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Development of Environment Friendly Paddy Ecosystem for Sustainable Rice Farming through Soil Amendments with Biochar and Alternate Wetting-Drying Irrigations

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Abstract

Climate change may badly affect the availability of water and soil nutrients to rice plant. Research experiments were conducted at the Environmental Science Departmental field, Bangladesh Agricultural University, Mymensingh during July 2017 to June 2019, to find out the suitable combination of biochar with inorganic fertilizers for minimizing seasonal yield scaled CH_4 emissions, reducing global warming potentials (GWPs) and sustainable rice farming under feasible irrigation practices. There were ten experimental treatments with different combinations of inorganic NPKS fertilizers and biochar (15 - 30 t/ha) under conventional flooding (CF) and alternate wetting-drying irrigations (AWDI). This study revealed that NPKS fertilization (50% of the recommended doze) with 15 t/ha biochar amendments under AWD irrigation maximized rice yield 6750 kg/ha and 4380 kg/ha in dry boro and wet aman seasons respectively, while the lowest rice yield 1850 kg/ha and 1550 kg/ha were recorded in continuously irrigated control treatment (T_1) during the dry and wet seasons respectively. Seasonal cumulative CH_4 emission, yield scaled CH_4 emission and GWPs were suppressed significantly with biochar amendments 15 - 30 t/ha under both conventional and AWDI irrigation systems during the wet and dry seasons of rice cultivation. Significant interactions were observed among biochar amendments and irrigation practices during the dry boro rice cultivation. 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 AWDI system. Finally, total global warming potentials (GWPs) were decreased by 6% - 15%, 13% - 30% with biochar amendments under conventional and AWDI irrigations respectively, in wet season; while global warming potentials (GWPs) also decreased by 14% - 25%, 11% - 42% with biochar amendments under conventional and AWDI irrigations, respectively, in the dry boro season. Biochar amendments increased water productivity index to some extent, but AWD irrigations significantly increased water productivity over the conventional irrigation in both wet and dry seasons. After experimental period, it was found that soil porosity, redox status, soil organic carbon (SOC) as well as overall soil properties were improved significantly with biochar amendments and AWD irrigations. Conclusively, biochar amendments @15 - 20 t/ha with half of the recommended inorganic (NPKS) fertilizers under alternate wetting-drying irrigations revealed an environment friendly integrated package approach to reduce seasonal cumulative CH_4 emissions as well as GWPs, while improving rice rhizosphere environment and rice productivity to meet the national food security.

Keywords

CH_4 Flux, GWPs, AWDI, Yield Scaled CH_4 Emission, Dry Boro Rice, Rainfed Aman Rice

1. Introduction

Rice is the staple food grain crop for the people of Bangladesh, which provides about 370 kcal energy from 100 g grains. In this country about 84% cropped area is used for rice cultivation, with total annual production 33.89 million metric tons (BBS, 2015). Bangladesh has a monsoon climate as well as hot humid subtropical climate with a four-month wet season and an eight-month dry season (Ahmad et al., 2014). The main rice growing seasons in Bangladesh are known as aman or wet season, aus or spring season and boro or dry season which is fully irrigated. Irrigated dry season boro rice is the main crop which is the highest yielding of the three rice seasons (Ahmed et al., 2013). BBS (2015) gives the average yield figures for boro rice as 3.86 tonnes/ha when sown with high-yielding conventional varieties, and an average of 4.75 tonnes/ha when sown with hybrid varieties. The average yield of rice in Bangladesh is about 3.0 t ha^{-1}, which is very low (BBS, 2015). Irrigation water supply is the prime requirement for sustainable rice farming, especially in the dry boro season, however, water scarcity is a vital problem for dry boro season rice production. In Bangladesh, irrigated boro rice (dry period) cultivation mainly contributes (about 55%) to total rice production (about 33.89 million tons) in the country. Unfortunately, irrigation water is a costly input to rice farming, which accounts for 28% of the total cost of rice production. It has been estimated that approximately 22 million hectares of irrigated dry-season rice may suffer from "economic water scarcity" in Asia by 2025 (Tuong, 2003). Furthermore, rice farming may become increasingly threatened due to climate change and extreme natural disasters in terms of increasing temperatures and uncertainty of precipitation, drought, floods and salinity (IPCC, 2007).

