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Effects of Irrigation Regimes and Rice Varieties on Methane Emissions and Yield of Dry Season Rice in Bangladesh

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Abstract: Adoption of the right rice variety and water-saving irrigation method could reduce greenhouse gas (GHG) emissions in lowland rice cultivation. A study was conducted at the research farm of Bangladesh Agricultural University, Mymensingh, Bangladesh, in 2019 during the Boro (dry) season to determine the impacts of different rice varieties (BRRI dhan29, BRRI dhan47, BRRI dhan69, Binadhan-8, Binadhan-10, and Binadhan-17) on methane (CH_4) emissions under two irrigation methods, i.e., alternate wetting and drying (AWD) and continuous flooding (CF). The treatments were laid out in a split-plot design, considering water regime as the main plots and rice variety as the sub-plots. The emission rates of CH_4 were determined by collecting air samples using the closed chamber technique and measuring the concentrations using a gas chromatograph. CH_4 emission rates varied with the growth and development of the rice varieties. The lowest cumulative CH_4 emission rate was observed in Binadhan-17, particularly under AWD irrigation. Across the rice varieties, AWD irrigation significantly reduced the cumulative CH_4 emissions by about 35% compared with CF. No significant variation in rice yield was observed between AWD (5.38 t ha^{-1}) and CF (5.16 t ha^{-1}). This study suggests that the cultivation of Binadhan-17 under AWD irrigation could be effective at reducing the carbon footprint of lowland rice fields.

Keywords: methane; rice cultivars; alternate wetting and drying; emission factor; rice yield

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1. Introduction

Rice is the staple food crop in Bangladesh and cultivated in is 11.4 million hectares (ha) across three crop growing seasons per year [1,2]. Of the three seasons, Boro (dry season, December/January to March/April) results in an area under rice crop (irrigated rice) production of 4.8 million ha [3]. The total rice production in Bangladesh was 36.6 million tons (t) in 2019/20, and Boro rice contributed the majority of the total production [3]. Although rice plays a critical role in food security, it is associated with environmental pollution due to the emissions of greenhouse gases (GHGs), particularly methane (CH_4).

Irrigated rice cultivation emits CH_4, one of the main GHGs responsible for global warming and climate change [4]. Lowland rice cultivation with continuous irrigation makes the soil environment anoxic, which favors the bacterial decomposition of organic materials through methanogenesis and produces CH_4 gas [5,6]. It is reported that rice cultivation accounts for 1.5% of all anthropogenic GHG emissions worldwide [7].

CH_4 emissions are influenced by various soil; climatic; and crop management factors, including irrigation systems, crop variety, and fertilizer management [7–9]. Continuous flooding (CF) irrigation, a common practice for lowland rice cultivation, produces a significant amount of CH_4 [7,10,11] and a limited amount of N_2O [12,13]. CF irrigation lowers the redox potential (−150 mV), which enhances methanogenesis and results in the increased production of CH_4 [14,15]. The CH_4 produced in the soils is emitted to the atmosphere through three different pathways—ebullition, diffusion, and plant-mediated transport [16]. The rice plant plays an important role, as more than 90% of CH_4 is emitted from waterlogged soil to the atmosphere via aerenchyma cells [16].

In Bangladesh, Boro rice cultivation consumes higher amounts of irrigation water, which is supplied through the extraction of groundwater. Because of continued extraction, the groundwater table has shown a declining trend [17] and this has increased the irrigation costs for farmers. Therefore, the significance of water-saving irrigation methods, such as alternate wetting and drying (AWD), is increasing because they can reduce water use by up to 38% without reducing yield compared with farmers' conventional irrigation method, i.e., CF [17]. Previous studies have reported that the adoption of AWD irrigation could reduce GHG emissions by up to 40% without any yield penalty [7,8,10,11,18,19]. AWD irrigation reduces the total GHG emissions from rice fields, mostly because of decreased CH_4 emissions, despite the fact that it may marginally increase N_2O emissions [18,20–22]. As a result, the most efficient strategy to reduce the global warming potential (GWP) of rice soil is to reduce the emission of CH_4 [7,23,24]. However, the impacts of AWD on rice yield are still contradictory and inconclusive [1,2,17,25,26]. More studies are needed across different soil types and different agroecological zones, rice-growing seasons, and crop management practices, including different varieties, to develop a comprehensive picture of the effects of water-saving irrigation on rice yield and GHG emissions.

In addition to irrigation regimes, rice variety could affect emissions. Previous studies have shown a considerable difference in emissions among the different rice cultivars. The differences in emission rates are associated with the amount of root exudates, decaying of root tissues and leaf litter, accumulation of photosynthate in grain and straw, and crop growth duration [14,27,28]. There is also the potential option to reduce CH_4 emissions through rice breeding, i.e., developing new varieties with a high-yielding capacity [29,30].

