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Mitigating Global Warming Potentials and Optimizing Rice Productivity through Synergistic Effects of Irrigation Practices and Soil Amendments in Drought Prone Areas of Bangladesh

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Abstract

Irrigation water availability has become a major crisis for rice cultivation in the North-West Barind Tract areas of Bangladesh. Therefore, field experiments were conducted at Mohadebpur, Naogaon and Nachole, Chapainawabganj districts to find out the suitable water savings irrigation technique for sustaining rice productivity and controlling global warming potentials with different combinations of vermicompost, phosphogypsum and chemical fertilizers. The maximum grain yield 6760 - 6800 kg·ha^{-1} were recorded in Vermicompost (10 t·ha^{-1}) with Phospho-gypsum (2.5 t·ha^{-1}) amendments along with reduced amount of Nitrogen fertilizer (N 25% of the recommended doze), followed by 6680-6700 kg ha^{-1} (Vermicompost 7.5 t·ha^{-1} + phospho-gypsum 2.0 t·ha^{-1} + N 50% RFD) under AWD irrigation. Aerobic irrigation saved 37.0% - 39.0% irrigation water, followed by 24.5% - 26.0% in alternate wetting and drying irrigation compared to the total required water (30,807 m^3 ha^{-1}) in conventional irrigation. The average cost for irrigation was calculated at 14,825 - 15,100 Tk·ha^{-1} under conventional irrigation, which decreased to 11,775 - 11,850 Tk·ha^{-1} for alternate wetting and drying, 9750 - 9825 Tk·ha^{-1} for aerobic irrigation, respectively. The seasonal cumulative CH_4 emission and GWPs for boro season rice cultivation significantly decreased with AWD and aerobic irrigation practices. The maximum seasonal cumulative CH_4 emission, 221 kg/ha and 195 - 217 kg/ha, was recorded in Vermicompost (2.5 t/ha) with Phospho-gypsum (1.0

t·ha^{-1}) amendments under conventional irrigation, which were decreased by 21% - 23.0% and 24% - 25.0% for AWD and aerobic irrigation practices, respectively. The maximum GWPs value is 4875 - 5425 kg CO_2-eq·ha^{-1} was estimated for conventional irrigation with vermicompost (2.5 t·ha^{-1}) plus Phospho-gypsum (1.0 t·ha^{-1}) amendments, which was decreased by 19% - 21% for AWD and 22% - 23% for aerobic irrigations, respectively. Soil physico-chemical properties were also improved with 7.5 - 10 t·ha^{-1} vermicompost and 2.0-2.5 t·ha^{-1} Phospho-gypsum amendments. Conclusively, the integration of environment friendly irrigation water management through alternate wetting and drying (AWD), and aerobic irrigation with Vermicompost amendments (7.5 - 10 t·ha^{-1}) and half of the recommended Nitrogenous fertilizer application may enhance the synergistic effect towards optimum rice productivity, increased water productivity, improved irrigation cost savings and ensure mitigation of GWPs during dry season irrigated rice cultivation.

Keywords

Rice Paddy, CH_4, Water Productivity, Vermicompost, Phospho-Gypsum, AWD, Aerobic Irrigation, GWPs

1. Introduction

Rice is one of the most important cereal food crops in Bangladesh, which covers 75% of total cropland area and 80% of the total irrigated area in the country (IRRI, 2010). Bangladesh is the 4th largest per-head rice-consuming and rice-producing country globally (FAOSTAT, 2015). The country population is almost 170 million and is expected to be 210 million in 2050 (United Nations, 2015). Due to increasing population growth, the country needs more rice production in the future, which may influence methane (CH_4) emissions from paddy fields. In Bangladesh, about 70% of the fresh water is diverted to irrigate rice fields. It has been estimated that 3000-5000 litres of water are required to produce 1.0 kg of rice (SAIC, 2007). Rice cultivation simultaneously contributes to the emission of methane (CH_4) and nitrous oxide (N_2O) gases. It has already been reported that rice fields contribute about 30% and 11% of global agricultural CH_4 and N_2O emissions, respectively (IPCC, 2007). The magnitude of CH_4 emissions from rice plants is regulated by complex and dynamic interactions among the plants, environment, and microorganisms (Das & Baruah, 2008). CH_4 produced in flooded rice soils is emitted by molecular diffusion, ebullition, or plant-mediated transport to the atmosphere. The major factors influencing CH_4 emission from paddy field are irrigation water management and drainage (Ma et al., 2013; Ali et al., 2021), organic amendments (Ali et al., 2021; Win et al., 2020), and rice crop establishment methods (Liu et al., 2013). The agriculture sector depends mainly on imported agro-chemical inputs, i.e., chemical fertilizers and pesticides, with high costs (Kaplan, 2016). Partial substitution of these chemical fertilizers with organic inputs may accelerate rice productivity and improve soil fertility.

Water management practices are vital factors to sustain rice productivity and control GHG emissions in paddy fields (Cheng et al., 2022). In major Asian rice-growing countries, a few water-saving irrigation methods have already been developed to reduce irrigation water and enhance water productivity, such as alternate wetting and drying (AWD) irrigation (Lampayan et al., 2013), aerobic rice system (Wang et al., 2002), and dry direct seeding rice (DDS) (Yang et al., 2023). Among them, AWD has quickly become one of the most widespread water-saving irrigation technologies in paddy fields. The AWDI systems save about 20% - 30% irrigation water compared to a conventional irrigation system. Sudhir-Yadav et al. (2011) estimated that AWD irrigation practices saved 50% irrigation water, and this savings could be increased to 70% by aerobic irrigation practices compared to conventional irrigation practices. The sustainability of the irrigated rice systems is increasingly threatened by a scarcity of freshwater resources. It is estimated that 17 million ha of irrigated rice may experience physical water scarcity and 22 million ha may face economic water scarcity in Asia by 2025 (Tuong & Bouman, 2003), which led to the adoption of water-saving AWD and aerobic rice systems.

In Bangladesh, the scarcity of irrigation water for rice cultivation has been increasing, which may affect rice production. Therefore, the efficiency of water use in irrigated rice production systems has to be developed. AWD irrigation techniques were introduced in Bangladesh in 2005, but still, only 5% of farmers used them. The studies show that the alternate wetting and drying techniques are reducing the environmental impacts without production loss. There are two great challenges of AWD for the country: one is growing more food for the expanding population, and the other is adverse environmental impacts of rice production by using AWD irrigation technologies.

Aerobic rice is a new term given by the IRRI for high-yielding rice grown under non-flooded conditions in non-puddled and unsaturated (aerobic) soil moisture contents (Bouman & Tuong, 2001). Soils are kept aerobic throughout the growing season in an aerobic rice production system. The aerobic irrigation is a potential water-saving technique through which irrigation water is supplied to keep the soil moisture content up to the field capacity level except wet soil conditions around early tillering, panicle initiation, and flowering stages (Bouman et al., 2007). Rahman and Masood (2012) reported that *Boro* rice cultivation following aerobic irrigation practice saved 50% - 60% irrigation water and increased farm income by reducing cost of production. By reducing water use during land preparation and limiting seepage, percolation, and evaporation, aerobic rice lowered total water use by 51% and revealed 32% - 88% higher water productivity than flooded rice (Bouman et al., 2005). The number of laborers utilized in aerobic rice cultivation is also lower compared to flooded rice (Wang et al., 2002), probably due to more labor is required for land preparation, such as puddling, transplanting, and irrigation activities for floodwater rice cultivation.