Irrigated rice farming is an integral part of rice production system in Bangladesh, which contributes greatly towards total annual rice production and food security. However, our rice cultivation especially in dry rabi season requires large amount of irrigation water, which is of great environmental concern due to energy crisis and methane (CH_4) emission from rice field to the atmosphere, which acts as a potential greenhouse gas with 25 times global warming potential than carbon dioxide (Nieder & Benbi, 2008). Boro rice cultivation is mostly dependent on irrigation water supply and the aman rice cultivation is partly irrigation water dependent. As groundwater is the main source of irrigation in Boro rice field in northwestern Bangladesh, higher abstraction rate of groundwater may cause negative impacts on groundwater resources in the region. The declining groundwater level may cause an increase in irrigation cost in the area and the economic losses of farmers. It has already been predicted that Bangladesh is going to face severe water crisis during dry season within the next couple of years. In this regard, alternate wetting and drying (AWD) of paddy field, developed by International Rice Research Institute, could save a significant volume of irrigation water 15% - 30% (Bouman et al., 2007) for rice production, mitigate CH_4 emission and sustain rice productivity.

The fertility of crop field in Bangladesh has been declining day by day due to continuous cropping and mining of nutrients, and indiscriminate use of chemical fertilizers. In this regard, biochar, mainly the carbon enriched materials with minute amount of plant nutrients obtained from organic matter under high pyrolysis temperature and oxygen limited condition (Lehmann & Rondon, 2006), could be the best organic manures to rejuvenate degraded soils. Biochar is an anaerobic pyrolysis product derived from organic material, resistant to easy degradation and capable of restoring soil carbon for a longer period of time by reducing greenhouse emission from soil to the atmosphere. Moreover, the use of biochar will cut down the amount of chemical fertilizers for rice cultivation and GHGs emissions may be suppressed by modifying the paddy ecosystem. It has already reported that combined application of rice husk biochar and FYM with reduced chemical fertilizer under less water inputs was found effective to sustain wheat crop yield in the highly vulnerable dry tropical agro-ecosystem of India (Singh et al., 2019). Furthermore, Singh et al. (2021) reported that compatible agricultural practices based on specific agroecosystem could be effective for climate change adaptations. Therefore, this study was undertaken to determine the suitable combination of biochar and chemical fertilizer (NPKS) for sustaining rice productivity, minimizing yield scaled methane emissions and improving paddy ecosystem through water savings AWDI system.

2. Materials and Methods

2.1. Experimental Location and Meteorological Condition

The present research work was conducted at Bangladesh Agricultural University

Field, Mymensingh during wet season, Aman rice (July to November 2017 & July to November 2018) and dry season boro rice cultivation (December 2017-May 2018; December 2018-May 2019). The experimental field was located at 24˚0'N latitude and 90˚25'E longitude at an elevation of 19 m above the sea level which falls under Agro-ecological region of the Old Brahmaputra Alluvial Tract (AEZ 9). The experimental field was medium high land with moderate drained condition. The soil was silty loam in texture (Sand: 23.5%, Silt: 73%, Clay: 3.5%) having a soil pH value 5.9, organic C 1.0%, total N 0.09%, available phosphorus (P) 11.5 ppm, available Sulphur (S) 11.0 ppm and exchangeable potassium (K) 0.09 ppm. The experimental area was under the sub-tropical climate that is characterized by high temperature, high humidity and heavy rainfall with occasional gusty winds in wet kharif season (April to September) and less rainfall associated with moderately low temperature during the dry rabi season (October to March).

2.2. Experimental Design, Treatments, Field Preparation and Rice Cultivation

The experiment was laid out in a randomized complete block design (RCBD) with ten treatments and three replications. The total numbers of plots were 30. Each plot size was 6 m × 5 m = 30 m^2. The experimental treatments are T_1 No NPKS, no amendments with conventional irrigation (CI); T_2 Farmers practice (100% recommended NPKS with CI; T_3 NPKS) 50% of the recommended NPKS with Biochar (@15 t/ha) under CI; T_4 NPKS 25% of the recommended dozeof NPKS with biochar (@20 t/ha) under CI; T_5 No NPKS with biochar (@30 t/ha) under CI; T_6 No NPKS, no amendments with AWDI irrigation; T_7 Farmers practice (100% recommended NPKS) with AWDI; T_8 NPKS (50% of the recommended dozeof NPKS with biochar@15 t/ha) under AWDI; T_9 NPKS 25% of the recommended dozeof NPKS with biochar@20 t/ha under AWDI; T_{10} No NPKS with Biochar (@30 t/ha) under AWDI. Rice cultivars BINA dhan-17and BINA dhan-10 were cultivated in wet aman and dry boro seasons, respectively.

