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Response of Rice Cultivars to Elevated Air Temperature and Soil Amendments: Implications towards Climate Change Adaptations and Mitigating Global Warming Potentials

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Abstract

Global mean surface air temperature is expected to increase 1.1˚C - 6.4˚C by the end of 21st century which may affect rice productivity and methane emissions in the future climate. This experiment was conducted to investigate the response of rice cultivars to elevated air temperature (+1.5˚C higher than ambient) and soil amendments in regards to rice yield, yield scaled methane emissions and global warming potentials. The experimental findings revealed that replacement of inorganic fertilizers (20% - 40% of recommended NPKS) with Vermicompost, Azolla biofertilizer, enriched sugarcane pressmud, rice husk biochar and silicate fertilization increased rice yield 13.0% - 23.0%, and 11.0% - 19.0% during wet aman and dry boro season, respectively. However, seasonal cumulative CH_4 fluxes were decreased by 9.0% - 25.0% and 5.0% - 19.0% during rainfed wet aman and irrigated dry boro rice cultivation, respectively with selected soil amendments. The maximum reduction in seasonal cumulative CH_4 flux (19.0% - 25.0%) was recorded with silicate fertilization and azolla biofertilizer amendments (9.0% - 13.0%), whereas maximum grain yield increment 10.0 % - 14.0% was found with Vermicompost and Sugarcane pressmud amendments compared to chemical fertilization (100% NPKS) treated soils at ambient air temperature. However, rice grain yield decreased drastically 43.0% - 50.0% at elevated air temperature (3˚C higher than ambient air temperature), eventhough accelerated the total cumulative CH_4 flux as well as GWPs in all treatments. Maximum seasonal mean GWPs were calculated at 391.0 kg CO_2 eq·ha^{-1} in rice husk biochar followed by sugarcane pressmud (mean GWP 387.0 kg CO_2 eq·ha^{-1}), while least GWPs were calculated at 285 - 305 kg CO_2 eq·ha^{-1} with silicate fertilizer and Azolla biofertilizer amendments. Rice cultivar BRRI dhan 87 revealed comparatively higher seasonal cumulative CH_4 fluxes, yield scaled CH_4 flux and GWPs than BRRI dhan 71 during wet aman rice growing season; while BRRI dhan 89 showed higher cumulative CH_4 flux and GWPs than BINA dhan 10 during irrigated boro rice cultivation. Conclusively, inorganic fertilizers may be partially (20% - 40% of the recommended NPKS) replaced with Vermicompost, azolla biofertilizer, silicate fertilizer and enriched sugarcane pressmud compost for sustainable rice production and decreasing GWPs under elevated air temperature condition.

Keywords

Rice Paddy, Soil Amendments, CH_4 Flux, GWPs, Elevated Air Temperature

1. Introduction

Bangladesh is predominantly a deltaic floodplain country with hot and humid sub-tropical climate. The country is most vulnerable to climate change due to increasing temperature and uncertainty of precipitation, thereby rice production may decline by 8.0% - 10.0% against 1990 baseline production level (IPCC, 2007). It has already been reported that the global mean surface air temperature has risen by 0.74˚C in the last century and is expected to increase 1.1˚C - 6.4˚C by 21st century (IPCC, 2014), thereby decreasing rice productivity, while yield scaled methane emissions as well as global warming potentials may be increased significantly. Bangladesh is the third largest producer of milled rice after China and India having annual production of 36.35 million metric tons (FAO, 2023). However, rapid population growth (>1000 persons perkm^2) and concomitant loss of agricultural lands may have detrimental effects on the fertility and productivity of agricultural land, while methane emissions might be accelerated due to increased temperature and flooded rice cultivation. Rice paddies are important source of atmospheric CH_4, which contributes significantly to greenhouse effect. The amount of CH_4 emitted from wetland paddy fields accounts for 10% - 20% of the total CH_4 emissions (50 Tg·yr^{-1} to 100 Tg·yr^{-1}) (Wassmann & Aulakh, 2000; IPCC, 2007). At present, the atmospheric average concentration of CH_4 is 1834 ppb (Nisbet, 2016), which has increased significantly due to agricultural management practices. Methanogenic bacteria thrive in flooded soils under oxygen limited condition, where organic matter is adequate; thereby methane gas is produced as the final product of organic matter decomposition (Conrad, 2002). This methane is released into the atmosphere through molecular diffusion, ebullition (bubbling), and plant-mediated transport through specialized plant structures called aerenchyma (Zheng et al., 2007).

In Bangladesh, chemical fertilizers have been widely introduced as a booster of crop production over the past 100 years to meet the growing demands for food production, however intensive use of inorganic and agrochemical fertilizers severely degraded soil fertility, crop yield and environment. Therefore, organic matter, in combination with inorganic fertilizers, could be a sustainable and cost-effective strategy for maximizing rice production while improving soil fertility and rice paddy ecosystem. However, organic amendments can largely increase methane (CH_4) production during irrigated rice cultivation periods (Khosa et al., 2010; Kim et al., 2014; Liu et al., 2014). It is assumed that methane (CH_4) emissions will be higher in organic rice paddies compared to conventional rice paddies, as the addition of organic matter has been shown to increase CH_4 production. Conversely, nitrous oxide (N_2O) emissions are expected to be lower in organic rice paddies due to the gradual release of mineral nitrogen (N) from organic manure, as opposed to the rapid release of N from synthetic fertilizers used in conventional rice cultivation. The sustainable production of rice can be achieved by adopting the integrated nutrient management strategies. Vermicompost is a major source of nitrogen, phosphorus and potassium that may be used for organic farming and as a component of integrated nutrient management for rice production as well as mitigation of methane emissions. Silicate slag, by-product of steel industry, is used in the manufacturing of silicate fertilizer; which contains a high amount of available silicate, free iron and manganese oxides, act as electron acceptors, thereby suppressing methanogens activity and reduce methane production in irrigated paddy field. Another feasible soil amendment is biochar, a charcoal containing high levels of concentrated organic carbon, high porosity and greater resistance to microbial degradation in soils (Liang et al., 2014). Besides the potential for improving soil fertility and rice productivity biochar may contribute to mitigate greenhouse gas emissions and increase carbon sequestration in soil (Lehmann & Rondon, 2006; Zhang et al., 2010). Azolla cyanobacterial mixture has been used as biofertilizer to supplement the N demand of the rice crop, which can partially replace the costly chemical N fertilizer under conditions of sustainable agriculture. In addition, its effect on methane (CH_4) and nitrous oxide (N_2O) emissions reduction has been reported by Bharati et al. (2000), Prasanna et al., (2002), Ali et al., (2012) and Kollah et al. (2016), while opposite effect was documented in Northeastern China (Chen et al., 1997). Similarly, sugarcane press mud (SPM), sugarcane filter-cake, byproduct of sugar industry, residue of the filtration of sugarcane juice, inoculated with fungal spores to enrich nutrients like C, N, P and S etc., maintain soil fertility, carbon sequestration, enhancing crop production and mitigating GHGs emissions (Kumar et al., 2017). The grain-filling stage is very susceptible to elevated temperatures (above 22˚C) and could reduce rice quality and grain weight due to day night temperature (34˚C/22˚C) variation (Chaturvedi et al., 2017). In China, reduction of 1000 grain weight and ripened grain ratio under the temperature treatments of 3.0˚C and 5.0˚C above the ambient air temperature resulted in significant grain yield loss for Dasanbyeo and Hwaseongbyeo rice genotypes, respectively, (Lee et al., 2015). Therefore, this experiment was undertaken to investigate the effectiveness of rice husk biochar, vermicompost, Azolla biofertilizer, and Sugarcane press mud (SPM) compost as soil amendments for enhancing rice productivity and minimizing CH_4 flux as well as GWPs through improving soil fertility at elevated air temperature conditions.

2. Materials and Methods

2.1. Experiment Site

A pot experiment was conducted in the Net house, Department of Environmental Science, Bangladesh Agricultural University, Mymensingh with BRRI dhan-89 and BINA dhan-10 during boro season rice cultivation (January 2020 to May 2020); with BRRI dhan71 and BRRI dhan 87 during wet season rice cultivation (July 2020 to November 2020). Experimental site is located at 24˚N latitude and 94˚E longitude (AEZ 9). The experimental soils were collected from (0 - 15) cm depth of the top soil of ideal paddy field of experiment filed. The experimental soil was silty loam texture type having a soil pH value of 6.4, SOM 1.78%, available P13.7 ppm, available K 16.3 ppm, low salt content (EC value 2.35 dS/m).