Barind Tract is located in the North West Hydrological region of Bangladesh, which covers Natore, Sirajganj, Naogaon, Nawabganj, Pabna, Rajshahi, Gaibandha, Jaipurhat, Dinajpur, Rangpur, and Bogura districts. Rice production in these areas faces multiple challenges. This region is characterized by very high temperatures and receives less amount of rainfall than other parts of the country. The annual temperature and rainfall are between 8˚C to 44˚C and 1500 mm to 2000 mm, respectively (Reza & Mazumder, 2005). The seasonal rainfall imbalance is badly affecting the groundwater level and the local agricultural production. The Monsoon season (June to September) covers 80% of the total rainfall of the area, whereas other seasons cover only the remaining 20% of 20% rainfall (Reza & Mazumder, 2005). It has already been reported that groundwater irrigation may become maladaptive in the context of a changing climate, which may deplete aquifers and increase salinity (Islam, 2021). Due to the water crisis, dry season b*oro* rice cultivation is getting difficult, unless any feasible irrigation water savings technology is introduced in the Barind tract areas. Furthermore, the uncertainty and inadequate supply of electricity hampers irrigation water supply, which may affect rice cultivation in the dry season. Therefore, this experiment was conducted at Mohadebpur, Naogaon and Nachole, Chapainawabganj, to determine the feasible water-saving irrigation technique and suitable combination of vermicompost with nitrogenous fertilizer for sustainable rice productivity, increasing water productivity, improving soil fertility, and decreasing GWPs during dry-season irrigated rice cultivation.

2. Materials and Methods

2.1. Experimental Location and Meteorological Conditions in Selected Sites

The study area was located in Natshail village of Mohadebpur upazila of Naogaon district in the north-west region of Bangladesh. Mohadebpur upazila occupies an area of 397.67 sq km, located between 24˚48' and 25˚01' north latitudes and between 88˚38' and 88˚53' east longitudes, at a height of 25 meters above sea level and belongs to the High Barind Tract (AEZ 26). Another study area was located in Jonakipara village of Nachole upazila of Chapainawabganj district in the north-west region of Bangladesh. Nachole upazila occupies an area of 283.67 square kilometers, located between 24˚38' and 24˚51' north latitudes and between 88˚15' and 88˚21' east longitudes at 25 meters above sea level and belongs to the High Barind Tract (AEZ 26). During the experimental period, the average maximum temperatures were recorded as 34.8˚C and 36.14˚C during 2017-2018 and 2018-2019, and the minimum temperatures were recorded as 8.35 and 10.43˚C, respectively. The average monthly humidity during the rice growing season was 65%. However, the monthly average distribution of rainfall from January to April was very low and uneven; the range of effective rainfall was 6.00 mm to 43.2 mm, which indicates the necessity of irrigation water for rice cultivation during dry rabi season.

2.2. Soil Properties of the Field Experimental Sites

The soil was clay loam in texture, having a low status of organic matter, including phosphorus and potassium. The pH of the soil recorded 6.1 - 6.4, organic matter 0.56% - 0.65%, total nitrogen 0.09% - 0.10%, phosphorus (P) 2.62 ppm, exchangeable K 0.16 - 0.20 meq.100 g^{-1} soil and Sulphur 12.9 - 13.6 ppm.

2.3. Experimental Setup According to Irrigation and Soil Amendments Treatments

The experiment was laid out in a randomized complete block design (RCBD) with three replications. The unit plot size was 10 m^2 (5 m × 2 m). Each 10 m^2 plot contained 210 seedlings. To facilitate cultural operations, proper spacing was kept among the plots and blocks. Field experiments were carried out during the periods from December 2017-May 2018 (dry irrigated *Boro* season) and December 2018-May 2019. In this study, three irrigation treatments were followed: Conventional irrigation (Ic), Alternate wetting and drying (AWD), and aerobic irrigation. Under each irrigation practice, four soil amendments were selected: T1: No NPKS, No amendments, T2: NPKS 100% recommended fertilizer (RFD) + Vermicompost (VC) 2.5 $t{\cdot}ha^{-1}$ + Phospho-gypsum (PG) 1.0 $t{\cdot}ha^{-1}$, T3: N (50% RFD) with recommended PKS + VC 7.5 $t{\cdot}ha^{-1}$ + PG 2.0 $t{\cdot}ha^{-1}$, T4: N (25% RFD) with recommended PKS + VC 10.0 $t{\cdot}ha^{-1}$ + PG 2.5 $t{\cdot}ha^{-1}$.

In conventional irrigation, 5 cm of standing water in the experimental field was maintained from rice seedling transplanting to establishment period and irrigation stopped before two weeks of harvesting. In case of AWD irrigation, perforated PVC pipes were installed in the experimental plots 10 days after transplanting (DAT) according to treatments for measuring soil water depletion to follow AWD techniques. The diameter of the pipe was 8 cm and the length was 25 cm. After irrigation water application, water entered through perforations and water level inside the pipe was at the same level as that of outside. With the progress of time when water level depleted in AWD plots, 5 cm irrigation was done when the depleting water table inside the pipe fell 15 cm below ground level.

2.4. Estimation of Water Requirement, Water Savings and Water Productivity

Water requirement for rice cultivation was computed by adding applied irrigation water, effective rainfall during growing season and water for land preparation (Rashid, 1997). Water use expressed as m^3/ha is the amount of irrigation water used at each experimental site that was estimated using a flow meter connected with irrigation pump plus the total amount of rainfall recorded during the rice growing period.

In the study, water saving percentage was calculated as follows:

$$\text{Water Savings}(\%) = \frac{\text{Water supplied in flooded plot} - \text{Water supplied in AWDI/Aerobic plot}}{\text{Water supplied in flooded plot}} \times 100$$

Water productivity is expressed as the ratio of grain yield (kg/ha) per unit water (m^3/ha) supplied, including rainfall (Jaafar et al., 2000) and calculated as follows:

$$\text{Water productivity}\left(\text{kg}/\text{m}^3\right)=\frac{\text{Grain Yield}\left(\frac{\text{kg}}{\text{ha}}\right)}{\text{Total water supplied}\left(\frac{\text{m}^3}{\text{ha}}\right)}$$

2.5. Gas Sampling, Analysis by GC and Estimation of Total Seasonal Cumulative CH_4 Flux

A modified closed-chamber method (Ali et al., 2008; Rolston, 1986) was used to estimate CH_4 emission during rice cultivation. Gas samples were collected by 50ml gas-tight syringes at 0, 15 and 30 minutes after chamber placement over flooded plots at different rice growth stages to get average CH_4 emissions. The dimension of closed chamber was 62 cm × 62 cm × 112 cm. Samples were analyzed to determine CH_4 concentration by gas chromatograph (Shimadzu, GC 2014, Japan) with a Flame Ionization Detector. The temperatures of column, injector and detector were adjusted at 100˚C, 200˚C and 200˚C, respectively. A closed-chamber equation (Rolston, 1986) was used to estimate methane fluxes for every treatment.

$$F=\rho\times V/A\times\Delta c/\Delta t\times 273/T$$

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

Total seasonal methane emission/flux for the entire cropping period was computed by the formula (Singh, 1999): Total CH_4 flux = $\sum_{i=1}^{n}\left(Ri\times Di\right)$, where, Ri = rate of methane flux ($g\cdot m^{-2}\cdot d^{-1}$) in the ith sampling interval, and n = number of sampling intervals.

2.6. CH_4 Flux Calculation

CH_4 flux was calculated based on following equation

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

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/m2/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.

2.7. Estimation of GWP and GHGI

To estimate the GWP, CO_2 is typically taken as the reference gas, and an increase or reduction in emission of CH_4 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 = 25 × CH_4, kg CO_2-equivalents·ha^{-1}) from CH_4 under various agricultural irrigation practices. In addition, the greenhouse gas intensity (GHGI) was calculated by dividing GWP by grain yield for rice (Mosier et al., 2006).

2.8. Investigation of Soil Properties

Soil redox potential (Eh) was measured during rice cultivation at certain time intervals by a glass electrode Eh meter. At·harvesting stage, soil bulk density (BD) was analyzed using cores (volume 100 cm^3, inner diameter 5 cm), filled with fresh moisture soils. The collected core samples were oven dried at 105˚C for 24 h, and then measured the weight of dried core samples was measured. Soil porosity was calculated using BD and particle density (PD, 2.89 Mg·m^{-3}) according to the equation: porosity (%) = (1 − BD/PD) × 100. At·harvesting stage, chemical properties of the collected soil samples were analyzed for organic carbon by wet oxidation method (Allison, 1965), organic matter content by multiplying the percent organic carbon with Van Bemmlen factor of 1.73, total nitrogen by Micro-kjeldhal method (Nelson et al., 1980), available phosphorus by Olsen method (Olsen & Sommers, 1982), exchangeable potassium by Flame photometer (Brown & Lilleland, 1946).

