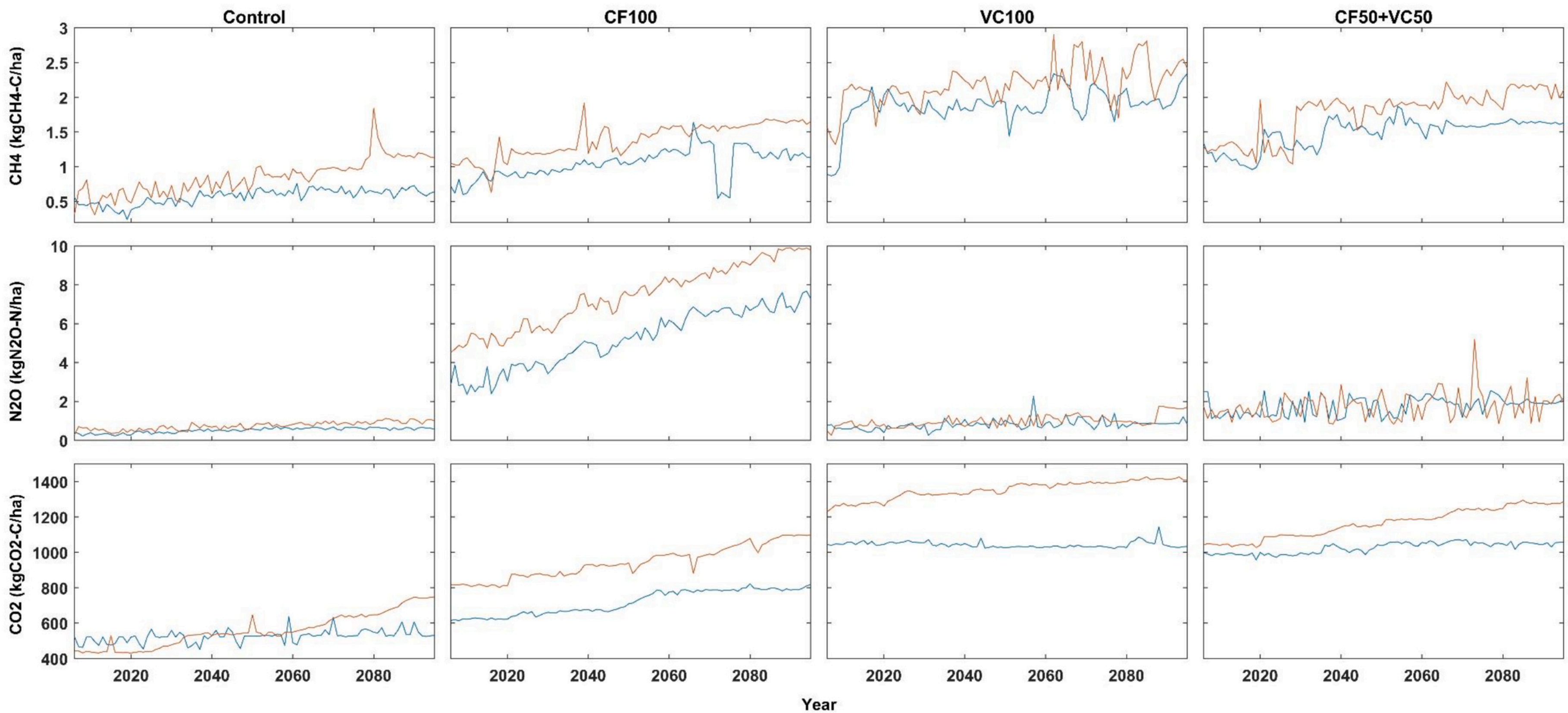

Fig. 2. Simulated values for CH_4, N_2O, and CO_2 flux for the different nutrient management (Control (No fertilizer), Chemical fertilizer (CF 100) Vermicompost (VC100), Integrated (CF 50 + VC 50) treatments) for the period of 2006–2095 in 4.5 scenario (blue line) and 8.5 Scenario (red line). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 3
GHG flux (kg year^{-1}) trend analysis in different nutrients management for the period of 2020–2095 (RCP 4.5 and RCP 8.5).

Nutrients management practices	Nitrous oxide		Methane		Carbon dioxide	
	Z-value	Sen's slope	Z-value	Sen's slope	Z-value	Sen's slope
			RCP 4.5			
Control	8.66¥	0.004	7.36¥	0.003	8.76¥	2.305
CF100	11.79¥	0.056	8.18¥	0.006	10.96¥	2.301
VC100	4.86¥	0.003	3.69¥	0.003	6.77¥	0.593
VC50 + CF50	2.30*	0.006	7.41¥	0.005	8.53¥	1.429
			RCP 8.5			
Control	9.07¥	0.007	10.06¥	0.008	10.68¥	3.593
CF100	12.57¥	0.061	10.52¥	0.008	11.82¥	3.425
VC100	5.93¥	0.007	6.24¥	0.006	11.66¥	1.779
VC50 + CF50	2.27*	0.005	8.33¥	0.010	11.88¥	3.056

Note: * means significant at α = 0.05; ¥ means significant at α = 0.001.