2.2. Experiment Design and Treatments

Experimental treatments were T1: Control, T2: (NPKS 100%, No amendments, T3: NPKS (80%) + 20% NPKS from azolla biofertilizer, T4: NPKS (60%) + 40% NPKS from azolla biofertilizer, T5: NPKS (80%) + 20% NPKS from Rice husk biochar, T6: NPKS (60%) + 40% NPKS from Rice husk biochar, T7: NPKS (80%) + 20% NPKS from Vermicompost, T8: NPKS (60%) + 40% NPKS from Vermicompost, T9: NPKS (80%) + 20% NPKS from Sugarcane pressmud (SPM), T10: NPKS (60%) + 40% NPKS from Sugarcane pressmud (SPM), T11: 80% NPKS +20% NPKS from Silicate fertilizer (SF), T12: 60% NPKS +4 0% NPKS from SF. The treatments were arranged with completely randomized design (CRD) and replicated three times for setting the pot experiment. Total number of pots was seventy two (72) where 36 for ambient temperature and 36 for elevated temperature. The treatments were assigned in two different temperature conditions: ambient air temperature condition (outside of greenhouse) and elevated air temperature condition (+1.5˚C higher inside greenhouse). During the experimentation, the average maximum temperature prevailed in the greenhouse condition was 35˚C - 38˚C and outside the greenhouse was below 35˚C.

2.3. Rice Genotypes

BRRI dhan 89 and BINA dhan 10 were planted in dry boro season, while BRRI dhan 71 and BRRI dhan 87 were planted during wet Aman season. BRRI dhan 89: BRRI dhan-89 rice cultivar was discovered by Bangladesh rice Research Institute in 2017. The life span of this breed is about 154 - 158 days. BRRI dhan 71: BRRI dhan-71 rice cultivar was invented by Bangladesh rice Research Institute in 2012. The lifetime of this rice cultivar is about 114 to117 days. BINA dhan 10: Bina dhan-10 rice cultivar was discovered by Bangladesh Institute of nuclear agriculture (BINA) in 2012. It was released for boro season. It's lifespan is about 127 - 132 days. BRRI dhan 87: BRRI dhan-87 rice cultivar was invented by Bangladesh rice Research Institute in 2017. This rice cultivar lifetime is about 122 days.

2.4. Soil Amendments and Application Rate

Soil amendments were mixed up with collected soils five days before rice seedlings transplantation in pot. The soil amendments were applied @ 2.0 t/ha, 8.0 t/ha, 5.0 t/ha, 4.0 t/ha and 0.5 t/ha for azolla biofertilizer, rice husk biochar, vermicompost, sugarcane press mud and silicate fertilizer, respectively. The experimental pots were filled with air dried soil (about 8.0 kg). Chemical fertilizers (N 90 kg/ha, P 15 kg/ha, K 45 kg/ha, S 8.0 kg/ha through urea, triple super phosphate, muriate of potash, gypsum) were added to soils based on integrated plant nutrients system for achieving high potential yield. The composition of Vermicompost was organic C 18.5%, total N 1.5%, cellulose 30%, available P 0.98%, available S 0.6%, potassium 1.2%, Fe 200 ppm and Mn 250 ppm. Enriched SPM compost contains organic C 35.0%, total N 1.6%, cellulose 24%, available P 1.55%, available S 0.95%, potassium 1.41%, Fe 1000 ppm and Mn 310 ppm. Rice husk biochar contains organic C 42.5%, total N 0.9%, cellulose 50%, Fe 250 ppm, S 200 ppm, Mn 500 ppm etc. Silicate fertilizer contains mainly Silicon (35%) with high amount of iron (1500 ppm).

2.5. CH_4 Gas Sampling and Analysis by Gas Chromatography

Gas samples were collected by the modified closed-chamber method (Rolston, 1986; Ali et al., 2008) during the rice cultivation. The dimension of close chambers was (100 cm). Gas samples were collected once a week started from 21 DAT until rice harvesting to get the average CH_4 emissions during the cropping season. At first, rice planted pot was kept on a water filled tray and then glass chamber was placed on it. Gas samples were collected by a 50 ml air-tight syringe at 0 min, 15 min and 30 min intervals after chamber placement over the rice planted pot. The samples were analyzed to determine the concentration of CH_4 gas by Gas Chromatograph (Shimadzu/GC 2014, Japan) equipped with a Flame Ionization Detector (FID). The analysis column used a stainless-steel column packed with Porapak NQ (Q 80 - 100 mess). The temperatures of column, injector and detector were adjusted at 100˚C, 200˚C, and 200˚C.

2.6. CH_4 Emission Rate

CH_4 emission rate was calculated by following equation (Rolston, 1986):

$$F = \rho \cdot \mathrm{V}/\mathrm{A} \cdot \Delta c/\Delta t \cdot 273/T$$

Here, F = methane emission rate (mg CH_4 $m^{-2}\cdot hr^{-1}$), ρ= gas density (0.714 $mg\cdot cm^{-3}$), V = volume of chamber (m^3), A = surface area of chamber (m^2), $\Delta c/\Delta t$ = rate of increase of CH_4 concentration in the chamber ($mg\cdot m^{-3}\cdot hr^{-1}$), T (absolute temperature) = 273 + mean temperature in chamber (˚C).

2.7. CH_4 Flux Was Calculated According to the Following Equation

$$E = \text{Slope (ppm/min)} \times \text{VC} \times \text{MW} \times 60 \times 24 \times 22.4\ (273 + \text{T}/273) \times \text{Ac} \times 1000$$

The emissions as Kg CH_4 (or Kg N_2O)/ha were derived from the slope of the linear regression curve of gas (CH_4 and N_2O) concentrations against the chamber closing time. The slope was referred to as mass per unit area per unit time (mg/m^2/h), where VC is the volume of the gas chamber in liters (L), MW is the molecular weight of the respective gas, 60 is minutes per hour and twenty four is hours of the day. The volume of 1 mol of gas in L at standard temperature and pressure is 22.4. T is the temperature inside the chamber (˚C) while 273 is the standard temperature of ˚K. AC is the chamber area (m^2) and 1000 is µg/mg.

The seasonal CH_4 flux for the entire cropping period was computed as reported by Singh et al. (1999):

$$\text{Seasonal } CH_4 \text{ flux} = \sum n_i = (R_i \times D_i)$$

2.8. Estimation of Global Warming Potentials (GWPs)

To estimate the GWP, CO_2 is typically taken as the reference gas, and an increase or reduction in emissions of CH_4 or N_2O is converted into "CO_2-equivalents" by means of their GWPs. In this study, we used the IPCC factors to calculate the combined GWP for 100 years, GWP = 28 × CH_4, kg CO_2-equivalents ha^{-1}) + 265 × N_2O, kg CO_2-equivalents ha^{-1} (IPCC, 2014). In addition, the greenhouse gas intensity (GHGI) was calculated by dividing GWP by the grain yield for rice (Mosier et al., 2006).

2.9. Soil Chemical Properties

Soil redox potential (Eh), leachate water pH, EC, TDS, and total dissolved iron (TDFe) conc. were measured at every week interval during rice cultivation. Soil organic carbon (SOC) (Allison, 1965), total-N% (Keeney & Nelson, 1982), available P (Colorimetric method, Olsen Sommers), available S (by the calcium chloride 0.15% extraction method), available Si (1M Na –acetate, pH 4.0, UV Spectrometer) were determined following standard methods. Exchangeable calcium (Ca), sodium (Na) and potassium (K) were extracted from soil using 1 M CH_3COONH_4 solution and their concentrations in the extract were directly determined by Flame Photometer (Model: FP 902 PG Instrument). Free iron oxides in soil were extracted by Diethylene Tri amine Penta Acetate (DTPA) solution and its concentration in the extract was determined directly by an Atomic Absorption Spectrophotometer (Loeppert & Inskeep, 1996). The concentrations of total dissolved iron and ferrous iron in the leached water samples were determined by 1,10-phenanthroline method. Ammonium (NH_4) concentration in water samples were determined by Indophenol blue method at 640 nm wave length using a UV spectrophotometer (UV–VI Mini 1240, Shimadzu Corporation, Kyoto, Japan). NO_3^- concentration in water samples were determined at 410 nm using a UV spectrophotometer (Brucine-sulfanilic acid method). After rice harvest, soil bulk density was determined using cores (volume 100 cm^3, inner diameter 5 cm), filled with fresh moisture soils. The collected soil core samples were oven dried at 105˚C for 24 h and then measured the weight of dried core samples. Soil porosity was calculated using the bulk density (BD) and particle density (PD, 2.65 Mg m^3) according to the equation: Porosity (%) = (1 − BD/PD) * 100.