2.3. Fertilizer Application

The fertilizer treatments were used in this experiment based on BARC fertilizer recommendation guide, 2012. Biochar as soil amendment was used in this experiment with NPKS. Standard doses of fertilizer were applied to the experimental field as recommended by Bangladesh Institute of Nuclear Agriculture (BINA) for BINA dhan-17. The whole amount of Urea, Triple Super Phosphate (TSP), Muriate of potash (MoP), Gypsum and Zinc Sulphate were applied for both Conventional flooding and AWDI practices. Urea was applied at final preparation, 40 - 45 days after transplant (DAT), 60 - 65 DAT, 75 - 85 DAT. The dose of fertilizer applied were urea 120 kg/ha, TSP 80 kg/ha, Muriate of potash 50 kg/ha, gypsum 30 kg/ha, Zinc Sulphate 1.5 kg/ha. The composition of the applied rice husk biochar were organic C 36%, total N 1.2%, P_2O_5 1.1%, K_2O 1.2%, SiO_2 1.0

ppm, SO_3 1.6 ppm, MnO 0.9 ppm, C/N ratio 30:1, pH 8.9.

2.4. Gas Sampling and Analysis

Gas samples were collected by the modified closed-chamber method (Rolston, 1986; Ali, 2008) during the rice cultivation. The dimension of each chamber was (120 cm × 60 cm × 60 cm). Gas samples were collected once a week after rice transplanting. Gas samples were collected by a 50 ml air-tight syringe at 0, 15 and 30 minutes intervals after chamber placement over the rice plants. 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 respectively.

2.5. Calculation of CH_4 Flux

CH_4 Flux ($F = \text{mg}\cdot\text{m}^{-2}\cdot\text{hr}^{-1}$) was calculated using the following formula (Rolston, 1986)

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

where, ρ = gas density (CH_4 = 0.714); V = volume of chamber (m^3); A = area surface of the chamber (m); $\Delta C/$ = average rate of increase of CH_4 gas concentration in the chamber; Δt = time and T = 273+ mean temperature within the chamber (˚C) [Conversion factor from ˚K to ˚C].

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

2.6. Estimation Global Warming Potential (GWP) of CH_4

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).

2.7. Determination of Water Savings

Water discharge from the irrigation pipe was calculated as the volume of water (m^3) flowing through the pipe and measured as cubic meter per second (m^3/s). The time required to maintaining appropriate water levels in the main plots during each irrigation was noted and summed to calculate the total volume of water applied to the plots throughout the cropping season. Water saving percentage was calculated using the formula:

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

2.8. Estimation of Water Productivity Index

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

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

2.9. Soil Properties

Soil redox potential (Eh) were measured during rice cultivation at certain time intervals by 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. Soil porosity was calculated using BD and particle density (PD, 2.89 $Mg \cdot m^{-3}$) 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, total nitrogen by Micro-kjeldhal method (Nelson & Sommers, 1980), available phosphorus by Colorimetric method (Olsen & Sommers, 1982), 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). Total iron and 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.

2.10. Statistical Analysis

The compiled and tabulated data of rice growth, yield, soil properties and CH_4 emission were statistically analyzed by Analysis of Variance (ANOVA) to examine whether treatment effects were significant or not. The mean differences among treatments were compared by Duncan's Multiple Range Test. The computer software MSTAT-C was used for statistical analysis.

3. Results

3.1. Trends of CH_4 Emission Rate and Soil Redox Potential during Rice Cultivation

CH_4 emission rates and soil redox potentials were significantly affected by biochar amendments and irrigation practices during the dry boro season and wet Aman season (**Figure 1** & **Figure 2**). In the dry boro season, CH_4 emission rate was very low within 7 - 14 DAT which increased gradually with plant development stages and peak CH_4 flux (approximately 40 mg CH_4 m^{-2} h^{-1}) was recorded in T2 treated (100% recommended NPKS under conventional irrigation) rice planted plot around 63 - 70 DAT (**Figure 1**).