In Bangladesh, the area under rice cultivation, particularly Boro rice, must be extended to meet the increasing food demand, which may cause significant CH_4 emissions and ultimately accelerate the effects of global warming. The role of rice in global food security is unavoidable as it is one of the three most essential food crops globally, after wheat and maize [31]. Most previous studies have been conducted to quantify the effects of fertilizer and water regime on GHG emissions from rice fields [7,10,11,32]. However, the impacts of different rice cultivars under various water regimes on CH_4 emissions, rice yields, and yield-contributing characteristics are not well documented. Therefore, the present investigation was conducted to determine the interaction effects of the rice variety and irrigation regime (AWD vs. CF) on rice yield and CH_4 emissions during the Boro (dry) season.

2. Materials and Methods

2.1. Experimental Sites and Weather Conditions

The field experiment was conducted at the research farm of Bangladesh Agricultural University, Mymensingh (latitude: 24°44′36″ N, longitude: 90°23′54″ E), during Boro season (January–May 2019). The experiment site had a tropical humid climate. The maximum rainfall was observed in April and the minimum in January. The highest air temperature (28 °C) was observed in May and the lowest (19 °C) in January. The average daily air temperature and rainfall are shown in Figure 1. The detailed soil physicochemical properties are shown in Table 1.

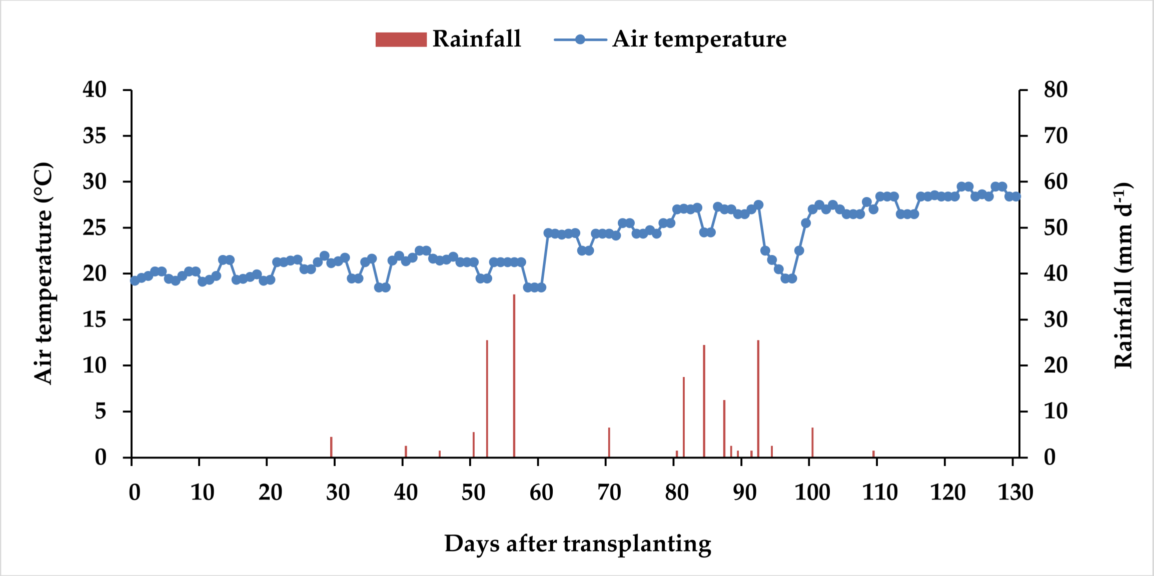

Figure 1. Average daily rainfall and air temperature during the rice-growing season (Source: Weather Station of Bangladesh Agriculture University, 2019).

Table 1. Physicochemical properties of the initial soil sample of the experimental field.

Parameter	Value	Methods	Reference
pH (soil:water = 1:2.5)	6.94	Glass electrode pH meter method	[33]
Organic carbon (%)	0.645	Wet oxidation method	[34]
Total nitrogen (%)	0.058	Micro-Kjeldahl method	[33]
Available phosphorus (mg kg^{-1})	5.56	Olsen method	[35]
Available sulfur (mg kg^{-1})	8.42	Turbidimetric method	[36]
Exchangeable potassium cmol(+) kg^{-1}	0.119	NH4OAC extraction method	[37]
Zinc (mg kg^{-1})	0.36	DTPA extraction method	[37]

2.2. Experimental Design and Treatments

The experimental treatments were laid out in a split-plot design with three replications. Two irrigation methods—AWD and CF—were considered as the main plots and six rice varieties: BRRI dhan69, BRRI dhan47, BRRI dhan29, Binadhan-8, Binadhan-17, and Binadhan-10 (Table 2) were considered as the sub-plots. In total, there were 36 plots, each having the dimensions of 5 m × 4 m = 20 m^2.

Table 2. Details of the six rice varieties used in the experiment.