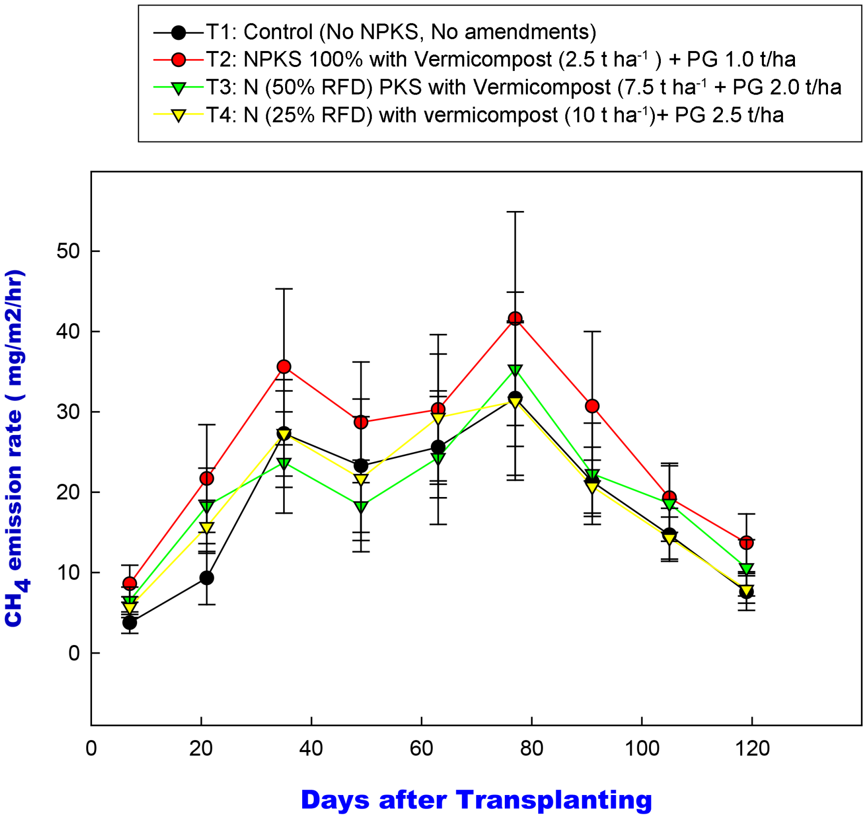
2.9. Statistical Analysis

At first, experimental data were entered into Microsoft Excel. Then, analysis of variance (ANOVA) was performed 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% and 1% significance level.

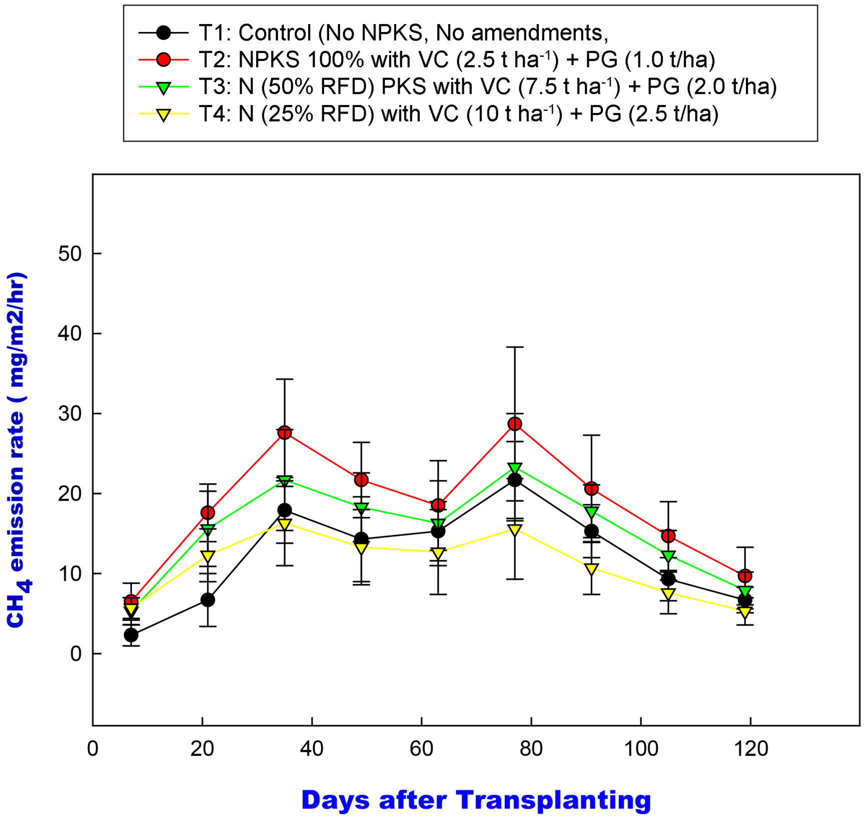
3. Results

3.1. CH_4 Emission Rate under Different Irrigation Practices and Soil Amendments

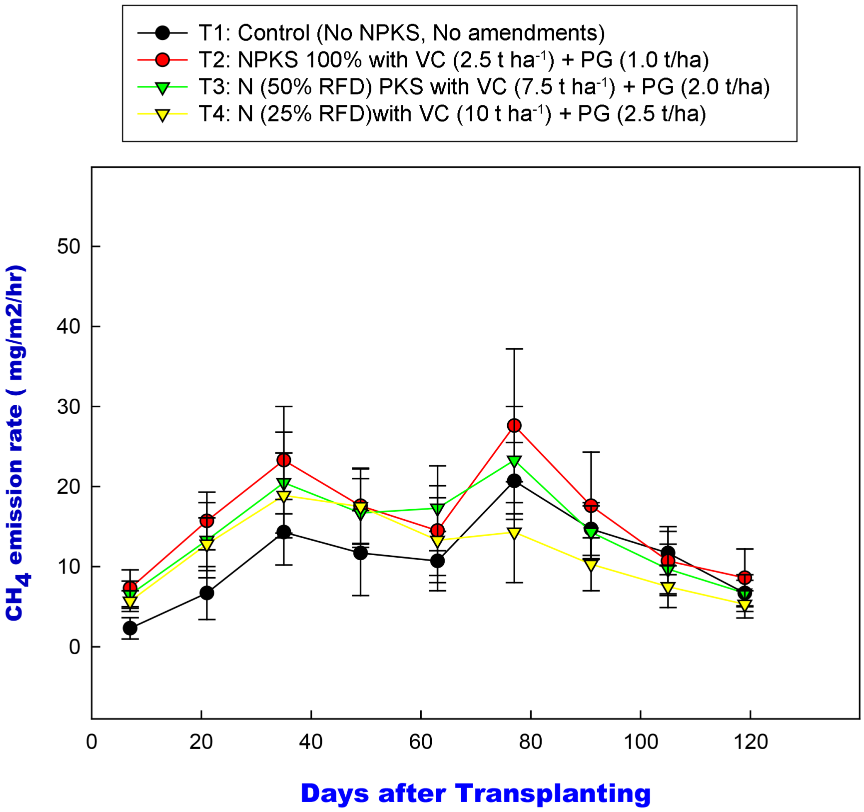
After rice was transplanted in the field, CH_4 emission rate within the first two weeks was low (**Figures 1(a)-(c)**, which increased significantly at active tillering stage (35 DAT) and peaked at flowering to heading stage (77 - 84 DAT). In general, higher CH_4 emission rates were recorded in conventional irrigation practices compared to AWD and aerobic irrigation practices (**Figures 1(a)-(c)**). Among the amendments, vermicompost (VC) at 7.5 - 10.0 t/ha with phosphogypsum (PG) 2.0 - 2.5 t/ha and half of the recommended N-fertilizers showed lower CH_4 emission rates compared to recommended (100%) N-fertilizers with VC 2.5 t/ha and PG 1.0 t/ha. At 77 DAT, CH_4 peak 30 - 35 mg/m^2/hr was observed in recommended chemicals with VC 2.5 t/ha and PG 1.0 t/ha (T2). After that, CH_4 emission rate sharply dropped with rice grain maturation. The least CH_4 emission was observed at 119 DAT before rice harvest.