2.10. Morpho-Physiological Parameters of Rice Plant

Data on plant height, productive tiller number per hill, leaf area, SPAD value, and CO_2 assimilation rates were measured at flowering to heading stage. The CO_2 assimilation rate was measured with Portable Photosynthesis system (LI-COR, LI 6400) and SPAD readings were measured by Chlorophyll meter (SPAD-502, Minolta Camera Co. Ltd., Osaka, Japan). A fully matured leaf from the top of the plant was selected for recording the SPAD values and the mean of five readings per plant was taken. During the maturity to harvesting stage, ripened grains (%) per hill, grain yield per hill, and other yield attributes were also recorded. Harvest index (HI) was also calculated.

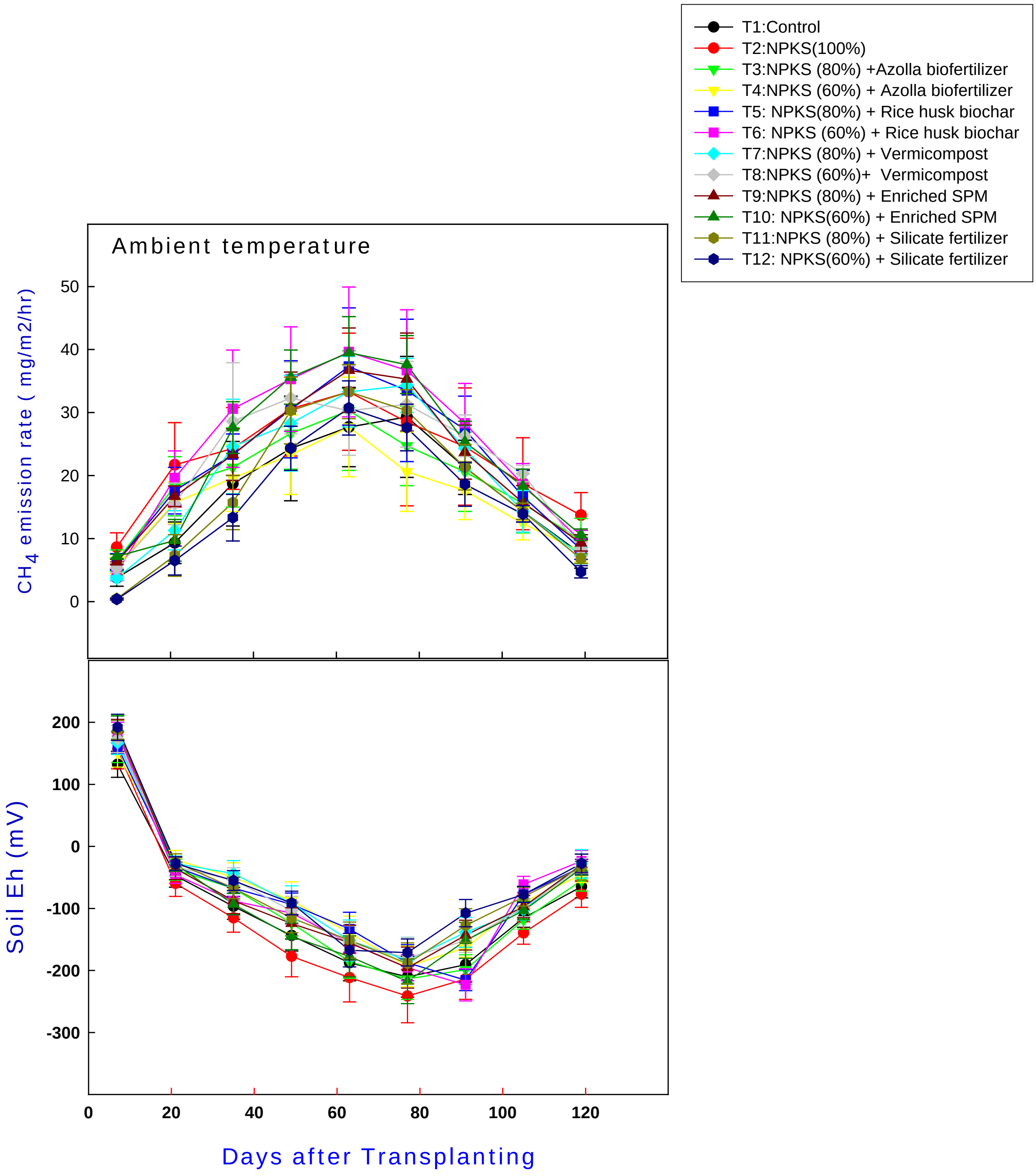
2.11. Statistical Analysis

At first experimental data were entered into Microsoft Excel. Then analysis of variance (ANOVA) was performed through using R software (R-4.3.3, 2024 version). Duncan's multiple range test (DMRT) was conducted to identify statistically significant differences between group means at a 5% significance level.