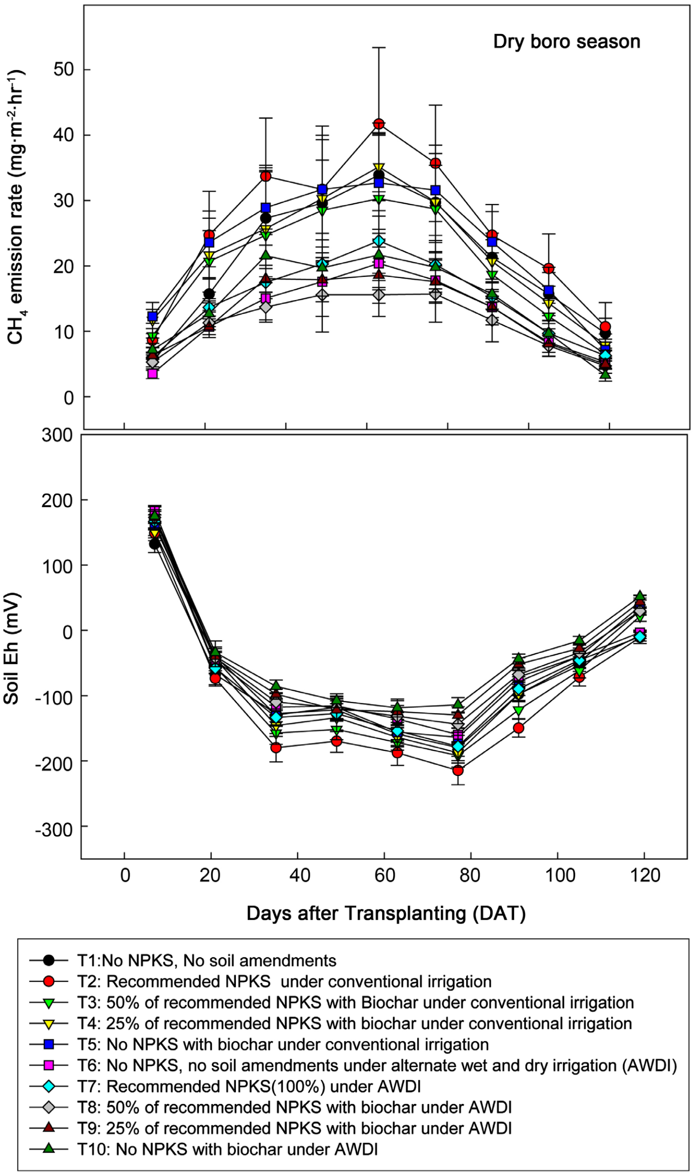

Figure 1. Trends of CH_4 fluxes and soil redox potentials during dry boro season rice cultivation (note: error bars indicate standard deviation among the mean values).

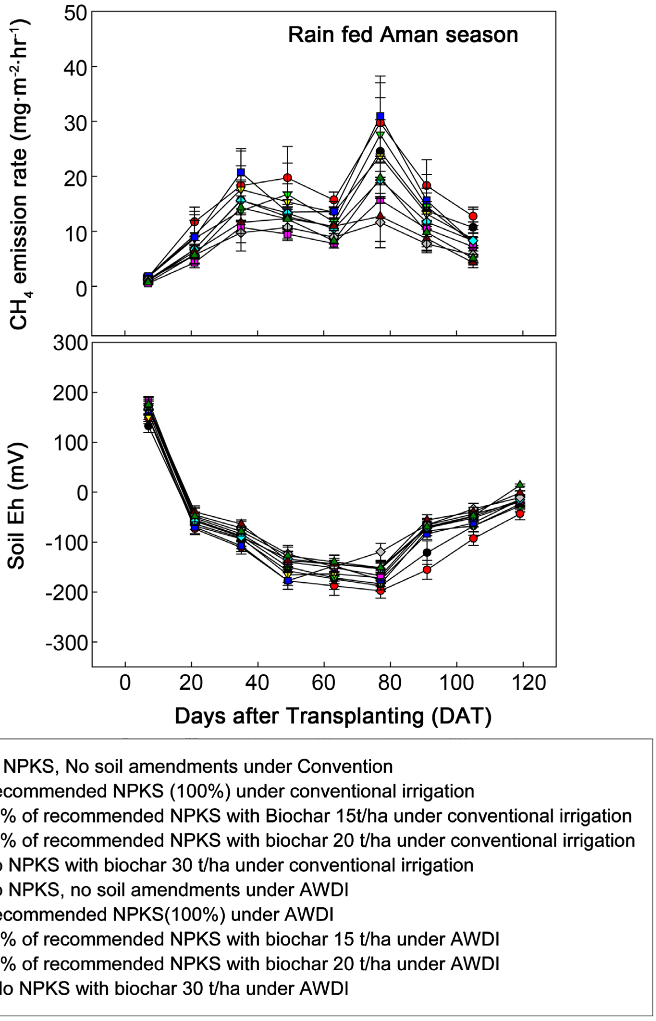

Figure 2. Trends of CH_4 fluxes and soil redox potentials (Eh) during wet Aman season rice cultivation (note: error bars indicate standard deviation among the mean values).