Code	Rice Variety	Variety Description
V_1	BRRI dhan69	Parentage: WuShan YouZhan/P1312777, Grain type: Medium bold, Potential yield: 7.3 t ha^{-1}, Requires 20% less inputs, GSR variety, Duration: 153 days
V_2	BRRI dhan47	Parentage: IR515111-B-B-34-B/TCCP266-2-49-B-B-3, Grain type: Medium bold, Potential yield: 6 t ha^{-1}, Duration: 152 days
V_3	BRRI dhan29	Parentage: BG90-2/BR 46-51-5, Grain type: Medium slender, Potential yield: 7.5 t ha^{-1}, Duration 160 days
V_4	Binadhan-8	Pedigree: IR66946-3R-1-1, Grain type: Medium bold, Potential yield: 5–7 t ha^{-1}, Duration: 130–135 days
V_5	Binadhan-17	Pedigree: (SAGC-7 (GSR)), Grain type: Medium bold, Potential yield: 7.5 t ha^{-1}, Requires less inputs, Saves 30% water, GSR variety, Duration: 118 days
V_6	Binadhan-10	Pedigree: IR64197-3B-14-2, Grain type: Medium slender, Potential yield: 5.5–6.0 t ha^{-1}, Duration 125–130 days

Source: http://www.brri.gov.bd (accessed on 12 October 2022) & http://www.bina.gov.bd/ (accessed on 12 October 2022).

2.3. Crop Management

The crops were irrigated as per their treatment. For AWD, the plots were irrigated when the floodwater depth dropped 15 cm below the soil surface. AWD irrigation was started 15 days after transplanting (DAT). To monitor the belowground water level, a 20 cm hole was dug in the rice field and a perforated plastic pipe was installed. This water regime was maintained until the flowering stage of the crop. From the flowering to the dough stage, 2–4 cm of standing water was maintained (Figure 2) in order to prevent any potential water stress on the crops. For CF, the floodwater depth for each plot was maintained at a range of 1 to 5 cm.

Standard doses of fertilizer were applied to the experimental field, as recommended by the Bangladesh Rice Research Institute (BRRI). The entire amount of urea at 180 kg ha^{-1}, triple superphosphate at 60 kg ha^{-1}, muriate of potash at 60 kg ha^{-1}, gypsum at 40 kg ha^{-1}, and zinc sulfate at 6.0 kg ha^{-1} were applied for both AWD and CF practices. Urea was applied in three equal splits at 10–15 DAT, 30–40 DAT, and 50–60 DAT. The rice seedlings were transplanted at a spacing of 25 cm × 15 cm.

The ten rice hills were harvested from each plot randomly just before harvesting to determine the tillers, effective tillers, grains per panicle, and 1000-grain weight. The rice grain yield was recorded by harvesting 125 rice hills from the middle of each plot. Harvested rice was threshed, cleaned by winnowing, and sun-dried. Grain yield was adjusted at 14% moisture content and converted to tons per hectare [1].

2.4. Gas Sampling and Analysis

The air samples were collected from each plot using the closed chamber technique [38] (Figure 3). Each chamber consisted of a base and a top. The chamber base was inserted into the soils 2–3 days before the first gas sampling, where it remained throughout the crop growing period. The dimensions of the closed chambers were 62 cm × 62 cm × 100 cm. The gas samples were collected between 09:00 a.m. and 11:00 a.m. at 10-day intervals across different growth stages (active trilling, flowering, heading, and ripening stages) to determine the average CH_4 emissions during the cropping season. In each gas sampling day, gas samples were collected from each chamber in 50 mL gas-tight syringes at 0, 15, and 30 min. The samples were analyzed to determine the concentration of CH_4 gas using gas chromatograph (Shimadzu 2014, Kyoto, Japan), equipped with a flame ionization detector. The gas chromatograph was equipped with a stainless-steel column packed with Porapak NQ (Q 80100 mesh). The temperatures of the column, injector, and detector were adjusted to 100 °C, 200 °C, and 200 °C, respectively.

2.5. Estimation of CH_4 Emission Rates and Cumulative Emissions

CH_4 emission rates were calculated from the slope of the linear regression curve against the chamber closure time, as explained by Islam et al. [7]. Cumulative CH_4 emissions were estimated by summing the daily emissions.

2.6. Estimation of the EF of CH_4, GWP, and GHGI

The emission factor (EF) of CH_4 (kg ha^{-1} day^{-1}) was calculated by dividing the total CH_4 emissions (kg ha^{-1}) by the active rice growth period (days).

The global warming potential (GWP; kg CO_2 equivalent ha^{-1}) of CH_4 was calculated using the following equation [7]:

$$\text{GWP (kg CO}_2\text{ equivalent ha}^{-1}) = (\text{TCH}_4 \times 28) \quad (1)$$

where TCH_4 is the total amount of CH_4 emissions (kg ha^{-1}) and 28 is the GWP value for CH_4.