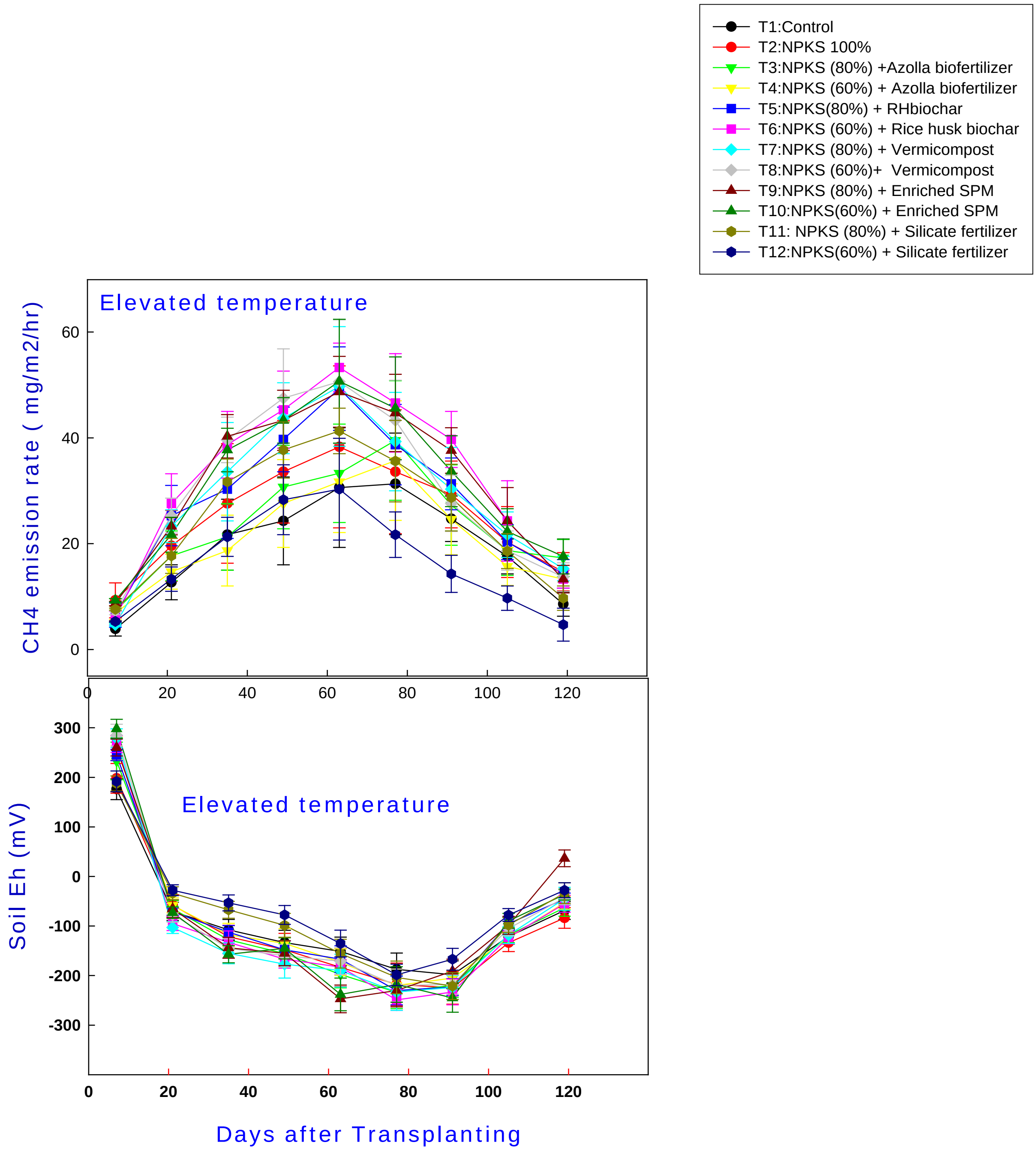
3. Results

3.1. Trends of CH_4 Emission Rate and Soil Redox Potential (Eh) under Ambient and Elevated Temperature Conditions

CH_4 emission rate within the first two weeks after rice was transplanted in potted soil was low under ambient temperature condition Figure 1(a), which increased significantly at 35 DAT onwards (active tillering stage) and peaked at 77 DAT-80 DAT (flowering to heading stage). Among the treatments, higher CH_4 emission rates were recorded in rice husk biochar amended pots (T5, T6) and sugarcane pressmud (SPM) amended (T9 and T10) rice planted pots, while lower CH_4 emissions were observed in T1 (control), NPKS (100%) fertilization (T2), Azolla biofertilizer (T3, T4), vermicompost (T7, T8) and silicate fertilization (T11, T12) treated rice planted pots. The first CH_4 peak (20 - 30 mg/m^2/hr) was observed at 35 days after rice transplanting (active tillering stage) followed by the highest peak (35 - 40 mg·m^{-2}·hr^{-1}) at 77 - 80 DAT (flowering stage). The maximum decrease in CH_4emission rate (15% - 30%) was obtained by silicate fertilization and azolla biofertilizer amendments and improved soil redox status (Eh) also observed in the amended potted soils (**Figure 1(a)**). After that, CH_4–C emission rate sharply dropped probably due to improved soil redox status at rice grain maturation, thereby least CH_4 emission was recorded around 120 DAT before rice harvest.



(a)



(b)

Figure 1. (a) Trends of CH4 emission rate and soil redox potential value (Soil Eh) with soil amendments at ambient temperature during dry boro season rice cultivation (BRRI dhan 89); (b) Trends of CH4 emission rate and soil Eh with soil amendments at elevated temperature during dry season boro rice cultivation (BRRI dhan 89).

On the other hand, higher CH_4 emission rate along with more intense redox potential status were observed under elevated temperature condition compared to ambient temperature grown rice planted pots, which may be due to rapid microbial activity and faster decomposition of soil organic matter. The first CH_4peak (35 mg/m^2/hr) was recorded at 35 DAT in 100% NPKS fertilized rice planted pots, while the 2nd CH_4 peak (48 mg/m²/hr) was observed at 77 - 80 DAT (**Figure 1(b)**). After three weeks of rice transplanting, intensive soil redox status developed (Eh value around −100 mV), which reached towards most intensive reduced condition (Eh value −200 to −250 mV) by 70 - 84 DAT (**Figure 1(b)**). At flowering to heading stage (70 DAT-84 DAT) the rice rhizosphere showed the most reduced conditions in almost all treatments, although silicate fertilization and azolla biofertilization amendments significantly ($p < 0.05$) improved (increased the soil Eh value) soil redox status, probably due to their high content of electron acceptors such as free iron oxides, Mn and S.

3.2. Seasonal Cumulative CH_4 Emission and GWPs

At ambient air temperature condition, the maximum seasonal cumulative CH_4 flux (15.67 - 15.90 g/m²) with mean GWP 391.0 kg CO_2 eq·ha^{-1} was found in rice husk biochar followed by sugarcane pressmud (15.30 - 15.70 g/m²; mean GWP 387.0 kg CO_2 eq·ha^{-1}), vermicompost amendment (13.7 - 14.30 g/m²; mean GWP 350 kg CO_2 eq·ha^{-1}), NPKS fertilized (13.50 - 13.70 g/m², mean GWP 340 kg CO_2 eq·ha^{-1}), Azolla biofertilization (11.60 - 12.80 g/m², mean GWP 305 kg CO_2 eq·ha^{-1}), silicate fertilized (10.50 - 12.30 g/m², mean GWP 285 kg CO_2 eq·ha^{-1}) and control treatment (8.6 - 10.63 g/m², mean GWP 240 kg CO_2 eq·ha^{-1}) during wet aman season BRRI dhan 87 cultivation. On the other hand, elevated air temperature accelerated the total cumulative methane flux in all amended rice plants. The maximum seasonal cumulative CH_4 flux 15.20 - 16.50 g/m² was found in rice husk biochar amendment (mean GWP 396 kg CO_2 eq·ha^{-1}) followed by sugarcane pressmud 15.50 - 16.30 g/m² (mean GWP 398 kg CO_2 eq·ha^{-1}), vermicompost amendment 14.90 - 15.60 g/m² (mean GWP 381 kg CO_2 eq·ha^{-1}), NPKS fertilized 15.10, g/m², (mean GWP 378 kg CO_2 eq·ha^{-1}), Azolla biofertilization 13.30 - 14.50 g/m² (GWP 348 kg CO_2 eq·ha^{-1}), silicate fertilized 11.30 - 12.50 g/m² (GWP 298 kg CO_2 eq·ha^{-1}) and control treatment (12.90 g/m², GWP 323 kg CO_2 eq·ha^{-1}).

In case of BRRI dhan 71, the least cumulative CH_4 flux 7.60 g/m² (mean GWP 190 kg CO_2 eq·ha^{-1}) was found in control (T1) treatment with maximum cumulative CH_4 flux 14.10 - 15.50 g/m² (mean GWP 372.0 kg CO_2 eq·ha^{-1}) was found in SPM amended soil under ambient air temperature. On the other hand, elevated air temperature significantly increased cumulative CH_4 flux in all treatments. The maximum increase in cumulative CH_4 fluxes (14.5% - 16.0%) and GWPs (10.7% - 11.6%) were observed in rice husk biochar and SPM amended soils.

During boro season rice cultivation, BRRI dhan 89 and BINA dhan 10 revealed maximum cumulative CH_4 fluxes, yield scale methane emissions and GWPs with rice husk biochar and SPM amendments in soils under both ambient and elevated air temperature conditions. At ambient air temperature, the maximum GWPs for BRRI dhan 89 cultivation were found 345 - 373 kg CO_2 eq·ha^{-1} in SPM and 365 - 370 kg CO_2 eq·ha^{-1} in biochar amendments, while least GWP was recorded 272 - 307 kg CO_2 eq·ha^{-1} in silicate amended rice planted soils. Elevated air temperature, resulted maximum GWPs with SPM (420 - 438 kg CO_2 eq·ha^{-1}), biochar (418 - 434 kg CO_2 eq·ha^{-1}) amendments, while least GWP 302 - 337 kg CO_2 eq·ha^{-1} was found in silicate amendment soil. In case of BINA dhan 10, the maximum GWP was found 382 - 391 kg CO_2 eq·ha^{-1} with biochar amendment (ambient temperature), which increased towards 383 - 402 kg CO_2. eq·ha^{-1} at elevated temperature. SPM amendment in soil caused maximum GWP 373 - 383 kg CO_2 eq·ha^{-1} (ambient temperature) which increased to 390 - 403 kg CO_2 eq·ha^{-1} at elevated air temperature. Silicate fertilizer amendment resulted minimum GWP 282 - 312 kg CO_2 eq·ha^{-1} (at ambient temperature) and 283 - 333 kg CO_2 eq·ha^{-1} at elevated temperature. Among the amendments, silicate fertilizer, azolla biofertilizer and vermicompost were found effective to decrease cumulative CH_4 fluxes, yield scaled CH_4 emission and GWPs. Rice cultivars also showed variation in regards to cumulative CH_4 fluxes, yield scaled CH_4 flux and GWPs. BRRI dhan 87 revealed comparatively higher seasonal cumulative CH_4 fluxes, yield scaled CH_4 flux and GWPs than BRRI dhan 71 during wet aman rice growing season; while higher seasonal cumulative CH_4 fluxes, yield scaled CH_4 flux and GWPs were found in BRRI dhan 89 compared to BINA dhan 10 cultivation during irrigated boro rice cultivation.