T1: Control (No NPKS, No amendments)
T2: NPKS 100% with Vermicompost (2.5 t ha-1) + PG 1.0 t/ha
T3: N (50% RFD) PKS with Vermicompost (7.5 t ha-1 + PG 2.0 t/ha
T4: N (25% RFD) with vermicompost (10 t ha-1)+ PG 2.5 t/ha
CH4 emission rate (mg/m2/hr)
0
10
20
30
40
50
0
20
40
60
80
100
120
Days after Transplanting

(a)


T1: Control (No NPKS, No amendments,
T2: NPKS 100% with VC (2.5 t ha-1) + PG (1.0 t/ha)
T3: N (50% RFD) PKS with VC (7.5 t ha-1) + PG (2.0 t/ha)
T4: N (25% RFD) with VC (10 t ha-1) + PG (2.5 t/ha)
CH4 emission rate (mg/m2/hr)
0
10
20
30
40
50
0
20
40
60
80
100
120
Days after Transplanting

(b)



(c)

Figure 1. (a) CH_4 emission rate with different combinations of Vermicompost and NPKS during boro season rice cultivation (Conventional flooding); (b) CH_4 emission rate with different combinations of Vermicompost, NPKs and PG during boro season rice cultivation (AWD); (c) CH_4 emission rate with different combinations of Vermicompost, NPKS and Pcduring boro season rice cultivation (Aerobic irrigation).

3.2. Cumulative CH_4 Flux for Irrigated Boro Rice Cultivation

In this study, maximum cumulative CH_4 flux was observed under conventional irrigation; however, AWD and aerobic irrigation practices significantly reduced the cumulative CH_4 flux for irrigated boro rice cultivation (Table 1). At Mohadebpur, Naogaon experimental field, the highest cumulative CH_4 emission was calculated 221 kg·ha^{-1}·season^{-1} in vermicompost (VC 2.5 t·ha^{-1}) amended field plot (NPKS 100% RFD + phospho-gypsum 1.0 t·ha^{-1}) under conventional irrigation; this decreased to 178.0 kg·ha^{-1} and 170.0 kg·ha^{-1} under AWD and aerobic irrigation practices, respectively. The increasing levels of vermicompost amendments 7.5 - 10.0 t·ha^{-1} and PG 2.0 - 2.5 t·ha^{-1} decreased cumulative CH_4 emissions by 11% - 17%, 13% - 23% and 13% - 21.7% under conventional irrigation, AWD and aerobic irrigation practices compared to Vermicompost (2.5 t·ha^{-1}) amendments with NPKS 100% plus phospho-gypsum (1.0 t/ha). At Nachole, Chapainawabganj district experimental site, the highest cumulative CH_4 was found 195.80 kg·ha^{-1}·season^{-1} (T2: NPKS 100% + Vermicompost 2.5 t·ha^{-1} + phospho-gypsum 2.5 t·ha^{-1}), followed by 172.20 (VC 7.5 t·ha^{-1} with N (50% of recommended dose) and 152.40

$kg \cdot ha^{-1} \cdot season^{-1}$ with VC 10.0 $t \cdot ha^{-1}$ with N (25% of recommended dose) under conventional irrigated field plots. For AWD and aerobic irrigation practices, the seasonal cumulative CH_4 emissions were decreased by 16% - 23.0% and 13% - 21.0% with VC 7.5 - 10.0 t/ha amendments compared to VC 2.5 t/ha application along with chemical fertilizers (**Table 1**).

3.3. Rice Grain Yield during *Boro* Rice Cultivation

Rice grain yield was significantly influenced by irrigation practices and soil amendments. Rice grain yield was significantly increased by AWD irrigation practices compared to conventional and aerobic irrigation practices. At Mohadebpur, the highest grain yield 6530 $kg \cdot ha^{-1}$ was recorded with 10.0 t/ha vermicompost, followed by 6450 $kg \cdot ha^{-1}$ and 6070 $kg \cdot ha^{-1}$ with 7.5 t/ha and 2.5 t/ha vermicompost amendments along with chemical fertilizers under conventional irrigation (**Table 1**). Alternate wetting and drying (AWD) irrigation revealed the highest grain yield 6800 $kg \cdot ha^{-1}$ with 10.0 t/ha vermicompost amendment, followed by 6680 $kg \cdot ha^{-1}$ and 6200 $kg \cdot ha^{-1}$ with 7.5 t/ha and 2.5 t/ha vermicompost amendments. In aerobic irrigation practice, the highest grain yield was found 5650 $kg \cdot ha^{-1}$ at 10.0 t/ha VC application, followed by 5570 $kg \cdot ha^{-1}$ and 5180 $kg \cdot ha^{-1}$ with 7.5 t/ha and 2.5 t/ha VC amendments, respectively.

At Nachole experimental site, rice grain yield was significantly increased by AWD and aerobic irrigation practices. AWD irrigation revealed the highest grain yield, 6850 $kg \cdot ha^{-1}$ followed by 6700 $kg \cdot ha^{-1}$ and 6300 $kg \cdot ha^{-1}$ were recorded with 10 t/ha VC, 7.5 t/ha VC, and 2.5 t/ha VC applications, respectively. In aerobic irrigation, the highest grain yield 5460 $kg \cdot ha^{-1}$ was found with 10.0 t/ha VC application, followed by 5380 $kg \cdot ha^{-1}$ with 7.5 t/ha VC amendment and 5060 $kg \cdot ha^{-1}$ with 2.5 t/ha VC application. In conventional irrigation, the highest grain yield, 6430 $kg \cdot ha^{-1}$ was found with 10.0 t/ha VC application, followed by 6350 $kg \cdot ha^{-1}$ with 7.5 t/ha VC and 5960 $kg \cdot ha^{-1}$ with 2.5 t/ha VC application. The lower grain yield in conventional irrigated field compared to AWD irrigation may be due to waterlogged conditions throughout the growing season, which affected rice yield components and grain yield (**Table 1**).

3.4. Yield Scaled CH_4 Emission (GHGI) during *Boro* Rice Cultivation

At Mohadebpur experimental site, the yield scaled CH_4 emission (GHGI) was significantly decreased with AWDI and aerobic irrigation practices compared to conventional irrigation practices. The highest yield scaled CH_4 emission (GHGI) from the conventional irrigated field plot was found 0.037 kg $CH_4 \cdot kg^{-1}$ (in T2), followed by 0.029 (T3) and 0.027 kg $CH_4 \cdot ha^{-1}$ (T4). In regards to AWD irrigation, the yield scaled CH_4 emission (GHGI) 0.028 kg $CH_4 \cdot kg^{-1}$ yield was found with 2.5 $t \cdot ha^{-1}$ VC amendments (NPKS 100% + Phospho-gypsum 2.5 $t \cdot ha^{-1}$), followed by 0.023 kg $CH_4 \cdot kg^{-1}$ yield and 0.020 kg $CH_4 \cdot kg^{-1}$ yield) with VC amendments 7.5 - 10.0 t/ha. In case of aerobic irrigation, the highest yield scaled CH_4 emission was recorded 0.033 kg $CH_4 \cdot kg^{-1}$ yield followed by 0.027 and 0.026 kg $CH_4 \cdot kg^{-1}$ yield.

At Nachole experimental site, the highest yield scaled CH_4 emission (GHGI) from the continuous irrigated plot was found in 0.032 kg $CH_4 \cdot kg^{-1}$ (T2), followed by 0.027 and 0.025 $kg \cdot ha^{-1}$. Conversely, under AWD treatment, the highest scaled CH_4 emission (GHGI) was recorded 0.025 kg $CH_4 \cdot kg^{-1}$) with VC amendment 2.5 t/ha followed by 0.020 and 0.019 kg $CH_4 \cdot kg^{-1}$ yield. In general, AWD and aerobic irrigation practices reduced yield scaled CH_4 emissions (GHGI) significantly than that of conventional irrigated field plots (Table 1).