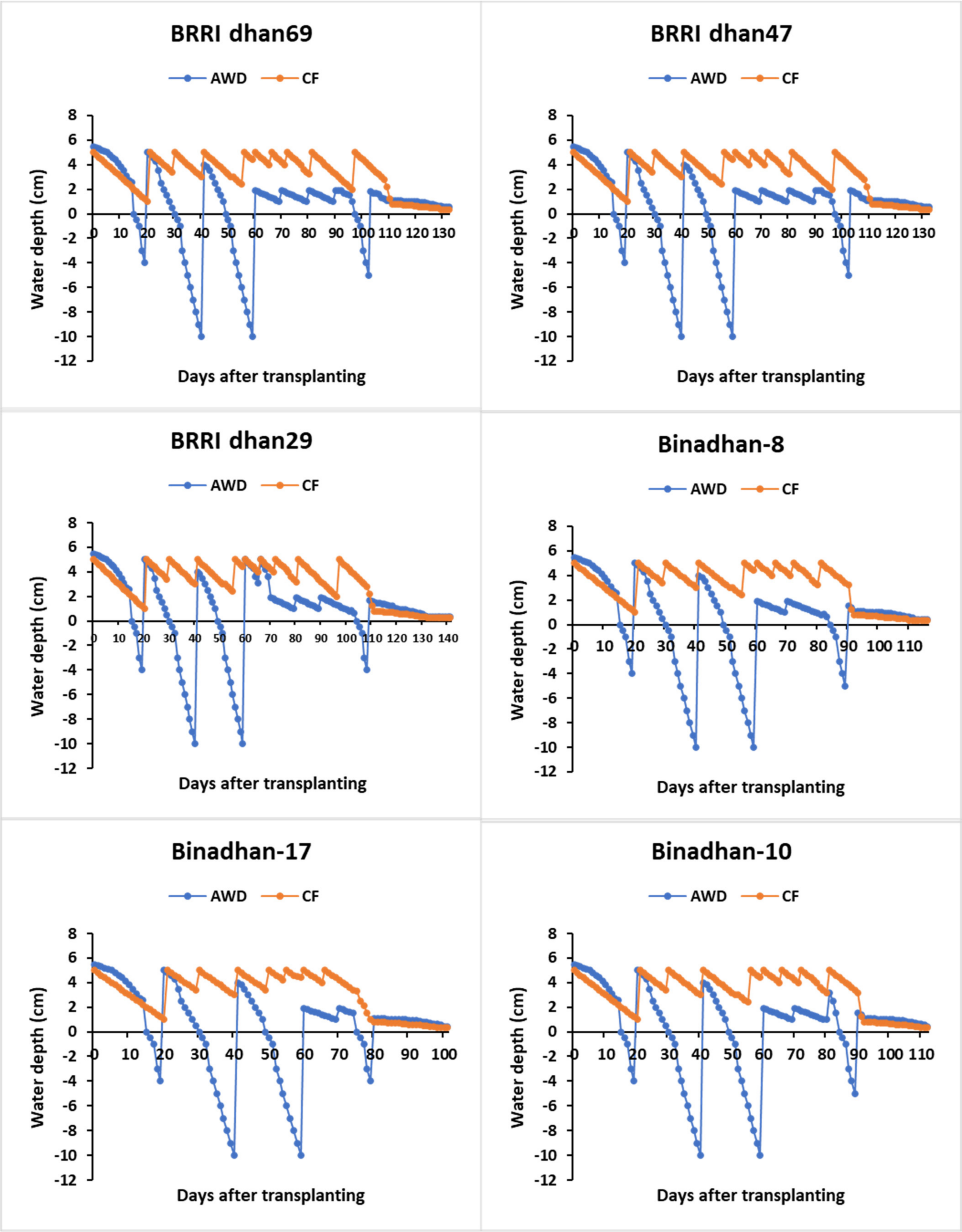

Figure 2. Daily floodwater depth across alternate wetting and drying (AWD) and continuous flooding (CF) plots during the rice- growing season.

Figure 3. Gas sampling from rice field.

The greenhouse gas intensity (GHGI; kg CO_2 equivalent kg^{-1} grain yield) was calculated by dividing the total GWP by grain yield (kg ha^{-1}) using the following equation [7]:

$$\text{GHGI} = \text{TGHG}/\text{Yield} \quad (2)$$

where GHGI is the total GHG emission per unit of rice yield (kg CO_2 eq kg^{-1} grain yield).

2.7. Statistical Analysis

Analysis of variance (ANOVA) of the yields, yield components, CH_4 emissions, GWP, and EF were conducted with the Statistical Tool for Agricultural Research (STAR 2.0.1, International Rice Research Institute, Philippines) software. The mean differences of the treatments were obtained from the least significant difference (LSD) test at a 5% level of probability.

3. Results

3.1. Effects of Rice Varieties and Irrigation Regimes on Yield and Yield-Contributing Characteristics

3.1.1. Number of Effective Tillers

There was no interaction effect of rice variety and irrigation regime on the number of effective tillers per m^2 (Table 3). The number of effective tillers per m^2 varied from 157.75 (BRRI dhan47) to 174.10 (BRRI dhan29). The irrigation method had a significant effect on the number of effective tillers per m^2. They were higher in AWD irrigation (184 m^2) than the CF method (151 m^{-2}).

Table 3. Effect of rice variety on the number of effective tiller per m^2, number of filled spikelets per panicle, and number of sterile spikelets per panicle.