3.3. Rice Grain Yield and CO_2 Assimilation Rate

Soil amendments with vermicompost, sugarcane pressmud, azolla biofertilizer, silicate fertilization and rice husk biochar significantly ($p < 0.05$) increased rice yield compared to inorganic chemicals (T2:100%NPKS) treated rice planted pot. During wet aman season rice grain yield was increased by 3.0% - 16% with soil amendments compared to chemical fertilization (100% NPKS) treated rice plants (600 g/m^2) under ambient temperature condition. The maximum grain yield was recorded with vermicompost (660 - 690.0 g/m^2, T7, T8) followed by enriched SPM (650 - 680.0, T9, T10), azolla biofertilation (640 - 670.0, T3, T4), silicate fertilization (620 - 650.0, T11, T12), rice husk biochar (610.0 - 630.0, T5, T6), inorganic NPKS (510 - 600 g/m^2, T2) and T1 (160 - 180 g/m^2 Control) treatments. However, rice grain yield was decreased sharply by 35.0% - 45.0% under elevated temperature irrespective of soil amendments and rice cultivars (Table 1).

Table 1. Rice yield, cumulative CH_4 emissions, CO_2 assimilation rate and GWPs with soilamendments under ambient and elevated temperature conditions (wet season rice cultivation season).

Treatments		BRRI dhan 87								BRRI dhan 71							
		Grain yield (g/m^2)	**Cumulative CH_4 flux** (g/m^2)	**Yield scale CH_4 emission**	CO_2 assimilation rate (μmol·m^{-2}·S^{-1})	GWPs (kg CO_2 eq·ha^{-1})	Nutrients Uptake (kg/ha)			**Grain yield** (g/m^2)	**Cumulative CH_4 flux** (g/m^2)	**Yield scale CH_4 emission**	GWPs (kg CO_2 eq·ha^{-1})	CO_2 assimilation rate (μmol·m^{-2}·S^{-1})	Nutrients Uptake (kg/ha)		
							N	P	K						N	P	K
Ambient Temperature	T1	180.60 e	6.5 g	0.036	10.6	161.7 f	17.5	3.8	3.2	160.67 e	7.90 f	0.049	198.0 f	9.8	15.7	3.4	2.9
	T2	600.60 d	14.90 b	0.024	16.3	**373.0 ab**	**58.4**	12.5	10.9	510.70 d	14.30 ab	0.028	358.0 ab	15.6	49.7	10.7	9.2

Continued

Ambient Temperature	T3	640.50 bc	13.80 c	0.021	17.8	345.33 c	62.8	13.4	11.6	530.00 cd	13.50 bc	0.025	338.0 c	17.3	51.6	11.1	9.6
	T4	670.0 ab	**12.70 d**	0.018	19.7	318.0 d	66.2	14.0	12.1	580.00 ab	12.70 d	0.021	318.0	18.5	56.4	12.2	10.5
	T5	610.0 c	**15.67 a**	0.025	16.9	**393.67 a**	**59.4**	12.9	11.1	520.60 cd	**15.10 bc**	0.029	378.0 ab	16.1	51.0	10.1	9.4
	T6	630.0 bc	**15.90 a**	0.023	18.1	**398.00 a**	61.3	13.3	11.4	550.33 b	**13.70 bc**	0.024	343.0 c	16.6	53.5	11.5	10.0
	T7	660.0 ab	13.80 c	0.021	18.6	360.83 b	64.3	13.8	12.0	570.70 ab	13.10 c	0.024	353.0 b	18.6	55.5	12.0	10.3
	T8	**690.0 a**	12.60 d	0.019	**20.6**	340. 0 c	67.2	**14.5**	**12.5**	**590.60 a**	11.50 e	0.023	338.0 c	19.3	57.4	12.3	10.6
	T9	650.0 ab	**15.30 a**	0.023	18.3	383.0 ab	63.3	13.6	11.7	550.60 b	**15.50 a**	0.028	388.0 a	17.6	53.5	11.6	10.1
	T10	680.00 a	**15.70 a**	0.021	**19.7**	**393.3 a**	66.4	14.3	12.3	570.00 ab	**14.10 b**	0.024	355.0 b	17.9	55.4	11.9	10.3
	T11	620.0 bc	**11.80 e**	0.019	18.6	287.3 d	61.0	13.1	11.2	520.0 b	12.60 d	0.024	315.0 d	17.3	50.6	10.9	9.4
	T12	650.0 b	**10.50 f**	0.016	19.3	257.6 e	63.5	13.7	11.8	540.0 ab	11.80 e	0.021	295.0 e	18.7	52.5	11.3	9.7
	CV	10.6	6.7		4.1	10.9	3.6	2.7	2.3	9.5	15.74	-	15.7	3.7	3.1	1.9	1.6
	LSD$_{0.05}$	21.3	2.62		3.7	35.5	1.7	0.95	0.80	14.3	3.48	-	17.5	2.1	1.3	0.87	0.55
Elevated Temperature	T1	130.33 e	10.80 e	0.083	9.7	271.33 f	12.8	2.9	2.4	110.00 e	12.80 g	0.116	320.0 f	8.6	11.2	2.3	2.0
	T2	330.67 bc	16.10 a	0.048	12.3	**440.0 a**	**32.2**	6.9	6.0	300.33 d	15.50 b	0.051	388.0 b	14.7	29.3	6.3	5.4
	T3	360.00 ab	14.50 bc	0.040	12.5	362.50 bc	35.2	7.5	6.5	310.67 cd	15.10 c	0.048	378.0 c	11.6	30.2	6.4	5.6
	T4	310.60 d	**13.30 c**	0.043	13,3	330.60 c	30.2	6.4	5.6	330.33 c	14.30 d	0.043	358.0 d	11.5	32.1	6.9	5.9
	T5	320.67 c	16.50 a	**0.051**	11,7	390.67 b	31.4	6.7	5.8	300.00 d	16.10 ab	0.053	403.0 ab	9.8	29.2	6.3	5.4
	T6	350.67 b	15.20 ab	**0.043**	12.0	380.83 b	34.2	7.3	6.3	310.00 ab	15.60 ab	0.050	390.0 b	11.7	30.1	6.5	5.6
	T7	360.00 ab	15.50 ab	0.043	13.2	**395.3 ab**	**35.1**	7.5	6.6	340.33 b	15.90 a	0.046	398.0 ab	12.5	33.1	7.1	6.2
	T8	380.70 a	14.90 b	0.039	13.7	385.00 b	37.1	8.0	6.9	370.00 a	15.70 ab	0.042	393.0 ab	13.1	36.0	7.8	6.7
	T9	350.3 b	**16.30 a**	**0.046**	12.1	365.70 bc	34.2	7.3	6.4	330.33 c	16.80 ab	0.051	420.0 a	12.6	32.1	6.9	5.9
	T10	**380.00 a**	**16.10 ab**	**0.042**	**12.7**	**338.0 bc**	37.0	7.9	6.9	360.67 ab	15.70 ab	0.043	393.0 ab	13.5	35.2	7.5	6.5
	T11	**340.0 cd**	12.50 cd	0.036	**12.3**	**313.0 d**	**33.1**	7.1	6.2	310.0 cd	13.80 e	0.045	345.0 e	12.3	30.2	6.5	5.6
	T12	**360.0 ab**	11.30 d	**0.031**	**12.6**	**288.0 e**	**35.1**	7.5	6.5	330.0 c	12.50 f	0.037	313.5 g	12.8	32.1	7.0	5.9
	CV	**5.6**	**11.03**		**3.1**	**9.7**	**3.5**	3.1	2.6	9.67	11.84	-	1.84	2.7	4.1	3.7	2.8
	LSD$_{0.05}$	**52.67**	**2.94**		**1.78**	**73.66**	**1.8**	1.3	0.87	51.85	2.91	-	72.97	1.65	1.9	1.1	0.58

Note: T1: Control, T2: NPKS 100%, No amendments, T3: NPKS (80%) + 20% NPKS from azolla biofertilizer, T4: NPKS (60%) + 40% NPKS from azolla biofertilizer, T5: (80%) NPKS + 20% NPKS from Rice husk biochar, T6: (60%) NPKS + 40% NPKS from Rice husk biochar, T7: (80%) NPKS + 20% NPKS from Vermicompost, T8: 60%) NPKS + 40% NPKS from Vermicompost, T9: (80%) NPKS + 20% NPKS from Sugarcane Pressmud, T10: (60%) NPKS + 40% NPKS from SPM, T11:80% NPKS + 20% NPKS from SF, T12: 60% NPKS + 40% NPKS from SF.