On the other hand, soil redox potential value started to decrease after rice transplanting and irrigation water application. Intense soil reduction condition (Eh value −200 mV to −250 mV) was developed under the conventional irrigation method within 70 - 77 DAT, which contributed significant amount of CH_4 emissions from rice field to the atmosphere (**Figure 1**). However, AWDI irrigation method showed less CH_4 emissions compared to conventional irrigation method. Biochar amended (20 - 30 t/ha) rice planted plots emitted lower CH_4 from conventional and AWDI practices, although biochar under AWDI mostly improved soil redox status and showed least amount of CH_4 emissions. During the rainfed aman rice cultivation CH_4 emission rate was very low within the 21 DAT which increased gradually with plant development stages and peaked (CH_4 flux 30 mg CH_4 m^{-2} h^{-1}) in T2 treated (100% recommended NPKS under conventional irrigation) rice planted plot at 77 DAT (**Figure 2**), thereafter decreased sharply towards rice harvesting stage.

Soil redox potential value also found highly negative (Eh value −180 mV to −220 mV) *i.e.* most reduction condition was observed around 77 DAT, which could be a vital factor for significant CH_4 emissions from rice rhizosphere to the atmosphere (**Figure 2**). Among the treatments, T2 treated rice planted plot showed maximum reductive condition under conventional irrigation, biochar amendments at 20 - 30 t/ha under AWDI improved soil redox status, which eventually lowered CH_4 emissions.

3.2. Cumulative CH_4 Flux, GWPs and Yield Scaled CH_4 Emissions (GHGI) under Biochar Amendments and AWDI

Cumulative CH_4 flux varied among the treatments, which may be due to biochar amendments and irrigation practices as well as seasonal effects. In the wet season, highest cumulative CH_4 flux (183.5 kg/ha/season) was observed in T2 (100% recommended NPKS without biochar) under conventional irrigation, while the lowest cumulative CH_4 flux (97.9 kg/ha/season) was recorded in T10 (biochar 30 t/ha) under AWDI irrigation (**Table 1**).

The maximum cumulative CH_4 flux (217 kg/ha/season) was found in T2 (100% recommended NPKS) under CI, while lowest cumulative CH_4 flux (98.6 kg/ha/season) was recorded in T10 (biochar 30 t/ha) under AWDI irrigation in the dry boro season (**Table 1**). Biochar amendments significantly decreased seasonal cumulative CH_4 emissions, GWPs and yield scaled CH_4 emissions (**Table 1**). In the wet season, biochar amendments 30 t/ha in T5 and T10 treated field plots showed the least amount of total cumulative CH_4 emissions, GWPs and yield scaled CH_4 emissions from rice field under the conventional and AWDI systems. It is interesting to mention that AWDI treated rice planted plots showed significantly lower amount of cumulative CH_4 emissions, GWPs and yield scaled CH_4 emissions compared to the conventional irrigated rice fields.

Rice cultivation during the dry boro season resulted significantly higher amount of total cumulative CH_4 emissions, GWPs and yield scaled CH_4 emissions compared to those parameters in wet Aman season (**Table 1**). Highest seasonal cumulative CH_4 emission (217 kg/ha/season) and GWPs (5425 kg CO_2 eq·ha^{-1}) were recorded from the NPKS (100%) fertilized plot (T2) under conventional irrigation, while the lowest seasonal cumulative CH_4 emission (98.6 kg/ha/season) and GWPs (2465 kg CO_2 eq·ha^{-1}) were found in T10 treated (biochar 30/ha) plot under AWDI irrigation system. Yield scaled CH_4 emissions (GHGI) were also recorded lowest in T9 (biochar 20 t/ha) and T10 (biochar 30/ha) treated plots under both conventional and AWDI systems (**Table 1**).

3.3. Post-Harvest Soil Properties

Biochar amendments increased soil porosity, SOC and T-N, soil pH, available phosphate, available Sulphur (S), exchangeable K^+ and free iron oxides in the post-harvest soils (**Table 2**).

Soil redox status also improved in the biochar amended field plots, probably due to the cumulative effects of free iron oxides (Fe_2O_3) in the rice rhizosphere

Table 1. Rice yield, water productivity, GWP and yield scaled CH_4 emission under different combinations of biochar and NPKS fertilizers in conventional and AWDI irrigation practices.