Table 4
Trend analysis of global warming potential of nutrients management for 2020–2095 in RCP4.5 and RCP 8.5 scenarios.

Global warming potential (kgCO2eq ha^{-1} year^{-1})				
Nutrients management practices	**RCP 4.5**		**RCP 8.5**	
	Z-value	Sen's slope	Z-value	Sen's slope
Control	10.01*	10.73	11.04*	16.72
CF100	12.02*	36.42	12.62*	42.56
VC100	6.86*	6.26	10.09*	10.64
VC50 + CF50	6.57*	8.42	8.58*	14.35
Global warming potential per kg grain (kgCO2eq^{-1}kg-grain)				
Nutrients management	**RCP 4.5**		**RCP 8.5**	
	Z-value	Sen's slope	Z-value	Sen's slope
Control	10.64*	0.009	11.58*	0.014
CF100	12.70*	0.014	13.11*	0.021
VC100	10.30*	0.004	12.41*	0.006
VC50 + CF50	10.71*	0.005	11.02*	0.008

Note: * means significant at α = 0.05.

inorganic nitrogen in the system and N_2O emissions observed (Bhattacharyya et al., 2012). Organic fertilizers such as vermicompost, on the other hand, are slow nitrogen release fertilizers and thus limit the availability of inorganic nitrogen for denitrification and thus lower the N_2O emissions (Zou et al., 2005).

The CO_2 and CH_4 emissions were observed maximum for VC100 treatment followed by integrated treatment CF50 + VC50. CO_2 emissions mainly result from organic decomposition and microbial respiration in aerobic soil conditions. The vermicompost-treated soils have abundant labile carbon and other processed nutrients, promoting such soil's microbial population. This labile carbon is easily oxidized to CO_2 by microbes in aerobic conditions through respiration. In the integrated treatment (CF50 + VC50), the induction of chemical fertilizer with vermicompost may reduce the microbial mineralization of organic matter for nitrogen source and is the reason for reduced emission of CO_2 in these treatments (Al-Kaisi et al., 2008). In CF100, the microbial population is least dependent on organic soil pool for their nitrogen requirement as readily available nitrogen source is provided; this leads to slow decomposition of soil organic matter and release of CO_2 (Sampanpanish, 2012). The additional CH_4 flux in organic fertilizer-based treatments (VC100) may be due to the hydrolysis of available organic matter in an aerobic environment leading to the formation of acetate or alcohol. These organic compounds now serve as preferred food for methanogens sitting in the randomly distributed oxygen-deprived soil pockets. It may trigger the formation of CH_4 in the randomly distributed