Varieties	**Water Management**	**Number of Effective Tiller per m^2**	**Number of Filled Spikelets per Panicle**	**Number of Sterile Spikelets per Panicle**	
		Mean of 2 Water Regimes	**Mean of 2 Water Regimes**	**AWD**	**CF**
BRRI dhan69	Mean	171.55 a	173.70 a	38.73 bc	23.53 b
BRRI dhan47		157.75 a	116.70 c	51.93 b	20.27 b
BRRI dhan29		174.10 a	152.60 ab	28.47 cd	25.13 b
Binadhan-8		173.24 a	121.27 c	31.80 c	22.60 b
Binadhan-17		165.04 a	147.90 b	76.47 a	51.53 a
Binadhan-10		165.59 a	122.60 c	14.27 d	14.07 b
Mean	AWD	184.41 a	138.90 a	40.27 a	
	CF	151.35 b	139.36 a	26.18 b	
ANOVA (*p* value)					
Varieties (V)		ns	*	*	
Irrigation (I)		*	ns	*	
V × I		ns	ns	*	

In a column, figures having the same letter(s) do not differ significantly, whereas figures with different letter(s) differ significantly, as per LSD at 5% level of significance. AWD = alternate wetting and drying; CF = continuous flooding; ANOVA = analysis of variance; * = significant; ns = non-significant.

3.1.2. Number of Filled Spikelets per Panicle

There was no interaction effect of rice variety and irrigation regime on the number of filled spikelets per panicle. However, it was significantly affected by rice variety, with the highest number observed in BRRI dhan69 (174) and the lowest in BRRI dhan47 (117) (Table 3). The number of filled spikelets per panicle was similar between the two irrigation methods.

3.1.3. Number of Sterile Spikelets per Panicle

There was an interaction effect of rice variety and irrigation regime on the number of sterile spikelets per panicle (Table 3). The highest number of sterile spikelets per panicle was recorded in Binadhan-17 under AWD irrigation and the lowest number of sterile spikelets per panicle was recorded in Binadhan-10 under CF irrigation. The number of sterile spikelets per panicle was not significantly influenced by the irrigation method.

3.1.4. Spikelet Fertility

There was an interaction effect of rice variety and irrigation regime on spikelet fertility (Table 4). The highest spikelet fertility (89.40%) was recorded in Binadhan-10 under AWD irrigation, which was statistically similar to BRRI dhan29. The lowest spikelet fertility (70.07%) was recorded in Binadhan-17 under AWD irrigation. Spikelet fertility was significantly influenced by the irrigation method; a higher percentage (84.54%) was observed under CF compared with AWD irrigation (78.35%).

Table 4. The effect of rice variety on spikelet fertility, spikelet sterility, 1000-grain weight, and grain yield.

Variety	Water Management	Spikelet Fertility (%)		Spikelet Sterility (%)		1000-Grain Weight (g)		Grain Yield (t ha^{-1})
		AWD	CF	AWD	CF	AWD	CF	Mean of 2 Irrigation
BRRI dhan69	Mean	79.80 b	88.87 a	20.20 b	11.13 b	23.81 a	24.80 b	5.79 a
BRRI dhan47		70.07 cd	84.80 a	30.60 a	15.20 b	23.63 a	26.37 a	5.36 b
BRRI dhan29		84.27 ab	85.80 a	15.73 bc	14.20 b	20.91 b	20.41 c	5.22 b
Binadhan-8		78.67 bc	85.93 a	21.33 b	14.07 b	25.16 a	26.79 a	5.17 b
Binadhan-17		67.93 d	72.73 b	32.07 a	27.27 a	20.49 b	20.84 c	5.05 b
Binadhan-10		89.40 a	89.13 a	10.60 c	10.87 b	25.63 a	26.97 a	5.04 b
Mean	AWD	78.35 b		21.75 a		23.26 b		5.38 a
	CF	84.54 a		15.45 b		24.36 a		5.16 a
ANOVA (*p* value)								
Varieties (V)		*		*		*		*
Irrigation (I)		*		*		*		*
V × I		*		*		*		ns

In a column, figures having the same letter(s) do not differ significantly whereas figures with different letter(s) differ significantly, as per LSD at a 5% level of significance. AWD = alternate wetting and drying; CF = continuous flooding; ANOVA = analysis of variance; * = significant; ns = non-significant.

3.1.5. Spikelet Sterility

There was an interaction effect of rice variety and irrigation regime on spikelet sterility (Table 4). The highest spikelet sterility (32.07%) was recorded in Binadhan-17 under AWD irrigation. Similarly, AWD irrigation produced higher sterility (22%) compared with CF irrigation (15%).

3.1.6. 1000-Grain Weight

There was an interaction effect of rice variety and irrigation regime on the 1000-grain weight (Table 4). The highest 1000-grain weight was recorded in Binadhan-10 under CF irrigation. Similarly, the lowest 1000-grain weight was recorded in Binadhan-17 under AWD irrigation. The 1000-grain weight was significantly influenced by the irrigation method; CF produced a higher weight (24.36 g) than the AWD irrigation (23.26 g).