3.5. GWPs during *Boro* Rice Cultivation

The GWPs decreased significantly with AWDI and aerobic irrigation practice treatments compared to conventional irrigation practices. At Mohadebpur experimental site, the highest GWPs value 5425 kg CO_2-eq$\cdot ha^{-1}$ was found in conventional irrigated field with 2.5 $t \cdot ha^{-1}$ VC amendments (NPKS 100% RFD + Phospho-gypsum 2.5 $t \cdot ha^{-1}$), which decreased significantly under AWD and aerobic irrigations. The maximum decrease in GWPs were obtained by 20% - 25% and 22% - 27% with 10.0 $t \cdot ha^{-1}$ Vermicompost amendments (plus phospho-gypsum 2.5 $t \cdot ha^{-1}$ + 25% recommended N/ha + recommended PKS/ha) for AWD and aerobic irrigations, respectively.

At Nachole experimental site, the highest GWPs 4875 kg CO_2-eq$\cdot ha^{-1}$ was observed in conventional irrigated field plot with VC amendment 2.5 t/ha (T_2) followed by 4305 and 3810 kg CO_2-eq$\cdot ha^{-1}$ in VC amendment 7.5 t/ha (T3) and VC 10.0 t/ha amendment (T4). In case of AWD irrigation, the highest GWPs was found 4000 kg CO_2-eq$\cdot ha^{-1}$ in VC amendment 2.5 t/ha (T_2) followed by 3365 kg CO_2-eq$\cdot ha^{-1}$ (T3) and 3085 kg CO_2-eq$\cdot ha^{-1}$ T_4. Under aerobic irrigation treatments, the lowest GWP 3025 kg CO_2-eq$\cdot ha^{-1}$ was noticed in VC amended (10 t/ha) field plot (T_4) followed 3695 and 3315 kg CO_2-eq$\cdot ha^{-1}$. In general, higher GWPs were found in conventional irrigated field plots compared to AWD and aerobic irrigations.

3.6. Irrigation Water Savings, Water Productivity and Irrigation Cost Effectiveness for *Boro* Rice Cultivation

At Mohadebpur experimental site, during boro rice cultivation, the required irrigation frequency was 16, average total volume of water was 30,807 $m^3 \cdot ha^{-1}$, average cost for irrigation was 15,100 $Tk \cdot ha^{-1}$ under conventional irrigation. In case of alternate wetting and drying (AWD), the irrigation frequency was 12, average total water volume was 22,800 $m^3 \cdot ha^{-1}$, average cost for irrigation was 11,850 $Tk \cdot ha^{-1}$, average water savings was 26.0% and the average irrigation cost saving was calculated as 3250 $Tk \cdot ha^{-1}$. For aerobic irrigation practice, the required irrigation frequency was 8, average total water volume was 18,838 $m^3 \cdot ha^{-1}$, average cost for irrigation was 9825 $Tk \cdot ha^{-1}$, average water saving was 39.0% and the average irrigation cost saving was 5275 $Tk \cdot ha^{-1}$ (Table 1). At Nachole experimental site, the required no. of irrigation was recorded as 16, average water volume was 29,500 $m^3 \cdot ha^{-1}$, average cost for irrigation was 14,168 $Tk \cdot ha^{-1}$ under conventional irrigation. For AWD irrigation, the required no. of irrigation was 12, the average water volume was 22,275 $m^3 \cdot ha^{-1}$, the average cost for irrigation was 11,775 $Tk \cdot ha^{-1}$; average irrigation water savings was recorded 24.5%; and the average cost savings for irrigation was 3050 $Tk \cdot ha^{-1}$. In case of aerobic irrigation, the required number of irrigation was recorded 8, average water volume was 18,600 $m^3 \cdot ha^{-1}$, average cost for irrigation was 9750 $Tk \cdot ha^{-1}$, average irrigation water savings was 37.0% and the average cost savings for irrigation was 5075 $Tk \cdot ha^{-1}$ (**Table 1**).

Water productivity value (WP) was increased with AWD and aerobic irrigation practices compared to conventional irrigated field plots at both locations. In addition, increasing levels of vermicompost amendments 7.5 - 10 t/ha also influenced towards higher grain yield and ultimately maximized water productivity. Alternate wetting and drying (AWD) irrigation revealed maximum water productivity value 0.270 - 0.297 $kg \cdot m^{-3}$ and 0.295 - 0.297 $kg \cdot m^{-3}$ with vermicompost amendments 7.5 - 10 t/ha at Mohadebpur and Nachole experimental field rice cultivation. Conversely, under aerobic irrigation practice, higher WPI value were recorded 0.285 - 0.295 $kg \cdot m^{-3}$ and 0.288 - 0.291 $kg \cdot m^{-3}$ with vermicompost 7.5 - 10 t/ha amendments compared to other field plots at both locations. In general, AWD and aerobic irrigation practices significantly increased the WPI with vermicompost 7.5 - 10 t/ha amendments (**Table 1**).

3.7. Soil Properties during Rice Cultivation and after Rice Harvest

Soil amendments with vermicompost and phosphogypsum increased soil porosity, SOC, T-N, soil pH, available phosphate, available sulfate, available silicate (SiO_2), and soluble iron oxides in the post-harvest soils (**Table 2**). Comparatively higher soil porosity was observed in AWD and aerobic irrigated field plots amended with higher levels of vermicompost compared to conventional irrigation. Maximum soil porosity 54.5% - 56.7% and 54% - 55% were recorded with VC 10 t/ha plus PG 2.5 t/ha amendments under AWD and aerobic irrigation practices, respectively.

After rice harvest, the soil organic carbon contents were found to be 1.15% - 1.43%, 1.27% - 1.65% and 1.30% - 1.68% in conventional irrigation, AWD and aerobic irrigation practices, respectively (**Table 2**). Comparatively, higher soil organic carbon contents were found in vermicompost (7.5 $t \cdot ha^{-1}$ - 10 $t \cdot ha^{-1}$) amended field plots under AWD and aerobic irrigated conditions. Total N contents also varied in post-harvest soil. The highest N content (0.19%) was found in Vermicompost amended soil (10 $t \cdot ha^{-1}$ with phospho-gypsum 2.5 $t \cdot ha^{-1}$) under AWD and aerobic irrigation practices, while the lowest N was detected (0.11%) in recommended fertilizer (NPKS 100%) applied field soil under conventional irrigation. The available P (23.5 - 31.5 ppm) and SiO_2 (67.5 - 71.3 ppm) contents increased significantly with increasing levels of vermicompost applications under AWD and aerobic irrigations. In addition, higher water soluble sulfate (27.5 - 35.5 ppm) and total dissolved iron contents (10.5 - 13.6 ppm) were detected in the VC 10.0 t/ha and PG 2.5t/ha amended field plots under AWD and aerobic irrigations

Table 1. Effect of irrigation practices and soil amendments on rice yield, cumulative CH_4 flux, yield scaled CH_4 emission, GWPs and WPI for *Boro* rice cultivation at two locations of Barind Tract area.