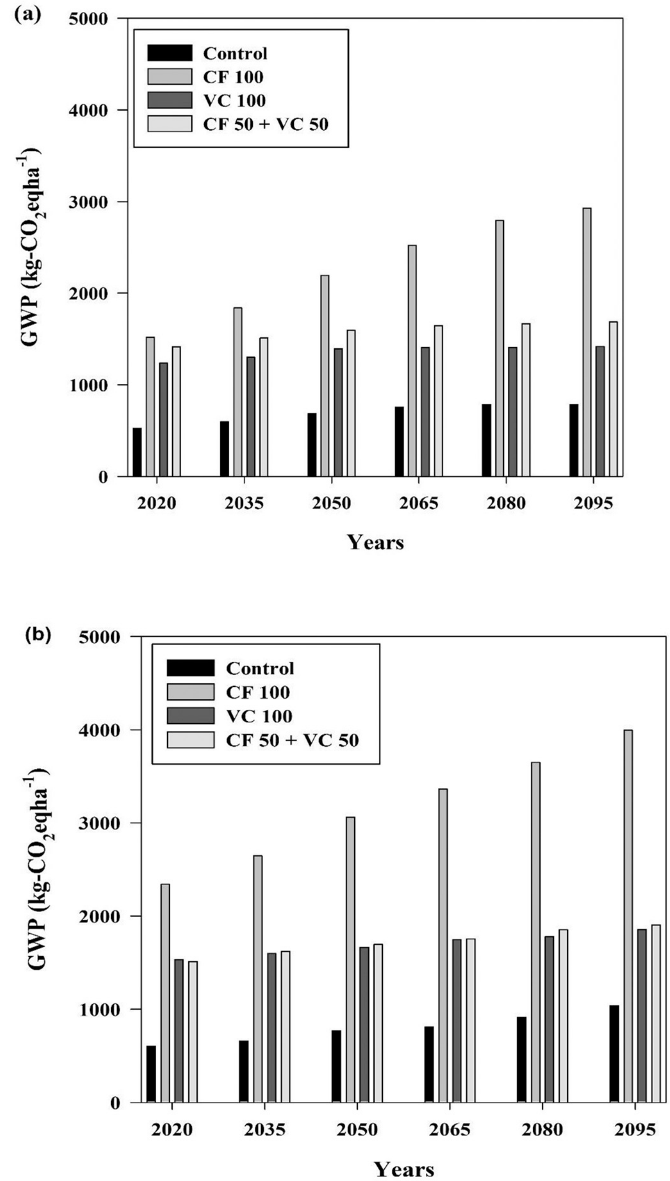

Fig. 3. Average Global Warming Potential (GWP) for different nutrient management treatments (Control (No fertilizer), Chemical fertilizer (CF 100) Vermicompost (VC100), Integrated (CF 50 + VC 50) treatments) in (a) 4.5 scenario (b) 8.5 Scenario.

anaerobic soil pockets (Kimura et al., 2004). Our results are consistent with previous observations, as they also showed that the inclusion of labile organic carbon input increase CH_4 and decreases N_2O emissions from rice fields (Cochran et al., 1997; Zwieten et al., 2007).

4.2. Effect of nutrient management on global warming potential and rice grain yield

The experiments and assessment with model simulations showed positive GWP trends in both scenarios for all treatments, indicating that a decrease in the emission of one gas is being offset by the increase in emission of another gas. This study's important finding is that it demands precise nutrient management practice that sets the prevalent atmospheric conditions in future emission or climate change contexts. The GWP is higher in the CF100 treatment due to a comparatively higher rate of N_2O emission. Since N_2O has the most significant radiative forcing among the considered GHGs here, that would also increase the

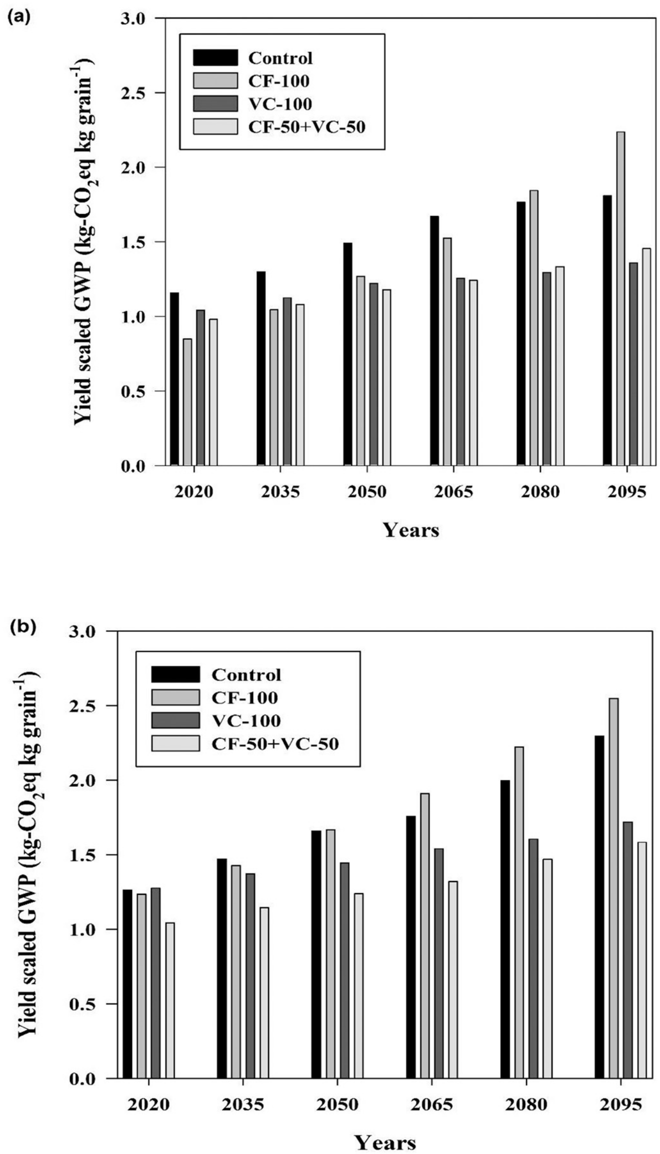

Fig. 4. Average Global Warming Potential (GWP) per kg grain production (Yield scaled GWP) for different nutrient management treatments (Control (No fertilizer), Chemical fertilizer (CF 100) Vermicompost (VC100), Integrated (CF 50 + VC 50) treatments) in (a) 4.5 scenario (b) 8.5 Scenario.