3.1.7. Grain Yield

There was no significant interaction effect of irrigation regime and rice variety on yield (Table 4). The grain yield ranged from 5.04 to 5.79 t ha^{-1}. The highest grain yield was observed in BRRI dhan69. The grain yields across AWD and CF irrigation were similar ($p > 0.05$).

3.2. Correlations between Yield-Contributing Characteristics of Rice Varieties

Grain yield showed a significant positive correlation with the number of filled spikelets per panicle (r = 0.437 **). However, there was no correlation with the number of effective tillers per m^2, number of sterile spikelets per panicle, spikelet fertility, spikelet sterility, or 1000-grain weight (Table 5).

Table 5. Pearson correlation between the yield contributing characters of rice varieties.

Dependent Variable	Independent Variable	Coefficient of Correlation (r)
Yield (t ha^{-1})	Number of effective tillers per m^2	0.257
	Number of filled spikelets per panicle	0.437 **
	Number of sterile spikelets per panicle	0.013
	Spikelet fertility (%)	0.030
	Spikelet sterility (%)	−0.024
	1000-grain weight (g)	−0.017

** Correlation is significant at the 1% level (two-tailed).

3.3. Dynamics of CH_4 Emissions

The amount and trend in CH_4 emission rates varied by water regime and rice variety (Figure 4). Emission peaks were observed at the tillering and flowering stages, irrespective of variety, under both irrigation regimes. The magnitudes of the emission rates were higher under CF irrigation compared with the AWD irrigation. CH_4 emission rates varied from 32.82 to 95.33 mg m^{-2} day^{-1} under AWD irrigation, while they ranged from 62.41 to 161.41 mg m^{-2} day^{-1} under CF irrigation (Figure 4). The emission rates were similar between two rice varieties, BRRI dhan29 and Binadhan17, but the total emissions were higher in BRRI dhan29 due to its longer growth duration (Table 2).

3.4. Cumulative CH_4 Emissions, EFs, GWP of CH_4, and GHGI

There was a significant interaction effect of rice variety and irrigation regime on the total CH_4 emissions, EFs, GWP, and GHGI (Table 6). The maximum total CH_4 emission was found in BRRI dhan29, while the lowest emission was recorded in Binadhan-17 under both the AWD and CF irrigation regimes (Table 6). The EFs ranged from 0.70 to 0.73 kg ha^{-1} day^{-1} under AWD irrigation and from 1.01 to 1.11 kg ha^{-1} day^{-1} under CF irrigation (Table 6). The lowest GWP was found in Binadhan17, while BRRI dhan29 showed the highest GWP under both AWD and CF irrigation. Similarly, the lowest GHGI was found in Binadhan17, while BRRI dhan29 showed a higher GHGI under both AWD and CF irrigation (Table 6). Across the rice varieties, AWD irrigation significantly reduced the cumulative CH_4 emissions and GHGI by about 35% and 37%, respectively, compared with CF irrigation (Table 6).