During dry boro season rice cultivation, the maximum grain yield 800 - 830 g/m^2, 770 - 800 g/m^2, 760 - 790 g/m^2, 760 - 780 g/m^2 were recorded with vermicompost (T7, T8), enriched SPM (T9, T10), Azolla biofertilization (T3, T4) and rice husk biochar (T5, T6) amendments at ambient temperature, which decreased drastically at elevated temperature condition in the greenhouse (Table 2).

In general, grain yield was decreased by 44.0% - 55.0% (Table 2) under elevated temperature condition. Akter et al. (2017) reported that rice grain yield was decreased by 30% - 52% under 2˚C - 3˚C higher than ambient temperature during dry boro season rice cultivation. Net photosynthetic CO$_2$ assimilation rate was 15.6 - 16.3 (μmol·m^{-2}·S^{-1}) at ambient temperature (29˚C - 31˚C), which increased significantly ($p < 0.05$) with azolla biofertilization, vermicompost, silicate and enriched SPM amendments, however, decreased sharply under elevated temperature (3˚C higher than ambient temperature). Combined application of organic and inorganic fertilizers (IPNS) significantly influenced N, P, K uptake by boro rice and aman rice cultivars under ambient and elevated temperature condition. Under ambient temperature condition, the increase in N uptake by rice plant over NPKS (100%) fertilized rice plant ranged 5% - 15%, where maximum (15%) increase was found by Vermicompost and SPM (14%) amendments. In case of P and K, uptake were increased by 6% - 16% and 8% - 15% compared to NPKS (100%) fertilized rice plant. However, under elevated temperature condition N, P.K uptake by rice plant drastically decreased, which affected rice grain yield to decrease significantly ($p < 0.01$).

Table 2. Rice yield, Cumulative CH_4 emissions and GWPs with soil amendments under ambient and elevated temperature (dry season irrigated rice cultivation).

Treatment		BRRI dhan 89								BINA dhan-10							
		Grain yield (g/m²)	Cumulative CH_4 (g/m²)	Yield scale CH_4 emission	CO_2 assimilation rate (μmol·m^{-2}·S^{-1})	GWPs (kgCO$_2$ eq·ha^{-1})	Nutrient Uptake (kg/ha)			Grain yield (g/m²)	Cumulative (CH_4 g/m²)	Yield scale CH_4 emission	GWPs (kgCO$_2$ eq·ha^{-1})	CO_2 assimilation rate (μmol·m^{-2}·S^{-1})	Nutrient Uptake (kg/ha)		
							N	P	K						N	P	K
Ambient Temperature	T1	210.00 f	10.63 g	0.051	11.7 e	267.6	25.4	4.4	4.3	190.00 f	8.60 e	0.045	190.00 e	10.9 f	18.7	3.9	3.9
	T2	710.0 e	**13.90 b**	0.019	18.6 d	343.6	69.0	14.9	14.8	630.33 d	13.50 b	0.021	**338.50 c**	16.3 e	37.1	13.2	13.2
	T3	760.6 c	12.80 d	0.016	21.3 c	322.0	74.1	15.9	15.9	660.67 bc	12.63 c	0.022	365.83 b	17.5 d	39.8	13.8	13.8
	T4	790.70 bc	11.60 f	0.015	23.5 b	**292.5**	77.1	16.5	16.5	690.80 b	11.50 d	0.021	364.17 b	18.7 d	40.8	14.5	14.5
	T5	760.3 bc	**14.30 ab**	0.019	19.3 d	**365.5**	73.8	16.0	15.9	650.00 cd	14.30 ab	0.023	382.50 ab	16.8 e	32.0	13.6	13.6
	T6	780.6 bc	**15.10** a	0.017	21.6 c	**378.0**	75.0	16.3	16.3	680.60 ab	**15.60 a**	0.019	**391.33 a**	17.3 d	34.1	14.2	14.2
	T7	800.6 ab	**13.50 ab**	0.018	24.7 b	373.3	77.1	16.7	16.7	700.50 b	12.70 ab	0.022	**370.6 ab**	21.5 b	40.8	14.6	14.6
	T8	830.0 a	13.10 b	0.016	27.5 a	392.5	80.6	17.3	17.3	720.60 a	13.10	0.022	338.6 c	23.7 a	43.7	15.1	15.1
	T9	770.80 bc	**14.90 a**	0.019	23.6 b	345.0	74.2	16.1	16.1	670.70 bc	**14.60 ab**	0.023	**373.3** a	20.8 c	37.9	14.1	14.1
	T10	800.50 ab	**15.30 a**	0.017	24.3 b	**373.6**	76.7	16.7	16.8	690.00 b	**14.70 ab**	0.021	**383.5 ab**	22.3 b	40.8	14.5	14.5
	T11	730.5 d	12.30 e	0.016	19.6 d	**307.5**	70.9	15.3	15.3	640.50 bc	12.50 c	0.019	**312.5 cd**	17.3 d	37.9	13.4	13.4
	T12	745.7cd	10.50 f	0.014	20.5 c	**272.5**	71.9	15.5	15.5	670.60 bc	11.30 d	0.017	**282.5 d**	18.5 d	39.8	14.1	14.1
	CV	10.65	11.58 f	-	6.3	0.21	4.3	0.95	1.1	11.7	8.96	-	8.96	5.7	4.7	2.5	2.6
	$LSD_{0.05}$	70.60	2.56	-	3.7	1.17	0.87	0.28	0.24	55.3	2.17	-	54.42	2.9	2.1	0.87	1.3
Elevated Temperature	T1	130.67 d	12.90 e	0.010	9.8 f	297.50	18.4	2.8	2.7	110.67 d	12.50 e	0.114	310.00 e	9.7	10.7	2.4	2.3
	T2	390.33 c	15.30 b	0.038	16.7 e	**383.50**	61.2	8.1	8.2	360.33 c	14.30	0.039	**358.50 c**	14.6	35.1	7.5	7.5
	T3	410.00 b	14.47 c	0.035	18.5 c	363.67	64.1	8.5	8.6	370.00 bc	13.60 b	0.039	365.60 bc	15.9	36.0	7.8	7.7
	T4	420.33 b	13.60 d	0.032	19.8 b	345.0	67.0	8.8	8.8	380.67 b	11.70 bc	0.036	340.0 d	16.6 c	36.9	7.9	8.0
	T5	335.90 bc	**16.70 a**	**0.049**	17.1 d	**418.3**	62.1	7.1	7.1	330.7 bc	**15.30 c**	0.046	383.0 ab	15.3	32.1	6.9	7.1
	T6	350.33 bc	**17.30 a**	0.042	17.6 d	**433.5**	63.1	7.3	7.3	350.67 ab	**16.10 d**	0.042	**402.6 a**	15.8	34.0	7.3	7.3
	T7	420.67 b	15.60 ab	0.037	18.5 c	408.0	68.0	8.8	8.8	400.00 ab	14.50	0.037	379.3 b	17.3 b	38.8	8.4	8.4
	T8	450.00 a	14.70 bc	0.032	20.6 a	393.0	69.9	9.4	9.4	430.33 a	14.10	0.033	358.0 cd	17.8 a	41.8	9.1	9.1

Continued

Elevated Temperature	T9	390.33 bc	**16.80** b	0.039	17.9 d	**420.0**	65.1	7.9	8.2	390.7 ab	**15.60**	0.037	**390.0 ab**	16.7	37.9	8.2	8.2
	T10	420.00 b	**17.50** bc	0.035	18.3 c	**438.0**	67.0	8.8	8.8	410.00 a	**15.10**	0.033	**403.3 a**	17.3 b	39.8	8.6	8.6
	T11	390.60 bc	13.50 d	0.034	17.5 d	**337.0**	64.1	8.1	8.2	370.6 b	11.50	0.031	**333.5 d**	16.1 c	36.0	7.8	7.8
	T12	410.70 b	12.10 f	0.029	17.8 d	**302.0**	66.1	8.6	8.6	380.3 ab	10.6 f	0.027	**283.5 f**	16.3 c	37.2	7.9	8.1
	CV	11.6	6.58		3.5	6.58	4.9	3.3	2.6	10.7	7.13		9.3	2.1	3.7	3.3	3.9
	$LSD_{0.05}$	31.8	1.73		1.87	39.7	1.15	0.75	0.35	45.6	1.94		41.6	1.6	1.5	0.93	1.1

Note: T1: Control, T2: NPKS 100%, No amendments, T3: NPKS (80%) + 20% NPKS from azolla biofertilizer, T4: NPKS (60%) + 40% NPKS from azolla biofertilizer, T5: (80%) NPKS + 20% NPKS from Rice husk biochar, T6: (60%) NPKS + 40% NPKS from Rice husk biochar, T7: (80%) NPKS + 20% NPKS from Vermicompost, T8: 60%) NPKS + 40% NPKS from Vermicompost, T9: (80%) NPKS + 20% NPKS from Sugarcane Pressmud, T10: (60%) NPKS + 40% NPKS from SPM, T11:80% NPKS + 20% NPKS from SF, T12: 60% NPKS + 40% NPKS from SF.