Rice growing seasons (A)	Treatments (B) Biochar amendments and irrigation practices	Grain yield (kg/ha)	Harvest Index (%)	Water productivity kg yield/m^3 water	Water required (L^{-1} kg rice production	Cumulative CH_4 flux (kg/ha/season)	GWP (kg CO_2 eq·ha^{-1})	GHGI (kg CH_4^{-1} kg grain yield/season)
Wet season (Rainfed aman)	T1: F0CI	1550h	30.9f	0.184	5400b	169.6bc	4240bc	0.109a
	T2: F1CI	4050f	41.7de	0.204	4900c	183.5b	4587ab	0.045c
	T3: F2CI	4200ef	42.5cd	0.214	4600cd	171.6bc	4290bc	0.040c
	T4: F3CI	4000ef	39.7de	0.221	4500d	163.5c	4087bc	0.041c
	T5: F4CI	3850f	38.5e	0.228	4300cd	155.6cd	3890c	0.04c
	T6: F0AWDI	1750gh	31.8ef	0.254	3900de	129.5e	3237d	0.074b
	T7: F1AWDI	4100ef	41,6d	0.373	2700f	135.6de	3497cd	0.033d
	T8: F2AWDI	4380e	43.5cd	0.415	2400fg	121.7ef	3042e	0.027e
	T9: F3AWDI	4250ef	41.2de	0.427	2300g	115.5f	2656f	0.027e
	T10: F4AWDI	4160ef	40.3d	0.435	2200g	97.9g	2447g	0.023e
Dry season (Boro)	T1: F0CI	1850gh	30.5f	0.165	6000a	177bc	4425b	0.095ab
	T2: F1CI	5500d	47.2ab	0.205	4900c	217a	5425a	0.039d
	T3: F2CI	6580ab	48.3a	0.227	4600cd	185ab	4625ab	0.028e
	T4: F3CI	6250bc	46.6b	0.239	4400de	176bc	4400b	0.028e
	T5: F4CI	5860cd	44.2c	0.223	4500d	163c	4075bc	0.027e
	T6: F0AWDI	2180g	32.6ef	0.264	3800e	155cd	3875c	0.071b
	T7: F1AWDI	5670cd	44.7c	0.436	2300g	169bc	4225bc	0.029e
	T8: F2AWDI	6750a	48.5a	0.523	2000h	151d	3750c	0.023e
	T9: F3AWDI	6480b	46.9b	0.520	1900hi	125ef	3125de	0.019e
	T10: F4AWDI	6050c	44.5c	0.530	1800i	98.6g	2465g	0.016f
ANOVA	A	***	**	**	**	***	**	**
	B	***	***	***	***	***	***	***
	A × B	***	**	**	**	**	**	**

Note. T$_1$: F0W1 (5 cm standing water No NPK) with level; T$_2$: F1W1 (NPKS 100%) with 5 cm standing water level; T$_3$: F2W1 (NPKS 50% + 15 t biochar/ha with 5 cm standing water level; T$_4$: F3W1:NPKS (25%) + 20 t/ha biochar/ha with 5 cm standing water level; T$_5$: F$_4$W1: No NPKS (0) + 25 t biochar/ha with 5 cm standing water level; T$_6$: F0W2: (No NPK) with AWDI irrigation; T7: F1W2: (NPKS (100%) + 5 t biochar/ha with AWDI; T8: F2W2: NPKS (50%) + 15 t biochar/ha with AWDI; T9: F3W2: NPKS (25%) + 20 t biochar/ha with AWDI; T10: F$_4$W2: No NPKS (0) + 25 t biochar/ha with AWDI.

which enhanced electron activity in soil and acted as electron acceptor, thereby enhanced soil porosity (Table 2). At the end of the experiment maximum increment in soil porosity, soil pH, SOC, SO_4-S and free iron oxides were found in biochar amended (20 - 30 t/ha) field plots under conventional and AWDI systems. This may be due to the mineralization of organic S from fertilizers and biochar. In addition, higher concentrations of free iron oxides in soil could be

Table 2. Effect of biochar amendments and AWDI irrigation practices on chemical properties of post-harvest soil (after two years of cropping).