Irrigation practices and soil amendments		Mohadebpur, Naogaon							Nachole, Chapainawabganj						
		Grain yield ($kg \cdot ha^{-1}$)	Cumulative CH_4 ($kg \cdot ha^{-1}$ $season^{-1}$)	Yield scaled CH_4 emission kg CH_4 kg^{-1} yield	GWPs ($kgCO_2$. $eq \cdot ha^{-1}$)	Total vol. of water reqd. m^3/ha	Water productivity ($kg \cdot m^{-3}$)	Cost for Irrigation Tk./ha	Grain yield ($kg \cdot ha^{-1}$)	Cumulative CH_4 $kg \cdot ha^{-1}$ $season^{-1}$	Yield scaled CH_4 emission (GHGI) kg CH_4 kg^{-1} yield	GWPs ($kgCO_2$. $eq \cdot ha^{-1}$)	Total vol.of water reqd. m^3/ha	Water productivity ($kg \cdot m^{-3}$)	Cost for Irrigation Tk./ha
Conventional irrigation	T_1: No NPKS, No amendments	1760f	192.0ab	0.097a	4805ab	30,700	0.057e	14,900	1550f	176.40a	0.090a	4410ab	29,200	0.053 e	14,500
	T_2: NPKS 100% RFD + VC 2.5 $t \cdot ha^{-1}$ + PG 1.0 $t \cdot ha^{-1}$	6070c	217.0a	0.037c	5425a	30,950	0.190cd	15,000	5960d	195.80a	0.032c	4875a	29,500	0.195	14,800
	T_3:: NPKS 50% RFD + VC 7.5 $t \cdot ha^{-1}$ + PG 2.0 $t \cdot ha^{-1}$	6450b	193.0ab	0.029cd	4825ab	30,700	0.210c	15,000	6350c	172.20ab	0.027d	4305ab	29,700	0.214	15,000
	T_4: NPKS 25% RFD + VC 10 $t \cdot ha^{-1}$ + PG 2.5 $t \cdot ha^{-1}$	6530ab	181.0b	0.027cd	4305bc	30,880	0.212c	15,500	6430bc	152.40cd	0.025d	3810bc	29,600	0.217	15,000
Alternate wetting and drying (AWD)	T_1: No NPKS, No amendments	1880f	169.0c	0.076b	4225c	22,800	0.082d	11,500	1680f	143.60d	0.069b	3590c	22,500	0.075	11,400
	T_2: NPKS 100% RFD + VC 2.5 $t \cdot ha^{-1}$ + PG 1.0 $t \cdot ha^{-1}$	6200c	178.0bc	0.028cd	4450b	22,700	0.270ab	11,900	6300c	160.80bc	0.025d	4020b	22,700	0.277	11,700
	T_3:: NPKS 50% RFD + VC 7.5 $t \cdot ha^{-1}$ + PG 2.0 $t \cdot ha^{-1}$	6680ab	155.0d	0.023d	3870d	22,900	0.290a	12,000	6700b	134.60de	0.020de	3365d	22,800	0.292	12,000
	T_4: NPKS 25% RFD + VC 10 $t \cdot ha^{-1}$ + PG 2.5 $t \cdot ha^{-1}$	6800a	137.0f	0.020e	3415f	22,900	0.297a	12,000	6760a	123.40g	0.019e	3085g	22,900	0.295	12,000
Aerobic irrigation	T_1: No NPKS, No amendments	1520g	155.0d	0.080ab	3875d	19,000	0.080d	9500	1550f	128.20f	0.072b	3205e	18,200	0.085	9.400
	T_2: NPKS 100% RFD + VC 2.5 $t \cdot ha^{-1}$ + PG 1.0 $t \cdot ha^{-1}$	5180e	170.0c	0.033cd	4250c	18,800	0.276ab	9800	5060e	153.80d	0.029cd	3825bc	18,700	0.271	9700
	T_3:: NPKS 50% RFD + VC 7.5 $t \cdot ha^{-1}$ + PG 2.0 $t \cdot ha^{-1}$	5570d	148.0e	0.027cd	3690e	18,850	0.295a	10,000	5380de	132.60e	0.025d	3315e	18,900	0.285	9,900
	T_4: NPKS 25% RFD + VC 10 $t \cdot ha^{-1}$ + PG 2.5 $t \cdot ha^{-1}$	5450de	133.0f	0.026cd	3320f	18,700	0.291a	10,000	5360de	121.20g	0.023de	3025f	18,600	0.288	10,000
LSD		1054.5	21.27	0.01	555.46	2250	0.04	1140	883.42	19.33	9.80	483.20	2760	0.05	1350
Level of significance		*	**	*	**	**	*	**	*	**	*	**	**		**
CV (%)		12.43	7.99	14.41	7.99	11.75	11.96	12.7	10.52	7.73	15.20	7.73	13.6	12.94	13.7

Table 2. Influence of soil amendments on postharvest soil properties under different irrigation practices.

Irrigation and soil amendments Treatments		Mohadebpur, Naogaon									Nachole, Chapainawabganj								
		Soil porosity (%)	Soil pH	SOC (%)	T-N (%)	Av. P (ppm)	Av.SiO₂ ppm	Soluble SO_4^{2-} (ppm)	Soluble Fe (ppm)	Soil Eh mV	Soil porosity (%)	Soil pH	SOC (%)	T-N %	Av. P (ppm)	Av.SiO₂ ppm	Soluble SO_4^{2-} (ppm)	Soluble Fe (ppm)	Soil Eh mV
Conventional irrigation	T_1: No NPKS, No amendments	47.5	6.13	0.95	0.07	9.50	43.6	5.10	3.3	−63.6	43.87	6.15	0.90	0.06	7.90	47.3	6.30	2.90	−51.6
	T_2: N100% RFD + VC 2.5 t·ha^{-1} + PG 1.0 t·ha^{-1}	48.6	6.27	1.15	0.11	13.60	54.6	11.60	5.7	−48.7	47.6	6.25	1.11	0.10	11.8	58.7	12.50	4.70	−43.5
	T_3: N 50% RFD + VC 7.5 t·ha^{-1} + PG 2.0 t·ha^{-1}	51.3	6.35	1.35	0.14	18.70	65.3	19.5	7.8	−37.6	49.7	6.34	1.30	0.12	18.9	69.3	21.30	7.30	−31.7
	T_4: N25% RFD + VC 10 t·ha^{-1} + PG 2.5 t·ha^{-1}	52.5	6.45	1.43	0.17	27.50	68.3	23.7	10.6	−30.5	51.8	6.43	1.45	0.15	24.50	73.6	28.60	8.50	−24.6
AWDI	T_1: No NPKS, No amendments	50.6	6.16	1.03	0.09	10.60	47.8	5.60	4.5	−51.7	50.5	6.14	0.98	0.08	9.87	49.8	7.30	2.60	−43.5
	T_2: N 100% RFD + VC 2.5 t·ha^{-1} + PG 1.0 t·ha^{-1}	52.5	6.34	1.27	0.14	17.50	55.6	13.80	6.7	−43.5	53.9	6.31	1.24	0.12	15.80	58.3	17.60	6.30	−33.6
	T_3: N 50% RFD + VC 7.5 t·ha^{-1} + PG 2.0 t·ha^{-1}	54.5	6.39	1.43	0.17	24.60	67.5	27.50	9.3	−29.7	54.6	6.35	1.38	0.16	21.70	69.8	29.60	8.30	−28.7
	T_4: N 25% RFD + VC 10 t·ha^{-1} + PG 2.5 t·ha^{-1}	56.3	6.43	1.65	0.19	31.50	71.3	33.60	13.7	−18.6	56.7	6.43	1.58	0.18	28.60	75.6	35.50	10.50	−15.6
Aerobic irrigation	T_1: No NPKS, No amendments	51.3	6.15	1.05	0.05	8.50	45.3	5.30	3.5	−48.3	50.9	6.13	1.05	0.04	9.87	48.6	6.50	2.50	−38.7
	T_2: N 100% RFD + VC 2.5 t·ha^{-1} + PG 1.0 t·ha^{-1}	53.7	6.24	1.30	0.15	15.3	57.8	12.50	5.3	−36.7	52.5	6.25	1.30	0.14	17.60	61.5	13.60	6.10	−31.5
	T_3: N 50% RFD + VC 7.5 t·ha^{-1} + PG 2.0 t·ha^{-1}	54.6	6.33	1.48	0.17	23.60	66.7	19.80	9.6	−28.6	53. 6	6.30	1.47	0.16	26.50	69.3	20.70	9.30	−24.6
	T_4: N 25% RFD + VC 10 t·ha^{-1} + PG 2.5 t·ha^{-1}	55.3	6.36	1.68	0.19	28.70	69.5	27.30	12.7	−18.3	54.7	6.35	1.65	0.18	30.30	71.3	28.30	13.50	−16.3
LSD		2.41	0.19	0.72	0.08	6.19	5.3	7.6	2.60	7.6	3.6	1.11	0.54	0.09	5.43	6.7	11.76	4.67	8.3
Level of significance		*	NS	*	*	*	*	*	*	**	*	NS	*	*	*	*	*	*	**
CV (%)		12.88	2.76	14.29	6.41	10.68	9.3	10.56	9.95	11.3	10.7	3.5	6.57	5.10	7.71	11.3	13.7	12.6	11.6

compared to standard fertilized with VC 2.5 t/ha and PG 1.0 t/ha amended plots under conventional irrigation.