3.4. Soil Properties after Rice Harvest

A significant ($p < 0.05$) improvement in soil physico-chemical properties with combined application of Azolla biofertilizer, rice husk biochar, vermicompost, sugarcane press mud compost and silicate fertilization alongwith NPKS fertilizer were found just before rice harvesting stage (Table 3).

Table 3. Influence of Soil amendments on soil properties after rice harvest.

Treatment	Soil porosity (%)	Soil bulk density (g/cm³)	pH	Eh (mV)	SOC (g/kg soil)	LOC mg/g soil	POXC (mg/kg soil)	T-N (%)	Available P (mg/kg)	Exchangeable K (cmole⁺/kg soil)	SO_4^{2-} (mg/kg)	Available SiO_2 (mg/kg)	Free iron oxide (g Fe/kg)
T1	44.67 e	1.22 a	6.50 e	−39.7	10.3 d	1.87	107.6	0.13 d	12.63 c	0.16	13.6	57.13 e	2.73 e
T2	47.00 d	1.20 ab	6.58 e	−28.6	11.6 c	3.15	145.3	0.23 ab	11.70 cd	0.29	19.6	66.7 cd	3.47 d
T3	49.60 cd	1.17 bc	6.57 ef	−21.3	12.3 b	2.95	168.7	0.21 ab	11.53 cd	0.71	27.7 d	79.3 d	4.33 c
T4	50.80 c	1.15 c	6.59 f	−15.6	13.6 ab	2.47	179.6	0.24 a	10.43 d	0.78	43.5 cd	93.7 bc	6.67 c
T5	51.00 c	1.14 cd	6.70 b	−20.3	13.7 ab	3.3	173.5	0.18 c	15.93 ab	0.38	23.7	107.3 c	5.3 b
T6	53.67 de	1.13 cd	6.73 b	−16.7	14.3 a	3.6	187.6	0.20 b	14.60 b	0.47	33.8	114.6 b	6.60 ab
T7	49.67 b	1.19 ab	6.60 c	−20.5	11.7 c	3.2	135.3	0.21 ab	12.70 c	0.75	22.7	74.3 d	3.77 a
T8	51.00 bc	1.18 b	6.65 d	−18.6	12.3 b	3.3	156.7	0.23 ab	12.53 c	0.89	27.5	79.6 c	4.37 c
T9	53.00 ab	1.14 cd	6.73 a	−21.7	13.3 ab	3.5	171.6	0.21 ab	16.67 a	0.65	37.6	85.7 c	5.6 c
T10	55.67 a	1.12 d	6.76 a	−18.3	14.6 a	3.7	189.3	0.23 ab	15.37 ab	0.74	49.3	116.6 b	7.7 b
T11	50.3 c	1.16 bc	6.87	−15.3	10.7 d	2.1	165.7	0.17 c	13.7	0.87	35.7	127.6 ab	6.3 ab
T12	51.7 ab	1.14 cd	6.90	−12.6	11.6 c	1.95	175.3	0.19 bc	14.5	0.95	48.3	138.5 a	8.6 a
CV	4.7	2.6	0.35	−5.76	4.6	1.28	9.7	8.3	6.1	0.45	9.6	9.6	7.3
LSD	2.198	0.02	0.03	2.142	1.504	0.67	7.6	0.03	1.404	0.13	1.727	3.25	1.575

Note: T1: Control, T2: NPKS 100%, No amendments, T3: NPKS (80%) + 20% NPKS from azolla biofertilizer, T4: NPKS (60%) + 40% NPKS from azolla biofertilizer, T5: (80%) NPKS + 20% NPKS from Rice husk biochar, T6: (60%) NPKS + 40% NPKS from Rice husk biochar, T7: (80%) NPKS + 20% NPKS from Vermicompost, T8: 60%) NPKS + 40% NPKS from Vermicompost, T9: (80%) NPKS + 20% NPKS from Sugarcane Pressmud, T10: (60%) NPKS + 40% NPKS from SPM, T11: 80% NPKS + 20% NPKS from SF, T12: 60% NPKS + 40% NPKS from SF.

Azolla biofertilizer, rice husk biochar, vermicompost and sugarcane press mud increased soil porosity, SOC, T-N, soil pH, available phosphate, available silica (SiO_2), sulphate, and free iron oxides in the post-harvest soils. Soil redox status also increased with azolla biofertilization, sugarcane press mud and silicate amendments, probably due to the cumulative effects of free iron oxides and sulphate which acted as electron acceptors, thereby, decreased methane production and eventually reduced CH_4 emission (Jackel & Schnell, 2000; Ali et al., 2008). Increased SOC with azolla biofertilizer, biochar and silicate amendments could be due to the slow decomposition of added materials and enhanced rice growth such as shoot and root biomass production, which contributed to the accumulation of SOC at rice harvesting stage. The maximum concentration of available silica, free iron oxide, available Fe, available Mn, S, P and K were found in the amended soils, which controlled CH_4 emissions. Jagadeesh Babu et al. (2006) reported that K induced higher oxidizing conditions in the rhizosphere of the rice plants, thereby inhibited CH_4 formation and its subsequent release to the atmosphere.

3.5. Correlations of CH_4 Emissions with Selected Rice Plant and Soil Properties

There were positive correlations of seasonal cumulative methane flux with the rice plant productive tillers/hill, aboveground biomass, grain yield and LOC (**Table 4**), being supported by Gogoi et al., (2005), while negative correlations were found with soil porosity, exchangeable K, soil Eh, available SiO_2, available P_2O_5, sulphate and free iron oxides content in soil, being supported by our previous research studies Ali et al. (2008, 2015).

Table 4. Pearson's Correlation Co-efficient of CH_4 emissions with selected rice plant growth, yield components and soil properties.

		Correlation coefficient (r)
Growth and yield components	Plant height (cm)	0.451
	Productive tillers·hill^{-1}	0.558*
	Above-ground biomass (g·hill^{-1})	0.687**
	Grain yield	0.648**
	Harvest index	0.556**
Soil properties	Soil porosity	−0.746***
	LOC	0.689**
	Soil pH	−0.359
	Soil Eh	−0.784***
	Available P_2O_5	−0.536*
	Available SiO_2	−0.648**
	Free iron oxide	−0.689**
	Ex. K	−0.487*
	SO_4^{2-}	−0.746***

4. Discussion

In paddy soil ecosystem, iron reduction mainly accounts for the decomposition of soil organic matter under anoxic conditions which ultimately contributes to methane production. In our study, the increasing trend of CH_4 emission rate from active tillering to flowering stage might be due to the availability of labile organic carbon (LOC) and development of intense reducing conditions (Eh value −100 mV to −240 mV) in the rice rhizosphere, being supported by Adhya et al. (1994); Neue (1993), van der Gon, et al., (1995) and Inubushi et al., (1997). It was also observed that CH_4 emission rates in rice husk biochar, and sugarcane pressmud amended rice planted soils were higher than chemical (NPKS) fertilized, azolla biofertilized, vermicompost and silicate fertilized rice planted soils. This may be due to the rapid decomposition of soil organic matter and availability of labile organic C from the rice husk biochar (C/N ratio 44:1) and sugarcane pressmud (C/N ratio 28:1) amended soils.