Treatments	Soil porosity (%)	pH	Soil Organic Carbon (g/kg)	Total Nitrogen (%)	Available P (ppm)	Available S (ppm)	Ex. K Potassium (meq/100g)	Soil Eh (mV)	Free iron oxide (g/kg)
Initial Soil	45.7	6.1	10.7	0.15	8.7	11.3	0.09	−10.3	3.7
Soil amendments	Post harvest soil properties (after two years of cropping)								
T1: F0CI	48.0	6.43	9.3	0.13	10.36	10.6	0.08	−21.7	3.3
T2: F1CI	49.6	6.58	13.6	0.18	14.67	13.5	0.10	−25.3	3.9
T3: F2CI	51.5	6.69	16.3	0.19	14.87	15.3	0.13	−9.3	4.7
T4: F3CI	53.3	6.75	17.9	0.16	14.47	16.7	0.15	−7.7	5.3
T5: F4CI	54.0	6.93	19.6	0.15	16.63	18.3	0.15	−8.3	6.7
T6: F0AWDI	50.7	6.50	10.9	0.11	10.70	9.7	0.09	−17.6	3.6
T7: F1AWDI	52.6	6.59	14.1	0.17	13.72	12.9	0.12	−14.3	4.0
T8: F2AWDI	54.7	6.71	16.7	0.20	15.97	14.6	0.14	−9.3	5.9
T9: F3AWDI	55.3	6.83	18.5	0.19	14.97	17.7	0.15	−6.5	6.8
T10: F4AWDI	56.0	6.91	20.6	0.17	14.73	19.5	0.16	−3.6	7.9
$LSD_{0.05}$	2.245	0.265	2.67	0.02	1.45	1.7	0.05	2.8	0.56
Level of significance	**	NS	**	**	*	*	*	***	***

from the total iron content in soil, where biochar amendment might have contributed as an additional source.

3.4. Correlation of Cumulative CH_4 Emissions with Grain Yield and Soil Properties

There were negative correlations between total seasonal CH_4 fluxes with grain yield, harvest index, soil pH, soil Eh, soil porosity, soil organic carbon, total N, available P and SO_4-S, free iron oxide contents in soil under both dry and wet seasons (Table 3), while positive correlations were recorded with rice plant productive tillers and aboveground biomass.

4. Discussion

In this study, the seasonal CH_4 emission trends were found significantly high in dry boro season compared to wet aman season, which may be due to the variation in yield potential of the rice cultivars, irrigation water supply and consumption, meteorological and rice rhizosphere environmental variations within the seasons. CH_4 flux was higher during reproductive stage of rice plant in all treatments, which may be due to higher availability of labile organic C from the decomposition of soil organic materials (Dubey, 2005), higher diffusion rate of CH_4 gas through rice root and shoot aerenchyma from rice rhizosphere zone

Table 3. Pearson's correlation co-efficient of CH_4 emissions with selected rice plant growth, yield components and soil properties.

		Correlation coefficient (r) Wet Season	Correlation coefficient (r) Dry Season
Growth and yield components	Plant height	0.454	0.398
	Productive tillers $hill^{-1}$	0.557*	0.648*
	Above ground biomass	0.679**	0.648*
	Grain yield	−0.487*	−0.581*
	Harvest index	−0.345	−0.438
Soil properties	Soil porosity	−0.786***	−0.568*
	Soil organic carbon	−0.05	−0.009
	T-N	−0.042	−0.057
	Soil pH	−0.359	−0.470
	Soil Eh	−0.788***	−0.689**
	Available P	−0.264	−0.175
	Available S	−0.589**	−0.668**
	Ex. K_2O	0.463	0.517*
	Free iron oxide	−0.687**	−0.835***

being supported by Kludge et al. (1993) and Hiya et al. (2020). The sharp fall in CH_4 emission rates at grain maturation stage in all the treatment combinations might be due to the aging of rice plant, leaf senescence, lack of available water and labile organic C as supported by Cai et al. (1997).