3.8. Soil Redox Potential (Soil Eh)

Soil redox status significantly varied under different irrigation practices. Soil amendments with Vermicompost and PG influenced to some extent the oxidation reduction status and the decomposition of organic matter, thereby formation of organic acids and hydrogen, finally CO_2 and CH_4 production rate. Comparatively more intensive reduced conditions (Eh value −100 to −230 mV) were developed at active tillering to panicle initiation stage in conventional irrigation than that of Eh value recorded (Eh value −87 to −220 mV) under AWD and aerobic irrigations. A significant amount of CH_4 formed in paddy field was converted to CO_2 due to oxygen penetration in rice rhizosphere for AWD and aerobic irrigations. At ripening stage (before rice harvesting) soil redox condition was found less reductive (Table 2), which may be due to the cumulative effects of ferric iron oxide and sulfate ion (released from vermicompost and phosphogypsum), being acted as electron acceptors, thereby reduced CH_4 emission by stimulating CH_4 oxidation at rice rhizosphere.

3.9. Correlation of CH_4 Emissions with Grain Yield, GWPs and Soil Properties

Total cumulative CH_4 flux showed negative correlations with grain yield, soil porosity, soil Eh, water soluble sulfate and iron oxides; while positive correlations were found with GWPs and SOC contents (Table 3), being supported by our previous research findings (Hiya et al., 2020).

Table 3. Correlation of seasonal cumulative CH_4 emissions with grain yield, GWPs and soil properties of selected field sites.

Correlation coefficient (r)							
	Parameters	Mohadebpur, Naogaon			Nachole, Chapainawabganj		
		Conventional irrigation	AWD	Aerobic	Conventional irrigation	AWD	Aerobic
Cumulative CH_4 emissions	Grain yield	−0.168	−0.143	−0.153	−0.175	−0.136	−0.147
	GWPs	0.885***	0.879***	0.864***	0.878***	0.875***	0.868***
	Soil porosity	−0.789***	−0.774**	−0.764**	−0.768**	−0.678**	−0.648**
	Soil organic carbon	0.036	0.0436	0.0473	0.0485	0.0430	0.045
	Soil Eh	−0.683**	−0.574*	−0.578**	−0.678**	−0.645**	−0.667**
	Available P	−0.369	−0.388	−0.374	−0.464	−0.478	−0.487
	Available SiO_2	−0.564*	−0.687**	−0.656**	−0.576*	−0.698**	−0.678**
	Soluble SO_4^{2-}	−0.643**	−0.764**	−0.748**	−0.657**	−0.785**	−0.678**
	Soluble Fe	−0.578*	−0.668**	−0.674**	−0.648**	−0.685**	−0.676**

4. Discussion

Bangladesh is one of the most climate change risk-vulnerable country. The country needs to produce more rice to meet up the food demand of the expanded population, where irrigated rice farming will play a major role. Although farmers generally prefer irrigated rice cultivation during dry boro season due to high production and yield performance of HYV rice genotypes, however, irrigated rice farming is a major source of CH_4 emission and high energy consumption, which eventually causes higher GWPs and cost of production. In fact, 20% - 30% of the rice production cost is incurred for irrigation only in case of irrigated rice, depending on soil type and mode of payment (Alam et al., 2009). It has been reported that about 79% of the total cultivated area in Bangladesh is irrigated by groundwater, whereas the remaining is irrigated by surface water (Qureshi et al., 2014). Unfortunately, the groundwater table became unstable and is declining due to climate change, thereby may affect badly on irrigated rice production badly. Considering the climate change and water crisis issues, efficient water-saving irrigation practices such as AWD and aerobic irrigation practices hold a vital role for sustainable water management and rice productivity. AWD is basically a water management system, which does not involve any extra investment, just using a perforated plastic pipe (PVC) or bamboo pipe, to measure the soil surface water layers. In this experiment, the total amount of irrigation water applied for boro season rice cultivation was estimated 29,500 - 30,800 $m^3 \cdot ha^{-1}$ (two seasons' average) under conventional irrigation system, which was reduced by 24.5% - 26.0% and 37% - 39.0% through the AWD and aerobic irrigation practices, respectively. The higher water requirement in conventional irrigation methods may be due to higher irrigation frequencies (16), seepage and runoff, and higher evapotranspiration compared to AWD (12) and aerobic irrigation (8) practices. Hiya et al. (2020) reported that the total volume of irrigation water applied for *Boro* rice cultivation at BAU Farm was 19,430 $m^3 \cdot ha^{-1,}$ which was decreased by 18.0, 16.0 and 13.0% through AWD irrigation at 20, 15 and 10 cm, respectively. It has been shown that one (01) ton of rice production requires approximately 2500 L of water with AWD; and 5000 L of water for conventional irrigation (Bouman, 2009). Furthermore, the maximum saving of irrigation water was found to be 50% (Peng et al., 2006) and 47% (Oo et al., 2018) with aerobic and AWD irrigation, respectively. It has also been reported that AWD irrigation practices increased rice production by 5% - 15%, while decreasing CH_4 emission by 40% - 70%, saving irrigation water 30% - 60% (J. Yang et al., 2016; Linquist, 2015), which may be due to periodic aerobic process and field dryness. It has also been reported that AWD irrigation reduces CH_4 emissions by 34% - 42% in paddy soils during the drying period (Yang et al., 2025), while stimulating N_2O emissions via nitrification (aerobic) (Tran et al., 2018) and denitrification (anaerobic) processes.

The irrigation water application cost was calculated 14,825 - 15,100 $Tk \cdot ha^{-1}$ for conventional irrigation systems, which was decreased to 11,775 - 11,850 $Tk \cdot ha^{-1}$, and 9750 - 9825 $Tk \cdot ha^{-1}$ for AWD and aerobic irrigation systems, respectively.

Rahaman et al. (2022) reported that irrigation cost for boro rice (medium high land) cultivation was 11,226 Tk/ha, which was higher than that low lying main haor areas rice cultivation. Kashem and Rahman (2018) reported that irrigation cost for boro rice cultivation in Rajshahi region was Tk. 5178/ha through prepaid irrigation programme, which was Tk. 10,963/ha for private irrigation programme.

The experimental findings confirmed maximum rice yield under AWD irrigation method irrespective of soil amendments with vermicompost, phosphogypsum and NPKS fertilizers application in both locations. Considering the yield performance at both locations, AWD irrigation revealed higher rice grain yield by 4.0%, 4.5% and 5.3% compared to the grain yield performance in conventional irrigation amended with vermicompost at 2.5 t/ha plus PG 1.0 t/ha, 7.5 t/ha plus PG 2.0 t/ha and 10.0 t/ha plus PG 2.5 t/ha applications. This yield increment with vermicompost and phosphogypsum amendments following AWD irrigation could be due to improved soil redox status (Eh oxidative-reductive condition) and better soil porosity, which enhanced higher nutrients availability to rice plant, thereby contributing to maximum yield performance compared to other irrigation methods. Several studies have shown an increase in rice yield for AWDI and aerobic irrigation practices compared to conventional irrigation (Zhang et al., 2009; Qin et al., 2010; Ye et al., 2013; Chu et al., 2015; Islam, 2021). It has also been reported that aerobic rice needs 30% - 51% less total water for land preparation, 32–88% higher crop productivity, 50% saving on labor (Wang et al., 2002) and reduced GHG emission by 50% (Weller et al., 2016) compared to Puddled transplanting rice (Bouman et al., 2005). However, the lack of stable yield performance and dry direct-seeded adapted varieties for aerobic systems is a major limitation in achieving the maximum yield potential under water and resource-limited conditions. Ali et al. (2019) also reported that AWD irrigation showed better rice yield performance and reduced cumulative CH_4 emission, enhanced water savings and water productivity during the dry season boro rice cultivation in Bangladesh. It was also reported that moderate wetting and drying increased rice yield, decreased water use and CH_4 emissions (Hiya et al. 2020; Yang et al., 2016). Ahmad et al. (2014) mentioned that boro water productivity varies within 0.95 - 1.35 kg/m^3 in the north west region of Bangladesh. In our field experiments, water productivity (WP) value increased with AWD and aerobic irrigation practices compared to conventional irrigated field plots at both locations. Alternate wetting and drying (AWD) irrigation revealed maximum water productivity values of 0.270 - 0.297 kg·m^{-3} and 0.277 - 0.295 kg·m^{-3} with vermicompost amendments 2.5-7.5-10 t/ha at both experimental field rice cultivation. Conversely, under aerobic irrigation practice, higher WP values were recorded, 0.276 - 0.295 kg·m^{-3} and 0.271 - 0.288 kg·m^{-3} with vermicompost 7.5 - 10 t/ha amendments compared to other field plots at both locations. It has been reported that the water productivity of rice varied within 0.20 - 1.2 kg grain m^{-3} water under safe AWD with the threshold of −15 cm (Bouman et al., 2007; Lampayan et al., 2004). Our water productivity value lies within the mentioned range, a bit low moderate productivity probably due to critical soil hydrological properties in the selected locations.