Among the amendments, silicate fertilizer and Azolla biofertilizer showed significantly ($p < 0.05$) lower CH_4 emission rate compared to other treatments, which may be due to the availability of free iron oxides, sulphate, Mn etc., being acted as electron acceptors, thereby suppressed methane production activity under improved rice rhizospheric redox status. In addition, the decreased CH_4 emission rate at rice plant maturation could be due to the aging effect and accumulation of electron acceptors such as free iron oxides, sulphate etc. in rice rhizosphere, which enhanced methane oxidation, thereby decreased CH_4 emission. This was supported by Aulakh et al. (2000) and Ali et al. (2008). Jugsujinda & Patrick (1996) and Jackel & Schnell (2000) reported that the ferric iron ($Fe^{3+)}$ reduction process delayed methane production, although methane production rate was maximum at flowering stage under intensive soil redox potential status (Eh value −250 mV).

In this study, the maximum seasonal cumulative CH_4 flux (15.67 - 15.90 g/m^2) with mean GWP 391.0 kgCO$_2$ eq·ha^{-1} and (15.30 - 15.70 g/m^2) with mean GWP 387.0 kg CO$_2$ eq·ha^{-1}) were found in rice husk biochar and sugarcane pressmud amended rice planted soils; whereas silicate fertilization (10.50 - 12.30 g/m^2, mean GWP 285 kg CO$_2$ eq·ha^{-1}), Azolla biofertilization (11.60 - 12.80 g/m^2, mean GWP 305 kg CO$_2$ eq·ha^{-1}), and control treatment (8.6 - 10.63 g/m^2, mean GWP 240 kg CO$_2$ eq·ha^{-1}) reveled significantly lower seasonal CH_4 flux. On average, seasonal cumulative CH_4 fluxes were decreased by 25.0%, 14.0%, 9.0% during wet aman season; 19.0%, 13.0% and 5.0% during boro rice cultivation with silicate fertilizer, azolla biofertilizer and vermicompost amendments, respectively. On the other hand, rice husk biochar and SPM amendments increased CH_4 fluxes by 6.0% - 9.0% and 2.0% - 9.0% respectively. It has already reported that cyanobacterial mixture plus *Azolla microphylla* applied to flood water rice field, enhanced CH4 oxidation and eventually decreased CH_4 emission (Bharati et al., 2000; Prasanna et al., 2002). Zhang et al. (2010) reported that biochar amendment increased rice yield by 12% - 14% in unfertilized soils and by 9% - 12% in N fertilized soils, respectively. They also found that total soil

CH_4–C emissions were increased by 34% - 41% in soils amended with biochar. Silicate fertilizer, azolla biofertilizer, vermicompost and sugarcane pressmud compost amended soils showed significantly higher amount of free iron oxides (Fe_2O_3), sulfate S, available SiO_2 compared to other treatments treated soils. Ali et al. (2015) reported that seasonal yield scaled CH_4 and N_2O emissions were decreased by combined application of NPK with silicate slag, biochar, phosphogypsum, etc. in Republic of Korea, Japan and Bangladesh paddy soils.

Rice cultivars also showed variation in regards to cumulative CH_4 fluxes, yield scaled CH_4 flux and GWPs. BRRI dhan 87 revealed comparatively higher seasonal cumulative CH_4 fluxes, yield scaled CH_4 flux and GWPs than BRRI dhan 71 during wet aman rice growing season; while higher seasonal cumulative CH_4 fluxes, yield scaled CH_4 flux and GWPs were found in BRRI dhan 89 compared to BINA dhan 10 cultivation during irrigated boro rice cultivation. In general, elevated temperature increased total cumulative CH_4 fluxes, yield scaled CH_4 flux and GWPs irrespective of rice cultivars and growing seasons. In this study, the mean seasonal Aman rice grain yield was recorded 550 g/m^2 in chemicals fertilized (T2: 100% NPKS) rice planted pot, which was increased by 22.7%, 20.9%, 19.0%, 15.0% and 12.7% with vermicompost, sugarcane pressmud, azolla biofertilizer, silicate fertilizer and rice husk biochar amendments. During irrigated boro season, the mean grain yield was found 680 g/m^2, which was increased by 19.8%, 15.4%, 13.9%, 13.2% and 11.0% with vermicompost, sugarcane pressmud compost, azolla biofertilizer, rice husk biochar and silicate fertilizer amendments respectively. The higher grain yield in the amended soils might be due to the higher availability of nutrients (N, P.K, S, K, Si, Ca, Mg etc.) to rice plant (Ali et al. 2008). Akter et al. (2017) reported that maximum rice grain yield (46 g/Pot) was found in BINA dhan 17 with Ca-silicate amendments (10 g/Pot), while lowest grain yield (26 g/Pot) was recorded in the control Pot. Ali et al., (2012) reported that silicate fertilization with urea and silicate in combination with ammonium sulphate reduced total CH4 flux by 18% - 23% and 21% - 26%, respectively, whereas rice grain yield was increased by 18% - 24% and 16% - 18%, respectively in rice paddy ecosystems around Mymensingh. Further, it has been reported that azolla anabaena in combination with urea and silicate fertilization decreased total seasonal CH_4 flux by 12% and increased rice grain yield by 10.6%; whereas cattle manure compost in combination with urea and silicate fertilizer decreased total seasonal CH_4 flux by 5.0% and increased rice grain yield by 15.0% (Ali et al., 2014). In this study, rice grain yield was decreased by 44.0% - 55.0% (**Table 2**), under elevated temperature condition, irrespective of treatments and cultivars., which may be due to heat stress at flowering to anthesis period, thereby decreased net CO_2 assimilation rates and photosynthetic productivity. Borell et al. (1997) reported 16% - 34% yield loss under elevated temperature conditions compared to ambient temperature condition in raised bed rice cultivation. Mon et al. (2024) reported that combined application of rice husk biochar (5 t/ha) and chicken manure compost increased rice grain yield without increasing CH_4 and N_2O emissions as well as GWPs. Maniruzzaman et al. (2018) reported that rice grain yield reduction would be 5%, 12%, 17% and 23% with temperature rises by 1˚C, 2˚C, 3˚C and 4˚Cover control (ambient) temperature at 380 ppm CO_2. Akter et al. (2017) reported that rice grain yield was decreased by 30% - 52% under 2˚C - 3˚C higher than ambient temperature during dry boro season rice cultivation.

The feasible soil amendments were found azolla biofertilizer, vermicompost and sugarcane pressmud considering availability to rice growers, economic feasibility, rice productivity as well as mitigating regional to global warming potential from rice farming.

5. Conclusion

Rice cultivar BRRI dhan 87 revealed comparatively higher seasonal cumulative CH_4 fluxes and GWPs than BRRI dhan 71 during wet aman rice growing season; while BRRI dhan 89 showed higher cumulative CH_4 flux and GWPs than BINA dhan 10 during irrigated boro rice cultivation. Replacement (20% - 40%) of inorganic fertilizers (NPKS) with vermicompost, Azolla biofertilizer, enriched SPM compost, rice husk biochar and silicate fertilization increased rice yield by 13.0% - 23.0% and 11.0% - 19.0% during aman and boro seasons, respectively. However, seasonal cumulative CH_4 fluxes were decreased by 9.0% - 25.0% during wet aman season and 5.0% - 19.0%, during boro rice cultivation with silicate fertilizer, azolla biofertilizer, SPM and rice husk biochar amendments. The maximum reduction in seasonal cumulative CH_4 flux was found with silicate fertilization (19.0% - 25.0%) and azolla biofertilizer amendments (9.0% - 13.0%), whereas maximum grain yield increments were found 13.0% - 14.0%, 9.0% - 10.0% and 8.0% - 9.0% with vermicompost, sugarcane pressmud compost, and azolla biofertilizer amendments respectively compared to recommended chemical fertilization (100% NPKS) at ambient air temperature condition. However, elevated air temperature stress decreased rice yield by 43.0% - 50.0% and 45% - 48.0% in aman and boro season rice cultivation respectively; while increased cumulative CH_4 flux by 4.0% - 8.0% and 10.0% - 15.0% irrespective of soil amendments. The research findings may be useful to the National level policy makers for reducing chemical fertilizer recommendation and including feasible soil amendments like Azolla biofertilize, vermicompost and enriched sugarcane pressmud for sustainable rice productivity and mitigating global warming potential in the changing climatic conditions.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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