In this study grain yield was significantly influenced by biochar amendments and irrigation practices. The findings confirmed that biochar amendments 15 - 20 t/ha with NPKS fertilizers (50% of the recommended doze) maximized rice yield under AWDI method. In the dry boro season, rice yield was increased by 19.6%, 13.6% and 6.5% with biochar amendments at 15 t/ha, 20 t/ha and 30 t/ha respectively, under conventional irrigation; whereas the corresponding yield increments were 19.0%, 14.2% and 6.9% respectively, under AWDI method. The yield increments with biochar amendments following AWDI could be due to the maximum productive tillers/hill and higher nutrients availability to rice grain compared to other treatments. Sanjit et al. (2016) reported that rice grain yield (5950 $kg \cdot ha^{-1}$) was a bit higher in conventional irrigation compared to the AWDI treated field plot yield (5820 $kg \cdot ha^{-1}$) during the dry boro season in Bangladesh. Ali et al. (2019) also reported that the AWDI treatment showed superiority for the rice yield performance and seasonal CH_4 emission reduction, water savings, and maximum water productivity index under the dry seasonal conditions 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). In this study, biochar applications 20 - 30 t/ha under alternate wetting and drying (AWDI) irrigation resulted least cumulative CH_4 emissions and GWPs, while highest water productivity and moderate yield performance were found in the rainfed wet season and dry boro season. The lower CH_4 emission under AWDI treated field plots may be due to increased aeration, stabilization of soil organic carbon, improved soil redox potential status and accumulation of free iron oxides, sulfate ions which acted as electron acceptors, thereby, reduced methanogens' activity. On the contrary, Ali et al. (2015) reported that biochar amendments in paddy soils increased cumulative CH_4 emissions. This contrasting result may be due to the variation in the composition of biochar as well as different agro-ecological zones. Zhang et al. (2012) reported that the soil amendment with biochar was found effective for mitigating CH_4 emission, which also increased rice yield by 25% - 26% compared to inorganic fertilizers. Ali et al. (2013) also 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. In this study, biochar amendments improved the soil redox status and soil porosity, mostly observed under the AWDI treated field plots. Consequently, total seasonal CH_4 emission significantly decreased in AWDI plot compared to the conventional irrigated rice field. Hiya et al. (2020) found that total GWP of CH_4 significantly decreased with AWDI treatments as compared to continuous flooded plots. This result also showed that AWD irrigation system is better than conventional irrigation in terms of water productivity index and water savings. Higher productivity index was found in biochar amended field plots under the AWDI method compared to conventional irrigation. Singh et al. (2019) reported that combined application of rice husk biochar and FYM with reduced chemical fertilizer under less water inputs was effective to sustain wheat crop yield in the highly vulnerable dry tropical agro-ecosystem of India. Hossain et al. (2016) reported that water productivity increased from 0.35 $kg \cdot m^{-3}$ to 0.65 $kg \cdot m^{-3}$ following better research management over the farmers' practice, environment friendly technology for reducing groundwater use in the irrigated ecosystem. Xiao et al. (2018) reported that rice straw biochar amendments at 20 t/ha and 40 t/ha significantly decreased CH_4 emissions by 29.7% and 15.6%, respectively, while rice yield was increased by 24% and 33% and irrigation water productivity was increased by 36% and 42%, respectively, over the control. In this study, biochar amendments 20 - 30 t/ha showed the maximum free iron oxide contents under both AWDI and conventional irrigated (CI) field soils, which was supported by Ali et al. (2014).

This study showed that there were negative correlations between total seasonal CH_4 fluxes with grain yield, water productivity index, soil pH, soil Eh, soil porosity, soil organic carbon, total N, available P and S (**Table 3**), while positive correlations were recorded with plant productive tillers and above ground biomass. Hiya et al. (2020) stated that total seasonal CH_4 flux was negatively correlated with grain yield, water productivity index, soil Eh, organic matter, total N, available P and S, soil porosity and soil pH under continuous irrigated treatment. Denier van Der Gon et al. (2002) reported that rice grain yield was negatively correlated with seasonal CH_4 flux. The increased water productivity of rice and water saving aspects will make farmers and other stakeholders to adopt AWDI technique. Therefore, biochar applications @ 15 - 20 t/ha with half of the recommended chemical fertilizers and adopting alternate wetting drying irrigations may be a feasible technique for reducing yield scaled CH_4 emission as well as GWPs and sustaining rice productivity through improving soil properties and rice rhizosphere environmental conditions.

5. Conclusion

The findings from the field experiments confirmed that biochar amendments @15 - 20 t/ha with half of the recommended chemical (NPKS) fertilizers maximized rice yield under AWDI method especially in dry boro season rice cultivation. Higher amendments of biochar @20 - 30 t/ha with alternate wetting and drying (AWDI) irrigation resulted least cumulative CH_4 emissions and GWPs, while the highest water productivity and moderate yield performance were found in the rainfed wet season and dry boro season. Therefore, biochar amendments @15 - 20 t/ha along with half of the recommended inorganic fertilizers under alternate wetting and drying irrigations may be adopted as an integrated package approach to adapt in hot humid and water scarce conditions for reducing yield scaled CH_4 emission as well as GWPs, while increasing water productivity and sustaining rice productivity to meet the national food security.

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Conflicts of Interest

There is no conflict of interest regarding publishing the findings of this research.

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