In this study, the highest cumulative CH_4 emission 221 kg·ha^{-1}·season^{-1} was recorded in vermicompost (VC 2.5 t·ha^{-1}) amended field plot (NPKS 100% RFD + PG 1.0 t·ha^{-1}) under conventional irrigation; this decreased to 178.0 kg·ha^{-1} and 170.0 kg·ha^{-1} under AWD and aerobic irrigation practices, respectively. The increasing levels of vermicompost amendments 7.5 - 10.0 t·ha^{-1} and PG 2.0 - 2.5 t·ha^{-1} decreased cumulative CH_4 emissions by 11% - 17%, 13% - 23% and 13% - 21.7% under conventional irrigation, AWD and aerobic irrigation practices compared to Vermicompost (2.5 t·ha^{-1}) amendments with NPKS 100% plus phosphogypsum (1.0 t·ha^{-1}). The contents of water soluble SO_4^{2-} and total dissolved Fe increased significantly in the selected experimental plots due to the higher application rates of vermicompost (7.5 - 10.0 t/ha) and phospho-gypsum (2.0 - 2.5 t/ha). The lower CH_4 emissions under AWD irrigations may be due to increased aeration (54.5% - 56.3% soil porosity), stabilization of soil organic carbon, improved soil redox potential status (−18.6 - 29.7 mv), accumulation of free iron oxides (9.3 - 13.7 ppm) and sulfate ions (27.5 - 33.6 ppm), which acted as electron acceptors, thereby, reduced methanogens' activity and increased methane oxidation. Vermicompost application increased the availability of nitrogen in soil mostly in the form of nitrate relative to ammonium due to better soil aeration (Chatterjee et al., 2021), thereby improving soil redox status and eventually reducing CH_4 emissions. Other studies also revealed that AWD reduced cumulative CH_4 emissions by 32% (Lakshani et al., 2023), 29% (Pramono et al., 2024), 37% (Matsuda et al., 2023), 49% (Chidthaisong et al., 2018), 52% - 55% (Anapalli et al., 2023) and 77% (Echegaray-Cabrera et al., 2024) compared to continuous flooding. Phospho-gypsum is used in rice fields due to its low cost, easy availability and nutrient content, such as high content of Ca, Silicon dioxide (SiO_2) and especially sulfate in gypsum, acting as electron acceptors, thereby increasing the activity of sulfate-reducing bacteria over methanogens for the common substrates (Hori et al., 1993). In our previous research trial in rice field, it has revealed that seasonal cumulative CH_4 flux was reduced by 25% - 27% and 32% - 38% under continuous and intermittent irrigations, respectively (Ali et al., 2009). It has also been reported that intermittent irrigations significantly reduced total seasonal CH_4 emissions by 27% compared to conventional (124 kg CH_4/ha) irrigated rice paddy field (Ali et al. 2013). Soil amendments with vermicompost and phosphogypsum in combination with chemical fertilizers increased soil organic C and total N, enhanced soluble sulfate and total dissolved iron Fe contents, thereby reducing cumulative CH_4 emissions in rice field, which is supported by our previous research findings (Ali et al., 2009). It has also been reported that dry seasonal cumulative CH_4 emissions were decreased by 14.7%, 18.9% and 24.8% with biochar amendments at 15 t/ha, 20 t/ha and 30 t/ha respectively under conventional irrigation; while cumulative CH_4 emissions were reduced by 10.6%, 26% and 41.6% respectively, under AWD irrigation system (Ali et al., 2021).

In our experimental sites, the maximum GWPs value 4875 - 5425 kg CO_2-eq·ha^{-1}

was found in conventional irrigated field with 2.5 t·ha^{-1} VC amendments (NPKS 100% RFD + Phospho-gypsum 2.5 t·ha^{-1}), which decreased significantly under AWD and aerobic irrigations. The maximum decrease in GWPs were obtained by 21.8% - 25% and 22% - 27% with 10.0 t·ha^{-1} Vermicompost amendments (plus phospho-gypsum 2.5 t·ha^{-1} + 25% recommended N/ha + recommended PKS/ha) for AWD and aerobic irrigations, respectively. Tran et al. (2018) also reported that global warming potentials (GWPs) of CH_4 and N_2O under AWDs were 26-29% lower than those under continuous flooding in Central Vietnam. AWD irrigation decreased total GWPs by 34% - 64% to those of continuous flooding in paddy fields of Central Taiwan region (Yang et al., 2025).

In this study, seasonal cumulative CH_4 emissions were found positively correlated with GWPs and SOC, while negative correlations were recorded with grain yield, soil porosity, soil Eh, available P, available SiO_2, water soluble sulfate and iron oxides; being supported by Hiya et al. (2020). Van Der Gon et al. (2002) also reported that rice grain yield was negatively correlated with seasonal CH_4 flux. The increased grain yield, water productivity, irrigation water volume and cost savings, mitigating cumulative CH_4 flux as well as GWPs may positively inspire rice growers to adopt AWD irrigation technique. At the same time, the Govt. Policy makers, Govt. Organizations and NGO should strengthen their coordination and linkage to implement the water savings AWD and aerobic irrigation technique for sustainable rice farming at other agro-ecological zones of the country and disseminate this water-saving AWD technology in other rice-growing countries.

5. Conclusion

The findings from the field experiments confirmed that Vermicompost (7.5 - 10 t/ha) with Phosphogypsum (2.0 - 2.5 t/ha) amendments and reduced application (50% - 25% of the recommended dose) Nitrogen fertilizer maximized grain yield 6680 - 6800 kg·ha^{-1} under alternate wetting and drying (AWD). In addition, AWD and aerobic irrigation techniques saved total water inputs 24% and 37%, respectively, reduced irrigation cost Tk. 3500/ha for AWD and 5500/ha for aerobic irrigation compared to conventional irrigation. The GWPs were decreased by 34% - 36% and 37% - 39%, while increased grain yield by 4% - 5.0% compared to continuous flooding, depending on soil characteristics such as moisture contents, soil temperature, soil redox status, degree of soil dryness, rice crop duration, and growth stage. Above all, AWD and aerobic irrigation practices are feasible in terms of reducing GHGs emission and GWPs, sustaining water productivity and water savings during dry-season rice cultivation in the drought-prone Barind Tract areas of Bangladesh. Therefore, the Government and non-organizations should work in a collaborative way to implement environment-friendly AWD and aero-bic irrigation practices in a wider way at different agro-ecological regions of the country.

Recommendations

Further experimental trials may be given in other agro-ecological regions of the country to evaluate the biophysical and economic suitability of irrigation practices along with inorganic and organic amendments for sustainable rice productivity.

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Conflicts of Interest

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

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