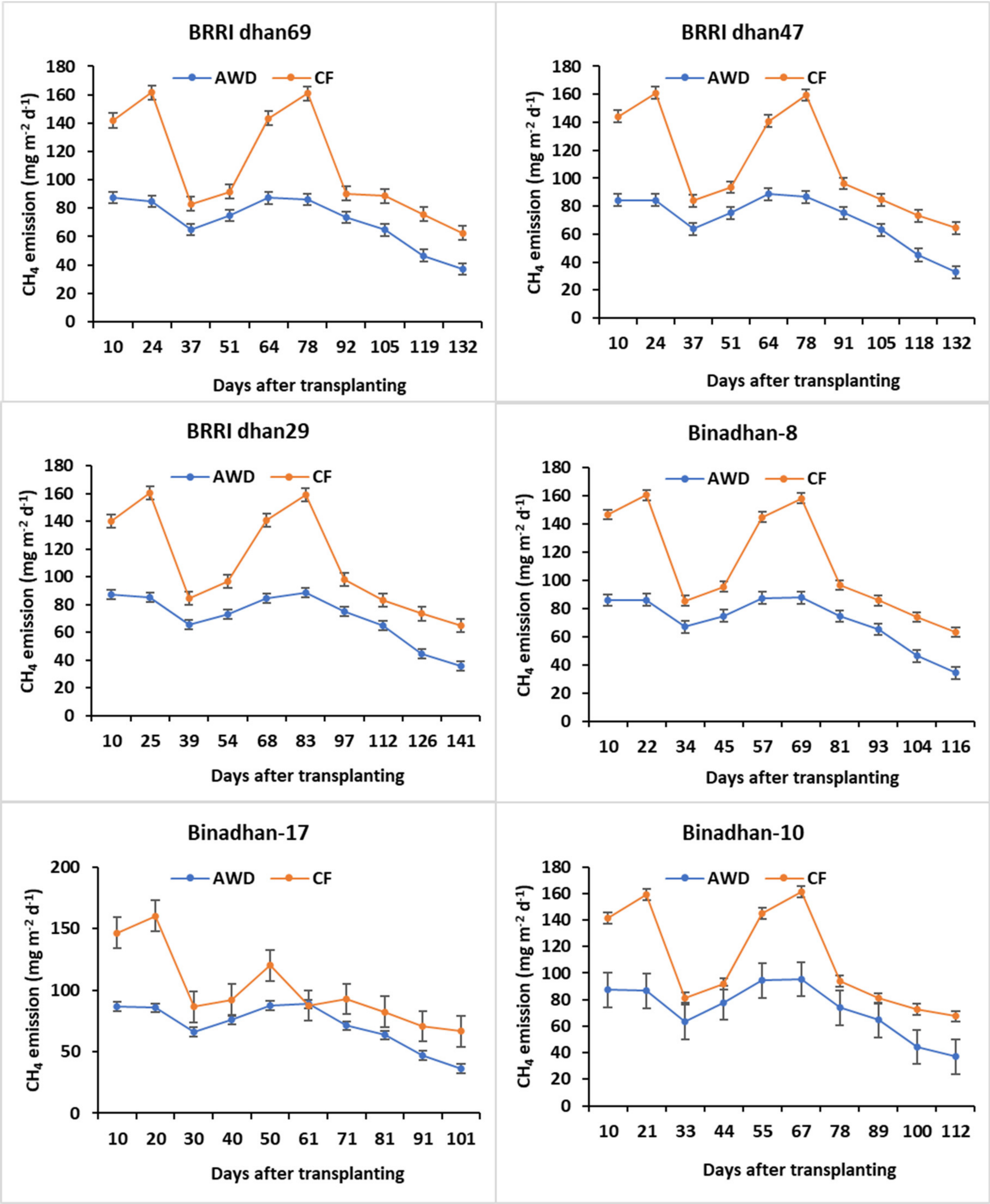

Figure 4. Effect of rice variety on CH$_4$ flux (mg m^{-2} day^{-1}) under alternate wetting and drying (AWD) and continuous flooding (CF) methods of irrigation. Vertical bars correspond to the standard error of means.

Table 6. Effect of rice variety and irrigation regime on total CH_4 emissions, EFs, GWP of CH_4, and GHGI (kg CO_2 equivalent kg^{-1} grain yield).

Varieties	**Water Management**	**Total CH_4 (kg ha^{-1} $season^{-1}$)**		**EF of CH_4 (kg ha^{-1} day^{-1})**		**GWP (kg CO_2 Equivalent ha^{-1}) of CH_4**		**GHGI (kg CO_2 Equivalent kg^{-1} Grain Yield)**	
		AWD	**CF**	**AWD**	**CF**	**AWD**	**CF**	**AWD**	**CF**
BRRI dhan69		108.31 b	168.21 ab	0.71 ab	1.10 a	3032.80 b	4710.00 ab	0.52 b	0.82 b
BRRI dhan47		106.25 b	167.38 b	0.70 b	1.10 a	2974.90 b	4686.70 b	0.53 b	0.92 ab
BRRI dhan29		112.67 a	176.13 a	0.70 ab	1.10 a	3154.70 a	4931.70 a	0.59 a	0.97 a
Binadhan-8		94.30 c	147.65 c	0.71 ab	1.11 a	2640.30 c	4134.10 c	0.51 b	0.81 b
Binadhan-17		81.37 d	115.59 d	0.71 ab	1.01 b	2278.40 d	3236.60 d	0.44 c	0.67 c
Binadhan-10		94.22 c	142.36 c	0.73 a	1.10 a	2638.30 c	3986.20 c	0.52 b	0.81 b
Mean	AWD	99.52 b		0.71 b		2786.60 b		0.52 b	
	CF	152.89 a		1.09 a		4280.90 a		0.83 a	
ANOVA (*p* value)									
Varieties (V)		*		*		*		*	
Irrigation (I)		*		*		*		*	
V × I		*		*		*		*	

In a column, figures the same letter(s) do not differ significantly, whereas figures with different letter(s) differ significantly, as per LSD at a 5% level of significance. AWD = Alternate wetting and drying, CF = Continuous flooding, ANOVA = Analysis of variance. * = significant, ns = non-significant.

4. Discussion

4.1. Rice Yield

AWD irrigation had no significant effect ($p > 0.05$) on rice grain yield compared to CF irrigation (Table 4). These results are in close agreement with previous findings [2,10]. The magnitude of grain yield depends on soil type and intensity of soil drying [2,39]. A similar yield between AWD and CF might be associated with similar filled spikelets per panicle (Table 3). Although AWD irrigation increased the effective tillers, it significantly reduced spikelet fertility (Table 4). Islam et al. [1] reported that AWD irrigation significantly reduced grain yield compared with CF irrigation. The difference between our findings and previous findings might be due to the different locations, soil types, growth duration of rice cultivars, climatic conditions, fertilizer management, and crop management [1,2,21,26]. While AWD irrigation in this study did not produce a significant yield advantage over CF irrigation, it reduced CH_4 emissions by about 35%.