CF100 treatment's GWP compared to other treatments. Furthermore, in a low emission scenario (RCP 4.5), VC100 might be a better option to reduce the GWP of rice production compared to conventional practice (CF100) during the early decades, but comparable to CF50 + VC50 in later decades of the century. However, in a high emissions scenario (RCP 8.5), opting for either VC100 or CF50 + VC50 can substantially reduce the GWP of rice production as compared to conventional practice (CF100). The GWP per one-kilogram grain production showed an increasing trend in future years in all treatments in both RCP scenarios due to the increased flux of one or other GHGs in each treatment. However, a progressive decrease in the grain yield is also observed with an increase in temperature in both climate scenarios. This finding is consistent with Peng et al. (2004), showing a gradual decrease in grain yield with increasing temperature. This study revealed that the highest rate of increase in GWP per kg grain was in the CF100 treatment and the lowest in organic fertilizer-based treatments in both RCP scenarios. This can be attributed to a better soil microbial population and more balanced nutrition for plants in vermicompost-based treatments, which confers better tolerance of rice plants for abiotic stress (Kumar and Verma, 2018).

4.3. Possible policy implications of the study

The study results indicate that including organic amendments in nutrient management strategies can reduce the detrimental increase in greenhouse gas emissions from paddy cultivation. The Government of India (GOI) has undertaken several initiatives to reduce the indiscriminate use of chemical fertilizers and pesticides to reduce GHG emissions from the agricultural sector. To augment the infrastructure for producing quality organic and biological inputs, GOI, in collaboration with National Bank for Agricultural and Rural Development, initiated the national project on organic farming, a capital investment subsidy scheme. Also, the National Mission for Sustainable Agriculture (NMSA) was formulated in 2010 to improve agricultural productivity sustainably. Under the NMSA, Soil Health Management (SHM) and Paramparagat Krishi Vikas Yojana (PKVY) schemes (Reddy, 2020) were initiated to promote organic farming. Under these schemes, GOI aims to form 10,000 clusters and bring about five lakh acres of agricultural area under organic farming. Besides these initiatives, to reduce GHG emissions, particularly from rice fields, Neem Coated Urea (NCU) scheme is intended to regulate the use of urea and minimize N_2O emissions from rice fields. This study confirms that using organic fertilizer (here i.e., vermicompost) is another way to reduce GHG emissions from rice fields. However, organic fertilizers are costlier than chemical fertilizers (as subsidy is provided on chemical fertilizers in India). In the initial years, rice productivity may decrease in organic fertilizer application compared to chemical fertilizers. This study indicates that besides using VC100, farmers can opt for VC50 + CF50, which reduces GHG emissions and GWP significantly, without a comparable decrease in yield to the sole use of chemical fertilizer (CF100). However, besides concentrating on promoting organic farming, GOI needs to focus on creating organic markets so that farmers can easily sell their organic produce without incurring much transaction costs associated with marketing.

Furthermore, there is an apprehension that using organic fertilizer may reduce rice yield during initial years of application. Our study revealed that using organic and inorganic fertilizer together (CF50 + VC50) in integrated manner (INM) can significantly reduce GHG emissions and GWP of rice production without any significant loss of grain yield. Hence, adopting such fertilizer management practices would protect the government from the burden of inflation originating due to loss of yield. Also, the policy makers must think about implementing a carbon credit policy more sternly. Rewarding farmers through carbon credit which is globally tradable would compensate for any loss in yield and further improve their benefits and returns. This is also a necessary step to popularize the suggested management practices. Furthermore, the government may also think to provide some subsidies and incentives for organic fertilizer to further strengthen the sustainability of recommended practice.

5. Conclusions

We indicated that a better nutrient management practice in rice cultivation could reduce possible environmental footprints of agriculture in future climate change scenarios, especially in subtropical India. The simulated GHG fluxes from rice fields during the growing season for two forcing scenarios, besides the crop yield, for the conventional practice of sole chemical fertilizer application and two alternative nutrient management practices indicated some exciting possibilities. For instance, the chemical fertilizer treatment contributes to global warming as it adds about 0.014 and 0.021 kg-CO2eq kg-grain^{-1}season^{-1} in the RCP 4.5 and 8.5 scenarios, respectively. However, the GWP of rice production in conventional practice can be successfully reduced by upto 70% by opting for sole organic fertilizer (VC100) or integrated nutrient management practice (CF50 + VC50) in both climates forcing scenarios.

Therefore, we suggest that nutrient management strategies consider the inclusion of organic fertilizers, like vermicompost, to reduce the environmental burden of rice production. Integrated nutrient management with CF50 + VC50 might be a feasible way to limit the GHG emission from rice fields and minimize global warming in future climate scenarios.

Data and code availability

The data and analyses codes used in this study can be made available on request.

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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.crsust.2022.100169.

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