Across the irrigation regimes, BRRI dhan29 produced the highest grain yield compared with the other varieties (Table 4). The highest grain yield under BRRI dhan29 could be linked with a higher number of effective tillers and filled spikelet per panicle and a lower spikelet sterility (Tables 4 and 5). In addition, the variation in genetic characteristics of rice varieties determines the potential yield, which is controlled by heredity [40,41]. The 1000-grain weight of six lowland rice varieties varied from 20.49 to 25.63 g and 20.41 to 26.97 g, with an average value of 23.26 and 24.36 g under AWD and CF irrigation, respectively. The 1000-grain weight is an almost stable varietal characteristic under most conditions [2,42], but in this study, it was significantly influenced by the different rice varieties. This indicates different rice varieties show different grain types, particularly bold or fine grain, which is controlled by varietal characteristics [42,43].

4.2. CH_4 Emissions, EFs, GWP, and GHGI

In general, CH_4 emission rates increase with increased of growth and development of rice plants until flowering, due to the good development of aerenchyma tissue, release of more root exudates, and fermentation of easily degradable soil organic matter in lowland rice cultivation [7,10,11,28,44]. In this study, CH_4 emission peaks were observed at the tillering and flowering stages under both AWD and CF irrigation regimes (Figure 4). This might be explained by the microbial degradation of rhizodeposition, root exudates, algal biomass, and microbial biomass during the tillering stage [28,45]. Similarly, higher emission peaks at the flowering stage might be attributed to higher methanogenesis and soil labile organic carbon [28,46]. Our results are consistent with previous findings [7,10,11,47]. Across the varieties, lower emission peaks were found in AWD irrigation compared with CF conditions throughout the rice-growing season, which might be attributed to the oxidation of CH_4 by the methanotrophs due to the drying of soil [7,28,48].

Both the rice variety and irrigation regime affected the total CH_4 emissions (Table 6). Across the irrigation regimes, the lowest CH_4 emission was recorded in Binadhan-17. The variation in CH_4 emissions among the rice cultivars was due to the difference in magnitudes of root exudates, decaying of root tissues and leaf litter, low photosynthate in grain, and difference in growth duration [14,27,28]. For example, Setyanto et al. [27] observed that the early maturing variety produces low CH_4 emissions (52–112 kg CH_4 ha^{-1}) compared with the late maturing variety (116–142 kg CH_4 ha^{-1}). In this study, Binadhan-17 showed maturity about 15–20 days earlier compared with the other tested varieties. Our results are supported by previous findings [27,49].

Irrigation regimes have a significant role in CH_4 emissions [7,10]. In this study, AWD irrigation significantly reduced CH_4 emissions by about 35% compared with CF irrigation (Table 6), as reported by previous studies [7,10,11,50]. Islam et al. [7] found a 37% reduction in CH_4 with AWD irrigation compared with CF conditions. The reduction in CH_4 emissions under AWD irrigation might be correlated with an increased O_2 supply during dry periods, leading to an aerobic soil environment in which CH_4 is oxidized by the methanotrophic bacteria. In contrast, CF conditions make the soil environment anaerobic, which enhances the anaerobic fermentation of degradable organic material to supply C sources for the methanogens, thus resulting in higher CH_4 emissions [15,28].

The CH_4 EFs were 0.71 and 1.09 kg ha^{-1} day^{-1} under AWD and CF irrigation, respectively (Table 6). Similar emission factors were reported by previous studies [7,10,11]. However, these EFs were lower compared with the IPCC default EF of 1.19 and 0.85 kg ha^{-1} day^{-1} for the world and South Asia (no residue incorporation), respectively [51]. Irrigation regime had a significant interaction effect with rice variety on GWP and GHGI (Table 6). The lower GHGI and GWP of CH_4 observed in Binadhan-17 compared with other tested varieties (Table 6) was in close agreement with previous studies [27,49]. However, AWD irrigation significantly reduced GWP and GHGI by about 35% and 37%, respectively, compared with CF irrigation (Table 6), similar to the findings reported by previous studies [7,52].

5. Conclusions

This study suggests that rice variety plays a vital role in mitigating CH_4 emissions. However, there could be some yield penalty with this reduction. The lowest CH_4 emission was found in Binadhan-17, but the rice yield was about 15% lower compared with BRRI dhan69. These results indicate that the carbon credit calculation should also consider crop yield, as it is important for achieving food security, particularly in developing countries. In this case, yield-scaled emissions are more important than area-scaled emissions. We suggest further studies be conducted in different agroclimatic zones of Bangladesh to confirm these findings. Regardless of the varietal role, AWD irrigation has the potential to reduce cumulative CH_4 emissions compared with CF irrigation, without any yield loss. Therefore, climate-smart variety selection in combination with environmentally friendly irrigation management is effective at mitigating GHG emissions in lowland rice cultivation.

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